Review Article

Cold plasma technique in controlling contamination and improving the physiological processes of cereal grains: a review

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Abstract

Today, almost half of the total human food needs, especially in Asia, is directly supplied from grains, and nearly 70% of the cultivated area of the world, which is one billion hectares, is occupied by grains. Therefore, finding non-destructive methods to increase seed quality in agriculture and industry should be developed. The cold plasma is a novel and efficient method in the agricultural and food sectors, which can be used for inactivation of surface microorganisms and excitation of seeds. This review presents a summary of the effectiveness of cold plasma treatment on the characteristics of four important cereal plants: wheat, rice, corn and barley. The focus is on the effects of this treatment on seed germination, surface property changes and water uptake of seeds, growth parameters of root, shoot and seedling length, biomass parameters and metabolic activities. By examining the research conducted by the researchers, it can be seen that the cereal seeds treated with cold plasma had better germination power, water absorption, shoot and shoot length, growth efficiency, shoot and root weight, and metabolic activity. This review can provide potential promising trends in utilizing plasma as a method to decrease the prevalence of harmful plant diseases transmitted through seeds and reduce dormancy of hard seeds.

Keywords: Cereal grain; cold plasma; seed treatment; biological feature

Introduction

Cold atmospheric plasma, has gained significant popularity in recent years. In the last few years, cold plasma finds extensive use in agriculture or plant biological applications including cultivation, surface sterilization, seed germination, pretreatment before drying, modification of surface properties, decontamination of seeds and disease control (Liao et al., 2020).

The use of different plasma devices has enabled extensive research on plasma treatment of seeds. These devices facilitate in-depth investigations into the physical, chemical, and biological processes triggered by plasma components (Maghsoudi, Balvardi, Ganjovi, & Amir-Mojahedi, 2023; Ranieri et al., 2021). There are two methods for plasma treatment of seeds, namely direct and indirect, which are determined by the interaction between the plasma and the samples (Gómez-Ramírez et al., 2017). In the indirect treatment system, the treated surface is placed at a distance from the plasma production point, and the produced plasma is transferred to the sample surface through the fed gas flow. This system produces UV and chemical species with longer life and less reactivity. In the direct treatment system, the treated product is relatively close to the place of plasma production. This system produces a higher concentration of reactive species. At high voltage, this system induces electrical conductivity in a product that has high internal moisture content and water activity. Local heating in this system can cause sensory damage such as burn symptoms or protein coagulation, as well as changes in aroma, texture, and appearance (Niemira, 2012).

Cold plasma can be readily produced through different types of electric discharges. The most frequently utilized methods include dielectric barrier discharges (DBD), plasma jets, corona discharges, gliding arcs, and microwave discharges (Adhikari et al., 2020). All of these plasmas are non-thermal, meaning that the discharge occurs at atmospheric temperature and pressure. The jet, corona, gliding arcs, and microwave discharges can treat the surfaces of large objects and is useful for improving the adhesion of materials in industrial processing (Kusano et al., 2014). The mild operating conditions and low temperature, along with the flexible reactor shape and the ability to use gas mixtures of DBD

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plasma, make it an attractive option for modifying temperature-sensitive surfaces, particularly agricultural products (Fang, Wang, Shao, Qiu, & Edmund, 2011). The seeds and seedlings can also be soaked or watered using plasma-activated water (PAW), which is made by exposing liquids to plasma. Similar effects on macroscopic plant properties have been observed when comparing the use of gaseous and aqueous treatments (Sajib et al., 2020; Sivachandiran & Khacef, 2017).

Cereals are a type of monocotyledonous herbaceous plant whose tiny seeds are edible. In many Asian and African countries, more than 80% of people's food is provided by grains. The share of cereals in the food of European people is 45-55% and in the United States it is approximately 20-30%. Wheat, rice, and corn are the three most important crops, each accounting for roughly a quarter of the annual grain production. To feed the projected global population of 9.8 billion people by 2050, there is a need for a 70-100% increase in the supply of cereal food (Godfray et al., 2010).

Increasing production rates are commonly seen as the answer to meet the growing demand. However, historical data indicate that the current production rates fall far short of what is needed to achieve the targets (Ray, Mueller, West, & Foley, 2013). On the other hand, desertification and adverse climatic and agricultural conditions such as drought and salt are spreading rapidly. Therefore, researchers are trying to find suitable methods to break seed dormancy and increase the percentage and speed of seed germination, and also to find cultivars that are more resistant to drought, salinity and disease in order to improve crop yield (Radjabian, Saboora, Hhasani, & Fallah-Hosseini, 2007).

The objective of this review is to present a summary of the extensive knowledge acquired by researchers in studying the impact of cold plasma on plant seeds, which is rapidly expanding. We chose the seeds of cereal plants because their presence in the diet is essential and food security must be ensured. Given the increasing attention towards plasma agriculture, it is valuable to provide an overview of the hypotheses and current evidence on the impact of plasma treatments on cereal seeds. The main essentials of our review are summarized in Fig. 1.

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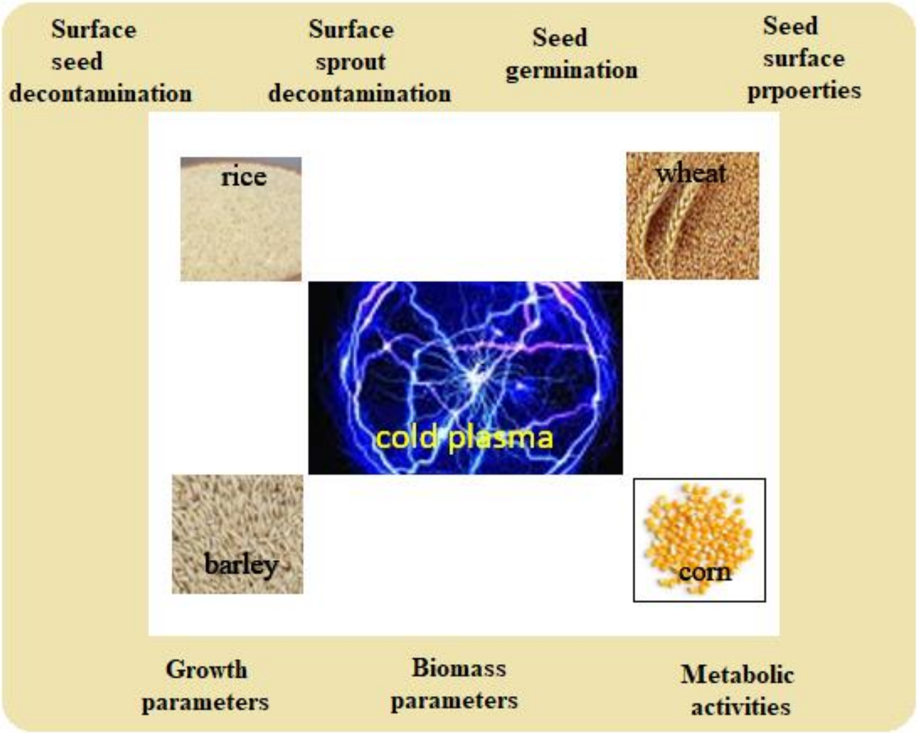

Fig. 1. Schematic overview of the effects of cold plasma on cereal grains

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Seed and sprout decontamination

Promising results have been reported by researchers in the use of cold plasma for decontaminating seed surfaces and plant sprouts from microbes and toxins. In a study conducted by Butscher et al. (2015), it was found that *Bacillius amyloliquefaciens* bacteria on wheat seeds could be effectively deactivated. This was achieved by exposing the seeds to low-pressure Ar/O_2 DBD plasma at radio frequencies ranging from 8.0 to 12.8 mbar, and with power levels between 700 and 900 W for a duration of 30 s. In a study conducted by Filatova et al. (2014), the effectiveness of low-pressure air plasma at a frequency 5.28 MHz for 2-10 minutes in eliminating phytopathogens from contaminated wheat seeds was demonstrated. The most favorable outcome was a 77% reduction in infection rate with a 5-minute exposure, while germination levels remained unchanged. Kabir et al. (2019) reported that Ar/Air and Ar/O_2 DBD plasma at a pressure of 10 torrs and 4.5 kHz frequency for 90 s led to the detoxification of cadmium in wheat. Selcuk, Oksuz & Basaran (2008) demonstrated that treatment of seeds with air plasma generated in a vacuum chamber with frequency of 1 kHz and voltage of 20 kV for 5-20 minutes could effectively decrease the presence of two types of filamentous fungi, namely *Aspergillus* spp. and *Penicillium* spp., on the surface of corn and wheat seeds. The researchers found that a notable reduction of 3-log could be achieved in just 15 minutes of plasma treatment.

The positive impact of atmospheric pressure plasma treatment, like low-pressure plasma, was linked to its ability to effectively deactivate pathogens on the surface of cereal seeds. Plasma was able to deactivate the microorganisms on the germinated seeds based on the discharge of the DBD (Fereydooni & Alizadeh, 2022). The mechanism of inactivation is related to the intracellular accumulation of reactive oxygen species, which causes the rupture of the outer membrane of the bacterial cell, disruption of protein activity, removal of the cytoplasm from the cell, and finally the death of the bacterial cell (Mendis, Rosenberg, & Azam, 2000). Butscher, Zimmermann, Schuppler & von Rohr (2016) conducted a study to investigate the impact of atmospheric pressure on the deactivation of bacterial cells on wheat seeds using argon plasma. They utilized DBD plasma at pulse voltage (6-10 kV) and pulse frequency (5-15 kHz) for this purpose. The results revealed that a 5- minute plasma treatment led to a 1 log reduction in the number of bacteria, whereas a 60- minute exposure resulted in a more significant 3 log reduction. In a study by Zahoranová et al. (2016), it was shown that applying coplanar surface barrier discharge at atmospheric pressure for 120 s, with a frequency of 14 kHz and voltage of 20 kV, led to a significant reduction in the initial natural bacterial load on artificially contaminated wheat seeds. The bacterial load, initially measured at 5.52 × 104 CFU/g, was reduced by 1 log. In addition, different effects of cold plasma treatment on the inactivation of fungi samples of *Fusarium nivale*, *F. culmorum*, *Trichothecium roseum*, *Aspergillus flavus* and *A. clavatus* was reported.

In a study conducted by Shi, Ileleji, Stroshine, Keener & Jensen (2017), it was discovered that treating corn with DBD atmospheric pressure plasma using two gases, air and MA65, resulted in a noteworthy decrease in aflatoxin levels. In their study, the plasma system was operated at 200W and 50 HZ generating 90 kV. The degradation of aflatoxin in corn reached 62% and 82% after 1 and 10 minutes of HVACP treatment in RH 40% air, respectively. Moreover, the application of cold atmospheric plasma had a notable effect on the reduction of Deoxynivalenol (a prominent mycotoxin found in grains) in barley seeds. The outcomes demonstrated that the treatment of cold atmospheric plasma for 6 and 10 minutes resulted in a decrease in Deoxynivalenol concentration by 48.9% and 54.4%, respectively (Feizollahi, Iqdiam, Vasanthan, Thilakarathna, & Roopesh, 2020). It is assumed that various degradation mechanisms, including chemical reactions with reactive species generated in cold plasma

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(such as O_3, O, OH, NO_x), decomposition after collision with electrons and ions, and UV light, are responsible for breaking down toxin molecules through cold plasma treatment (Ten Bosch et al., 2017). The cold plasma system can increase its performance to further reduce Deoxynivalenol by adjusting various process factors such as voltage and frequency, type of feed gas, relative air humidity, and etc.
Los et al. (2018) conducted a study on the decontamination of various bacteria species (*E. coli* NCTC and *B. atrophaeus*) and fungi *P. verrucosum* DSM. Their research revealed that treatment of 20 minutes of DBD plasma at 80 kV voltage showed promise in controlling both native microflora and pathogenic microorganisms on wheat and barley. DBD air plasma also resulted in a significant decrease in the initial concentration of pathogenic bacteria (*Bacillus cereus*, *B. subtilis*, and *E. coli* O157:H7) inoculated on brown rice, reducing it from 8 log CFU/mL to an undetectable level (2.3 log CFU/g) within 20 minutes (Lee et al., 2016). Lee et al. (2018) also found similar outcomes with brown and white cooked rice. They observed reductions of 2.01-log in *Bacillus cereus* and *Escherichia coli* bacteria after subjecting the rice to 20 minutes of treatment with air plasma (250 W, 15 kHz).

Seed germination

Seed germination, as an essential factor for the survival of plant species, starts with water absorption, stimulating physiological activities that eventually result in ending seed dormancy (Nonogaki, 2014). Several studies have been conducted in agriculture to explore techniques for enhancing seed germination, ultimately improving crop growth and yield. Seed priming causes biological and physiological changes in the seed and plant, which results in better germination and proper seedling establishment (Lutts et al., 2016; Zulfiqar, 2021). There are many seed priming techniques including halo priming, hydro priming, osmose priming, hormonal priming, chemical priming, physical, and biological priming (Ali et al., 2017). Recently, cold plasma seed treatment has gained much attention as a physicochemical priming technology, especially for cereal crops (Adhikari et al., 2020). ROS and RNS present in plasma have a wide range of regulatory functions involved in various processes of plant growth and development, including germination, metabolism, signal transduction, nutrient uptake, improvement of seedling growth, and abiotic/biotic stress tolerance (Yong et al., 2019). Treating seeds with plasma by changing the shape of the seed coat and inducing seed germination reduces germination time, enhances disease resistance, and accelerates growth and development (Nalwa, Thakur, Vikram, Rane, & Vaid, 2017; Rasooli, Barzin, Mahabadi, & Entezari, 2021).

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So far, many researches have been carried out on the effect of cold plasma treatment on the germination of cereal seeds. According to a study conducted by Yodpitak et al. (2019), it was discovered that subjecting brown rice to DBD argon plasma for 75 s stimulation resulted in a notable increase (84%) in germination rate. A study carried out by Amnuaysin, Korakotchakorn, Chittapun & Poolyarat (2018) found that subjecting rice seeds to DBD air plasma treatment for 60 s led to a significant improvement in both vigor index and germination speed. Chen et al. (2016) discovered similar outcomes whereby the germination speed and early vigor of brown rice seedlings were enhanced following a 10-minutes treatment exposure to low-pressure plasma. They attributed this enhancement to the increased a-amylase activity. Penado, Mahinay & Culaba (2017) investigated the effects of atmospheric air plasma jet treatment on the germination of rice (*Oryza sativa L.*). They observed that plasma treatment led to a decrease in trichomes on the seed's surface. This could decrease potentially enhance the seed's ability to absorb water, resulting in a significant change in seed germ length. However, the treatment did not affect the overall germination count of the seeds after the 72-h germination period.

Velichko et al. (2019) treated wheat seeds with atmospheric pressure plasma from a jet and dielectric barrier discharge operating in argon gas for 15 to 300 s. The plasma jet treatment resulted in a slight increase in germination, with the treated samples showing a germination rate of 98.7% compared to the control samples' rate of 97.0%. The average time it took for germination to occur decreased from 3.90 days for the control samples to 3.67 days for the treated ones. Notably, the germination time decreased significantly when the treatment time exceeded 60 s. The speed of germination begins to decline after treatment times surpassing 30 s. This decline can be attributed to the influence of the hot argon stream, which reaches a temperature of 103 °C. In contrast, when using atmospheric pressure DBD, this effect is minimal, and the growth properties of the seeds are solely impacted by the active species produced by the discharge. By examining the effect of plasma treatment with two types of operating gases, air and SF_6, on wheat seeds, Selcuk et al. (2008) showed that the germination rate of wheat seeds treated with plasma was not greatly affected. In addition, there was no noticeable variation in the germination rate among seeds that were exposed to air and SF_6 plasma gases for 5, 10, or 15 minutes. Similarly, by investigating the effect of surface discharge plasma on wheat seeds, Dobrin, Magureanu, Mandache & Ionita (2015) reported that germination was less affected by treatment compared to growth parameters.

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PAW can impact water consumption during the germination phase and lead to the production of hybrid cereal seeds with a superior germination rate. In a study conducted by Chalise et al. (2023), the effectiveness of PAW created through gliding discharge plasma was examined in relation to wheat seed germination. The findings indicated that a treatment duration of 15 minutes resulted in improved germination rates and a higher yield of wheat products. In a similar manner, a study conducted by Wang, Cheng & Sun (2023) demonstrated the positive effects of treating wheat seeds with PAW generated by an atmospheric pressure Ar-O_2 plasma jet. The researchers found that a treatment duration of 3 minutes with PAW resulted in enhanced germination, vigor index, and seedling growth. Ahn, Gill & Ruzic (2019) also proved that corn seeds hybridized with PAW can have a germination rate of nearly 100%. Kabir et al. (2019) discovered that the harmful effects of Cadmium on cellular and protein features were significantly reduced by treating wheat seeds with Ar/O_2 and Ar/Air plasma before germination. Therefore, plasma treatment may also contribute to the decreased uptake and movement of Cadmium in wheat plants whose seed was previously treated by plasma. Guo et al. (2017) demonstrated that treating wheat seeds with DBD plasma for 4 minutes led to an impressive 27.2% increase in germination potential and a corresponding 27.6% boost in germination rate. The research also demonstrated that plasma treatment had a positive effect on reducing damage caused by membrane lipid peroxidation. This was achieved by enhancing the activities of antioxidant enzymes such as superoxide dismutase, catalase, and peroxidase, which indicated an improved tolerance to environmental stress. Additionally, plasma treatment was found to promote the generation of abscisic acid in wheat seedlings. Hui et al. (2020) attributed the increase in wheat seed germination to the significant effect of active species produced by plasma on secondary metabolism during seed germination. They identified the buildup of charges caused by plasma charged particles on the cell membrane's surface, the creation of electrostatic force, and the resulting harm to the cell membrane as the cause for enhanced permeability of the cell membrane and seed coat. This phenomenon speeds up the absorption of water and nutrients, ultimately bolstering seed germination.

Other researchers, including Jiang et al. (2014); Li et al. (2017); Los, Ziuzina, Boehm, Cullen & Bourke (2019); Meng et al. (2017); Roy, Hasan, Talukder, Hossain & Chowdhury (2018), mentioned the increase in the germination and growth of wheat seeds treated with atmospheric pressure plasma. Starič et al. (2022) employed both direct and indirect treatment methods to examine the germination

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process of wheat seeds. They generated plasma using glow and afterglow discharge techniques, with oxygen feed gas, under low pressure conditions. The research findings indicated that plasma treatment had no significant impact on the germination rate, except for the seeds treated under 90 s treatment, which experienced a notable decrease in germination rate and root growth due to the change in the morphology of wheat grain pericarp. In another study, Sidik et al. (2018) investigated the effect of helium gas-fed jet plasma on corn seeds. The research demonstrated that when the seeds underwent a 3-minute treatment, they exhibited a higher germination speed and improved growth compared to the untreated seeds. However, it is worth noting that the germination rate for both treated and untreated seeds was 86%. In a study conducted by Feizollahi et al. (2020), barley grains were subjected to DBD plasma in humid air. The study revealed that treating the grains for either 1 or 10 minutes resulted in a reduction in root length, root surface area, shoot length, and the number of roots, compared to the untreated control group. Interestingly, a 6-minute treatment improved these parameters significantly, with seeds exposed to 6 minutes of plasma radiation exhibiting the highest germination percentage at 93.3%. In general, based on the conducted studies by Park et al. (2018), it has been found that cold plasma treatment can generally affect the rate of seed germination. This is achieved by altering seed water absorption, seed surface characteristics, biological reactions within the seeds, as well as protein structure and internal functional metabolites like gamma-aminobutyric acid.

Surface property changes and water uptake of seeds

The absorption of water by seeds is dependent on three primary factors: the seed's composition, the permeability of its coat, and water availability (McDonald, 1994). So far, cold plasma technology has shown positive effects on both the surface characteristics and internal content of grains. The plasma treatment enhances water absorption in seeds by reducing surface energy. The seed's hydrophilicity, or its ability to absorb water, is determined by measuring the contact angle formed by a water drop. The study conducted by Chen et al. (2016) demonstrated that exposing brown rice to plasma resulted in increased water uptake compared to untreated brown rice. The maximum level of water uptake was observed to be 30.2% in samples that were exposed to 3 kV air plasma for 10 minutes after a germination period of 24 h. Lee et al. (2016) found that plasma-treated brown rice exhibited higher water absorption than regular brown rice for all soaking durations. The maximum water uptake, reaching 24.78%, was observed after 5 h of soaking. The increase in water uptake ratio was associated

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with a decrease in cooking time. The plasma treatment altered the microstructure of the rice bran layers, making it easier for water to penetrate into the brown rice kernel (Chen, Chen, & Chang, 2012). Increasing the time of plasma treatment showed more effectiveness on the seeds and as a result reduced the cooking time. In addition, the hardness of cold plasma treated rice was significantly lower than untreated brown rice.

Tissue changes in parboiled rice under low-pressure cold plasma were analyzed by Sarangapani, Devi, Thirundas, Annapure & Deshmukh (2015). They observed significant alterations in the surface morphology. Following the treatment, the grain's surface exhibited cracks and indentations known as "surface etching." Plasma treatment altered the grains' natural surface structure, leading to modifications in cooking and textural characteristics. The treatment of 50 W for 15 minutes induced more etching, resulting in shorter cooking time, decreased contact angle, increased water uptake ratio, and higher surface energy. Similar results were presented by Chen et al. (2012) who investigated on properties of the surface, cooking, texture, and iodine staining of brown rice. Their results revealed that plasma treatment causes the surface of brown rice to be etched, enabling the rice kernel to absorb water more easily during soaking. As a result of this treatment, the cooking time for brown rice is shortened, the iodine-stained area is increased and the cooked rice has a tender texture and is more enjoyable to eat. In a study conducted by Liu, Wang, Chen & Li (2021), it was found that subjecting milled rice to a 120 W helium plasma treatment for 20 s resulted in improved cooking properties of milled rice. This was achieved by creating a rough kernel surface, increasing water absorption rate, weakening the protein network, and speeding up starch gelatinization. Thirumdas, Deshmukh & Annapure (2015) analyzed the effect of air plasma at a pressure of 0.15 mbar on the water absorption and cooking time of basmati rice. The water absorption was found to be directly related to the power and time of plasma treatment, which is likely associated with the reduction of cooking time and the modification of the grain surface. The shorter cooking time of plasma treated rice can be explained by the fragmentation of starch, the opening up of the kernel structure, and the degradation of other components. These changes allow the rice kernel to absorb more water, leading to a reduction in cooking time (Sabularse, Liuzzo, Rao, & Grodner, 1991).

Velichko et al. (2019) conducted a study on the surface modification and chemical structures of wheat seeds coat using jet and DBD plasma treatment. They observed that the water imbibition capacity of wheat seeds increased by 20-30% after being exposed to plasma radiation for 15-30 s. This

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enhancement in water imbibition can be attributed to the increased hydrophilicity of the seed surface, leading to a decrease in the apparent contact angle. Bormashenko, Grynyov, Bormashenko & Drori (2012) observed a significant change in the wettability of wheat seeds, where the contact angle decreased from 115 ° to zero. Interestingly, the amount of water absorption did not change significantly and only the treated seeds experienced a slight increase in water absorption. The results were attributed to the oxidation of the grain surface by plasma. Sera, Spatenka, Šerý, Vrchotova & Hruskova (2010) visually observed that plasma treated wheat seeds at a pressure of 140 Pa exhibited quicker wetting compared to the control seeds. However, they did not provide quantitative measurements of water imbibition. In another study, Starič et al. (2022) investigated the changes in the morphology of the seed pericarp and the chemical characteristics of the wheat grain surface treated with plasma through SEM and AFM. The seed pericarp's morphology was changed and its roughness increased as a result of extended direct plasma treatment. The extent of functionalization was more noticeable in direct compared to indirect treatment.

The alteration in seed wettability was found to be related to the oxidation of lipid layers and the functionalization of the seed surface. Zahoranová et al. (2016) also reported that the water uptake in wheat seeds increased with higher exposure doses of plasma. After 2 h treatment with coplanar surface DBD, the water uptake ranged from 6.41 to 9.60 mg, and after 8 h, it ranged from 12.53 to 16.07 mg per seed, compared to the control. The water absorbed by the plasma treated seeds triggers the hydrolytic amylase enzyme, helping in the metabolic process of breaking down stored starch and protein in seeds (Kikuchi, Koizumi, Ishida, & Kano, 2006). Treatment of cereal seeds with PAW also improves the surface characteristics. Chalise et al. (2023) reported the wettability and contact angle of wheat seeds increased and decreased significantly after being treated with PAW for 15 minutes, respectively. The increase in wettability is believed to be due to the presence of ultra-violet light and OH radicals, which are the main components of atmospheric plasma.

Growth parameters (root, shoot and seedling length)

The parameters of root growth play a crucial role in effectively utilizing the soil and absorbing minerals, particularly for nutrients that have limited mobility. The growth of roots has a significant impact on the development of strong shoots and the overall yield of crops, particularly in soils with low nutrient levels (Wang, Thorup-Kristensen, Jensen, & Magid, 2016). The growth of roots can be

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influenced by cold plasma treatment, thereby altering the plants' capacity to explore soil and absorb water and nutrients (Pérez-Pizá et al., 2020). The impact of cold plasma and PAW on the growth parameters is closely connected to the effects mentioned earlier regarding germination. Yodpitak et al. (2019) reported an increase in the height of seedlings and root growth of brown rice after 75 s of argon plasma exposure to 69% and 57% compared to the control, respectively. Also, the root length, and seedling height decreased when the treatment time exceeded 75-100 s for all rice cultivars. The enhancement of seedling growth attributes of rice seed, such as shoot length and the contents of photosynthetic pigments of seedlings as a result of being treated with plasma for 10 s was also reported by Amnuaysin et al. (2018). The increase in seed permeability can be related to the improvement of nutrient absorption capacity, which potentially facilitates the growth of seedlings. In a study by Chen et al. (2016) they determined the effects of low pressure plasma on the seedling lengths of brown rice by 37% increase compared to the control. There were no significant differences observed between the samples treated with plasma and the control group, as per statistical analysis. For the rice variety *Oryza sativa L.*, Penado et al. (2017) reported an improvement in the growth process of samples treated with air plasma jet considering the effect on the increase in the length of the seed shoot, which is related to the speed of seed root expansion. In another study, J. Liu et al. (2021) did not observe significant changes in the ratio of grain length to width by researching the effect of radio frequency helium plasma treatment for 20-120 s on Chinese milled rice.

The advantageous effects of using short treatment times (ranging from 4 - 7 minutes) of surface DBD in air, nitrogen, and argon were observed in terms of the germination rate, water absorption, lengths of roots and shoots of wheat. Conversely, prolonged exposure had detrimental effects on the seeds, leading to a significant decrease in the percentage of germination (Meng et al., 2017). Similarly according to the findings of Velichko et al. (2019) a brief plasma jet treatment lasting 15-60 s induced the development of the wheat seed root system while having minimal effects on sprout length. However, when the treatment time was prolonged, the high temperature of the argon flow became the primary factor affecting the growth. Hot flow of argon negatively affected the potential for plant growth. According to Filatova et al. (2014), the shoot length increased when exposed to RF plasma treatment in a vacuum and the germination reached a maximum point.

The effect of plasma gas type on growth parameters has also been reported in some researches. In a study conducted by Selcuk et al. (2008), it was demonstrated that the germination percentage, shoot

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height, and root length of the treated seeds were not affected by either air or SF_6 gases plasmas. Wheat roots and sprouts length improvement was reported also in Dobrin et al. (2015). According to them, the roots of the plasma treated seeds were found to be distributed more towards longer lengths compared to the untreated samples. Furthermore, there was a significant difference in the root-to-shoot ratio between the untreated wheat (0.88) and the treated seeds (1.2). The reason for this is likely the gentler plasma treatment, with an average discharge power of 2.7 W. As a result, the seeds are not damaged at this low power level. The effect of air cold plasma treatment on barley germination parameters was investigated by Feizollahi et al. (2020). The treatment of seeds for 1 and 10 minutes resulted in a decrease in the number of roots, shoot length, root surface area and root length compared to the untreated samples. However, the 6- minute treatment showed some improvement in root volume, average root diameter, and germination percentage, although not significantly. Similarly, Mazandarani, Goudarzi, Ghafoorifard & Eskandari (2020) reported that treatment of barley seeds with 80 W DBD plasma increases the shoot height and root length by 38.55% and 31.93% compared to the untreated seeds, respectively. By investigating the effect of three types of plasma including RF, microwave and DBD in vacuum and atmospheric pressure conditions on the growth and germination of corn seeds, Ahn et al. (2019) reported that corns treated with RF plasma had a higher growth rate under vacuum conditions. Chalise et al. (2023) presented results indicating that wheat seeds treated with 15 minutes of PAW treatment and 5 minutes of treatment with DBD exhibited longer root and spike lengths compared to the control sample. The PAW provided the necessary reactive nitrogen species for plant growth such that nitrate and nitrite species acting as fertilizers. This is the reason behind these results.

Biomass parameters

Cold plasma treatment can lead to notable alterations in various biomass parameters. These parameters include the dry weights of roots and sprouts, stem diameter, plant height, and plant growth efficiency. In a study conducted by Sera et al. (2010), it was found that the shoot dry weight increased significantly after 3 minutes of microwave plasma treatment compared to samples treated for 10, 20, and 40 minutes. Additionally, a highest root-to-shoot ratio was observed after 5 minutes of plasma exposure. In their study on DBD treatment, Guo et al. (2018) demonstrated that all biomass parameters reached their maximum values at different discharge voltages. Also, Saberi, Sanavy, Zare & Ghomi

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(2019) found that 180 s of plasma treatment increased the grain and spike yield by 58 and 75%, respectively, compared to the control sample.

UV radiation in plasma affects growth parameters only during long-term treatment. Additionally, temperatures below 70 °C do not have a significant impact on the seedling mass when exposed to hot air (Ghaly & Sutherland, 1984). Therefore, the type of plasma treatment influences the sprout and root lengths, dry weight, and root-to-shoot ratio. In a study conducted by Henselová, Slováková, Martinka & Zahoranová (2012), it was found that treating maize with a diffuse coplanar surface DBD in air resulted in a 21% increase in length, a 10% increase in fresh weight, and a 14% increase in dry weight. Compared to the untreated sample, higher weight of roots and sprouts of wheat seeds treated with surface DBD plasma was obtained by Dobrin et al. (2015). Chalise et al. (2023) showed that the growth parameters of wheat seed, including spike length, fruit number, and root length, were improved through the direct plasma treatment and the utilization of PAW. Moreover, increasing the duration of treatment led to higher concentrations of reactive species and a decrease in water pH, ultimately enhancing productivity. According to Hui et al. (2020), there was an increase in plant height growth, number of leaves and fresh and dry weight in wheat plants treated with a combination of air and helium plasma in a vacuum setting, compared to the control group.

The growth and yield of wheat greatly depend on the number of leaves it possesses. Increasing the number of leaves enhances the plant's ability to absorb light energy, leading to improved organic matter synthesis efficiency. This is vital for the optimal growth of wheat and ultimately results in improved yield. In a study conducted by Jiang et al. (2014), wheat seeds were subjected to helium plasma treatment, and the researchers examined various growth parameters during the phonological growth stage of the wheat plants. The results showed that the treated plants exhibited significant improvements in plant height (21.8%), root length (11.0%), fresh weight (7.0%), stem diameter (9.0%), leaf area (13%), and leaf thickness (25.5%) compared to the control group. This suggests that the application of cold plasma treatment can enhance the growth of wheat. Furthermore, the treated wheat yielded a 5.89% higher yield compared to the control group. Numerous studies have also examined the impact of cold plasma treatment on brown rice seeds. These studies consistently found that the treated seeds exhibited increased fresh weight and dry weight of shoots and roots, as well as higher growth

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efficiency compared to the control group (Amnuaysin et al., 2018; J. Liu et al., 2021; Park, Puligundla, & Mok, 2020).

Metabolic activities

The treatment of cold plasma and PAW also have an impact on the characteristics of the internal components of seeds or plants associated with alterations in metabolite activity. Chen et al. (2016) studied the changes in a-amylase and antioxidant activity, gamma-aminobutyric acid (GABA) of germinated brown rice after 3-kV DBD treatment. The increasing activities of ABTS and DPPH radicals, a-amylase, phenol and GABA was recorded after a 24 h germination time. Similarly, Park et al. (2020) also reported positive changes of DPPH, ABTS and phenolic content of brown rice sprouts after jet plasma treatment. Researchers demonstrated that the penetration of active species through the porous seed coat inside the caryopses, where they interact with plant cells, is responsible for alterations in seed chemical properties including phenolic compounds contents after a plasma treatment (Sera et al., 2010). Relatively high concentrations of phenolic compounds in germinated seeds may be attributed to the release of phenolic compounds bound to the cell wall, as the breakdown of the cell wall takes place during germination (Gujral, Sharma, Kumar, & Singh, 2012). During germination, a significant increase in free phenolic acid content and ferulic acid content of brown rice has been observed (Tian, Nakamura, & Kayahara, 2004).

The enhanced ability of DPPH radical scavenging may be attributed to the softening of the seed coat caused by oxidants derived from jet plasma and then the penetration of some active species into the seed. This penetration may potentially benefit physiological reactions (Li et al., 2017). Sookwong et al. (2014) reported a decrease in the phenolic content of treated brown rice 72 and 96 h before germination. In addition, plasma processing may affect the activity of saccharolytic enzymes, potentially enhancing the production of free phenolic compounds that were partially dissolved and lost in the soaking water during the pre-germination process. High moisture in rice seeds can increase the risk of mold growth and reduce the rate of rice germination. The study of Guo et al. (2023) indicated that plasma treatment had no significant impact on the moisture content of rice grains during the 8-minute treatment period. Also, the electrical conductivity of rice grain leachate, which is a crucial factor in determining cell membrane permeability, showed a slight increase after a 6- minute plasma treatment.

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Chen, Hung, Lin & Liou (2015) suggested that the improvement of brown rice quality during 3-month storage is related to the reduction of fatty acid and α-amylase of samples treated with 3-kV plasma. Reduction of oxidative damage in wheat grain tissues treated with Ar/O_2 and Ar/Air plasma through the positive regulation of antioxidant enzymes SOD and CAT and their related genes was reported by Kabir et al. (2019). According to research of Los et al. (2019), 180 s of direct plasma treatment caused an acceptable increase in nitrite and nitrate levels, an increase in titratable total acidity content, and an increase in malondialdehyde wheat grain aldehyde. After treating wheat seeds with DBD plasma, Li et al. (2017) observed an increase in the levels of osmotic adjustment products, proline, and soluble sugars in wheat seedlings. They also noted a decrease in malondialdehyde content. Furthermore, the activity of superoxide dismutase and peroxidase in the treated samples also showed an increase. Also, according to researches of Wang et al. (2023), 3- minute treatment of wheat seeds with PAW enhanced the photosynthetic pigments, free amino acids, total phenolic content, protein content, antioxidant activity, enzyme activity and mineral content of seeds grown for 14 days. Table 1 presents an overview of the all types of cereals studied after plasma treatment.

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Table 1- Summary of studies conducted on the cereal seeds after treatment with cold plasma and PAW. Abbreviations: alternating current (AC); radio frequency (RF); total phenolic compounds (TPC); antioxidant activity (DPPH), gamma-aminobutyric acid (GABA), scanning electron microscope (SEM); malondialdehyde (MDA)

Type of cereal	Plasma source/device	Parameters studied	References
Brown rice, cultivars: ST1, PL1, KDML 105, RD 6, NS, LP	DBD (100-200 W, RF, 25-300 s, argon)	germination percentage, root length, seedling height, TPC, vitamin E, phytosterols, triterpenoids, anthocyanins	(Yodpitak et al., 2019)
Brown rice, cultivars: KhaoDawk Mali 105	DBD (5.5 kHz, 18 kV, 10-60 s, air)	shoot length, fresh and dry weight of shoot and roots, carotenoid, chlorophyll a, chlorophyll b	(Amnuaysin et al., 2018)
Brown rice, cultivars: Taikeng 9	DBD (high voltage DC, 1–3 kV, 1.2 mA, 800 Pa, 10 minutes, air)	germination and vigor of the seedlings, GABA, DPPH, water uptake, α-amylase, TPC	(Chen et al., 2016)
Brown rice, cultivar: Riceberry	Jet (400 kHz, 3–5 kV, 10-14 W, 5-10 s, argon and oxygen)	TPC, GABA, germination rates, relative quantities of chemicals	(Sookwong et al., 2014)
Brown rice, cultivar: NSCI RC298	Jet (high voltage AC, 15 kV, 60 Hz, air)	SEM images, germination percent, germ lengths	(Penado et al., 2017)
Brown rice, cultivar	Jet (0-40 W, 50 -600 kHz, 10 kV,	colony count of *Aspergillus flavus*	(Suhem, Matan,

not specified	RF, argon)		Nisoa, & Matan, 2013)
Brown rice, cultivar: Chindeul	DBD (15 kHz, 250 W, 5-20 minutes, air)	aerobic bacterial count, *Bacillus cereus*, *Bacillus subtilis*, *E coli*, color changes, pH, water uptake, α-amylase activity, hardness	(Lee et al., 2016)
Brown rice, cultivar not specified	Jet (high voltage DC, 20 kV, 58 kHz, 1.5 A, 0-10 minutes, air)	DPPH, ABTS, TPC, weight of seedlings, length of seedlings, α- amylase and β- amylase activity	(Park et al., 2020)
Rice grain, cultivar: Late indica	DBD (high voltage AC, 25 kV, 2-8 minutes)	ochratoxin A, deoxynivalenol, electrical conductivity, MDA, seed germination, moisture content, starch content, globulin, α- amylase, albumin, prolamin, glutein	(Guo et al., 2023)
Parboiled rice, cultivar: Sb Boiled Aiyre	DBD (13.56 MHz, 30-50 W, 5-15 minutes, 0.15 mbar, air)	moisture content, fat, protein, ash, carbohydrates, cooking time, water uptake, cooking loss, hardness, cohesiveness, color, whiteness index	(Sarangapani et al., 2015)
Brown rice, cultivar: Taikeng 9	DBD (high voltage DC, 1–3 kV, 1.2 mA, 6 Torr, 30 minutes, air)	Moisture, protein, lipid, ash, carbohydrate, cooking time, elongation ratio, width expansion ratio, water absorption, cooking loss, adhesiveness, hardness, brittleness, cohesiveness, elasticity, chewiness	(Chen et al., 2012)
Brown rice, cultivar: Nan-jing 46	DBD (40-50 kV, 90-180 s, air)	major volatile organic compounds, fatty acid, color change	(Q. Liu et al., 2021)
Milled Rice, cultivar: four japonica rice and two indica rice	DBD (13.56 MHz, 80-120 W, 140 pa, 20-120 s, helium)	cooking time, hardness, adhesiveness, elasticity, gruel solid loss, enthalpy of gelatinization, water contact angle, free fatty acid content, water absorption, chalky rice rate	(J. Liu et al., 2021)
Basmati rice, cultivar not specified	DBD (13.56 MHz, 30-40 W, 5-10 minutes, air)	cooking time, water uptake, hardness, stickiness, contact angle, surface energy, hydrophilic	(Thirumdas et al., 2015)
Wheat seeds, cultivar not specified	Jet (RF 13.56 MHz, 300W, 15-300 s, argon) and DBD (22.5 kHz, 30 W, 2-10 s, argon)	average length, dry weights of roots and sprouts, germination time, water imbibition, contact angle	(Velichko et al., 2019)
Wheat seeds, cultivar not specified	glow discharge (1 kHz, 20 kV, 500 mTorr, 300 W, 30 s-30 min, air or SF_6)	inactivation of *Aspergillus spp.* and *Penicillum spp.*, shoot height	(Selcuk et al., 2008)
Wheat seeds, cultivar not specified	surface DBD (50 Hz, sinusoidal voltage, air)	roots and sprouts length and dry weight, number of roots, contact angle	(Dobrin et al., 2015)
Wheat seeds, cultivar	PAW (high voltage DC, 0–15 kV,	germination rate, contact angle, wettability, growth	(Chalise et al.,

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not specified	5-15 minutes, air) and DBD (50 Hz, 0–45 kV, 1-5 minutes, air)	rate, germination potential, total number of fruits, root length, spike length	2023)
wheat seeds, cultivar: BARI Gom 22	Jet (10 Torrs, 5–10 kV, 3–8 kHz, 90 s, argon/air and argon/oxigen)	root and shoot cadmium concentration, total soluble protein, enzymes SOD and CAT, SEM images, root and shoot length and dry weight, total chlorophyll, electrolyte leakage, cell death	(Kabir et al., 2019)
Wheat seeds, cultivar: Xiaoyan 22	DBD (50 Hz, 13 kV, 4 minutes, air)	seed germination, , osmotic products, lipid peroxidation, seedling growth, reactive oxygen species, DPPH, abscisic acid, expression of drought-resistant genes under drought stress	(Guo et al., 2017)
Wheat seeds, cultivar: Shannong 12	DBD (80-100 W, 130–160 Pa, 15 s, air and helium)	seed germination, yield, plant height	(Hui et al., 2020)
Wheat seeds, cultivar: Ingenio	DBD (RF, 13.56 MHz, 50 Pa, 200 W, 30-90 s, oxygen)	contact angle, surface morphology, surface roughness, chemical analysis of surface, water uptake, moisture, germination rate, α- amylase, root length, number of seedlings	(Starič et al., 2022)
Wheat seeds, cultivar not specified	DBD (120 kV, 50 Hz, 30-180 s, air)	contact angle, moisture content, pH and acidity, water uptake, MDA, hydrogen peroxide, nitrite and nitrate concentrations, SEM	(Los et al., 2019)
Wheat seeds, cultivar not specified	DBD (3×10^9 MHz, 60-100 W, 150 Pa, 15 s, helium)	seed germination, yield, plant height, root length, fresh weight, stem diameter, leaf area, leaf thickness,	(Jiang et al., 2014)
Wheat seeds, cultivar: Xiaoyan 22	DBD (50 Hz, 13 kV, 1-13 minutes, air)	germination potential, germination rate, germination index, vigor index, root length, shoot length, fresh weight, dry weight of the seedlings, proline and soluble sugar contents of seedling, MDA, superoxide dismutase and peroxidase enzymes, SEM	(Li et al., 2017)
Wheat seeds, cultivar: Xiaoyan 22	DBD (13 kV, 50 Hz, oxygen, air, argon, and nitrogen)	germination properties, shoot and root length, SEM, permeability, seedlings soluble protein	(Meng et al., 2017)
Wheat seeds, cultivar: Apache and Bezostaya 1	DBD (glow discharge, RF, 50 Pa, 200 W, 5-30 s and afterglow discharge, 600 W, 3-5 s, oxigen)	germination, root growth, SEM, fresh weight of seedlings	(Starič, Grobelnik Mlakar, & Junkar, 2021)
wheat seeds, cultivar not specified	glow discharge (1–6 kV, 3–5 kHz, 10 Torr, 3-15 minutes, air and air/O_2)	SEM, water absorption, seed germination, chlorophyll contents, growth Study, yield	(Roy et al., 2018)
wheat seeds, cultivar:	PAW generated by plasma jet	seed germination, pH, total soluble solids, color,	(Wang et al.,

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Jimai 23	(high voltage AC, 7.0 kV, 600 W, 1-5 minutes, 98% Ar and 2% O_2)	vitamin C, soluble protein contents, pigments contents, enzyme activities of SOD, PPO and POD, TPC, DPPH, free amino acids, mineral contents	2023)
wheat seeds, cultivar: Bari 21	DBD (10 Torr, 5–10 kV, 3–8 kHz, 1-12 minutes, air)	SEM, seed germination, shoots length, number of tiller, fresh and dry weight, roots length, enzyme activities of SOD, APX, relative gene of TaSOD, and TaCAT, H_2O_2 and NO concentration of root and shoot, total soluble protein and sugar, fat and moisture content, crude fiber, ash, yield	(Hasan et al., 2022)
wheat seeds, cultivar: Eva	coplanar surface DBD (400 W, 10-600 s, air)	germination rate, dry weight, vigor of seedlings, wettability, surface microflora, inactivation of *Fusarium nivale*, *F. culmorum*, *Trichothecium roseum*, *Aspergillus flavus*, *A. clavatus*	(Zahoranová et al., 2016)
Yellow dent corn hybrid	PAW generated by plasma jet (RF plasma 2.45 GHz, 800 W, 10 minutes, helium-air)	germination, growth, and product yield	(Ahn et al., 2019)
Dent yellow corn	DBD (50 Hz, 90 kV, 1-30 minutes, air and MA65)	SEM, NOx and ozone concentration, aflatoxin level in corn	(Shi et al., 2017)
Corn, cultivar not specified	(high voltage AC, 20 kHz, 3-10 minutes, helium)	germination and growth rate	(Sidik et al., 2018)
Raw barley grains	DBD (high voltage AC, 0–34 kV, 300 W, 2-10 minutes, air)	reduction of deoxynivalenol, moisture content, measurements of ozone, nitrous gas, and hydrogen peroxide concentration, protein, glucan content, germination rate	(Feizollahi et al., 2020)
Barley seeds, cultivar not specified	DBD (40-120 W, 15 s, air)	germination parameters, SEM, water penetration, effect of storage time	(Mazandarani et al., 2020)
Wheat, cultivar: Ireland and barley with cultivar: United Kingdom	DBD (80 kV, 50 Hz, 5-20 minutes, air)	Inactivation of *Bacillus atrophaeus, E. coli*, *P. verrucosum*, *B. atrophaeus*, germination percentage, quality properties	(Los et al., 2018)

Limitations and future of cold plasma in food industry

The introduction of any new technology into the food industry is challenging due to the perception that it is disruptive, risky, and difficult to implement in a mature and low-margin industry while facing day-

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to-day competitive pressure(Keener & Misra, 2016). Therefore, for atmospheric cold plasma to be successfully adopted in the food industry, it is important to consider several nontechnical factors. The primary focus should be on the consumer's needs, as they desire to consume fresh, high-quality food without any chemical preservatives. Food safety and maintaining consumer confidence in a particular food category is gradually established and falls under the responsibility of manufacturers, distributors, processors, regulatory agencies and retailers. Hence, the utilization of cold plasma technology in the food industry relies not only on ensuring food safety but also on satisfying consumer needs. Other factors that lead manufacturers, processors and distributors to use cold plasma technology include: (1) Potential extension of product shelf life and reduced consumer food waste; (2) Maximum preservation of food quality and decreased food processing and storage losses; (3) Low energy requirement, making it a more environmentally friendly option compared to current technology; (4) Reduced operational and maintenance expenses; (5) Improved food safety through elimination of pesticide and chemical residues; and (6) Environmentally friendly technology that promotes sustainability, as it solely requires air and electricity to generate efficient plasma. There is a limitation of cold plasma technology in the case of high-fat foods, which is responsible for the formation of secondary metabolites. These metabolites have an impact on the shelf life of fat-rich foods (Sarangapani, Keogh, Dunne, Bourke, & Cullen, 2017). Some researchers also reported that the treatment of high-fat dairy food with cold plasma causes its oxidation (Coutinho et al., 2018).

Conclusions

Cold plasma has gained significant popularity as a seed treatment, thanks to its capability to operate in low-temperature conditions without causing any harm to the seed surface. Various methods are used to generate the cold plasma, which makes comparing different results somewhat difficult. This review presents a summary of the impacts of cold plasma on various types of cereal seeds. The text is made up of sections that describe the effect of plasma on seed and sprout decontamination, germination, surface property changes, growth and biomass parameters and metabolic activities. This overview suggests that cold plasma may also have a strong presence in different agricultural sectors, particularly in relation to applications for cereal seeds. Based on the works reviewed, it can be concluded that exposure to cold plasma or PAW has a significant impact on various properties of cereal seeds. Namely, germination begins with water absorption, and the ability to absorb water can be greatly affected by plasma activity.

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The surface properties and certain physiological parameters of seeds could also be modified. Oxidation processes by reactive species can enhance water adsorption capability by improving seed coat wettability. Additionally, these processes may be linked to gas exchanges and electrolyte leakage in the seeds. It is probable that cold plasma could effectively alter the dormancy of hard seeds by influencing seed permeability. Cold plasma also can have a positive impact on seed germination, growth, and the characteristics of seedlings. In addition, cold plasma can be used effectively for decontaminating the surfaces of cereal seeds. The findings presented in the text are summarized in Table 1. This table offers an overview of prior studies conducted on cereal family plant seeds using cold plasma.

To further explore the impact of plasma on cereal seeds, it is recommended to analyze the alterations in the surface morphology of plasma-treated cereal seeds. Additionally, it is important to examine the resulting products derived from cereals, such as flour, starch, oil, and others. Furthermore, assessing the long-term effectiveness of plasma treatment is crucial for controlling pests in stored grains.

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Author Contribution Statement

Gather information and literature search, review sources and writing manuscript: Maryam Pourbagher; presenting ideas, reviewing sources, critically revised the work and writing articles: Roghayeh Pourbagher; supervision, conceptualization, resources, review and editing: Mohammad Hossein Abbaspour-Fard.

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References

Adhikari, B., Adhikari, M., Ghimire, B., Adhikari, B. C., Park, G., & Choi, E. H. (2020). Cold plasma seed priming modulates growth, redox homeostasis and stress response by inducing reactive species in tomato (Solanum lycopersicum). *Free Radical Biology and Medicine*, *156*, 57-69.

Ahn, C., Gill, J., & Ruzic, D. N. (2019). Growth of plasma-treated corn seeds under realistic conditions. *Scientific reports*, *9*(1), 4355.

Ali, Q., Daud, M., Haider, M. Z., Ali, S., Rizwan, M., Aslam, N., Noman, A., Iqbal, N., Shahzad, F., & Deeba, F. (2017). Seed priming by sodium nitroprusside improves salt tolerance in wheat (Triticum aestivum L.) by enhancing physiological and biochemical parameters. *Plant Physiology and Biochemistry*, *119*, 50-58.

Amnuaysin, N., Korakotchakorn, H., Chittapun, S., & Poolyarat, N. (2018). Seed germination and seedling growth of rice in response to atmospheric air dielectric-barrier discharge plasma. *Songklanakarin Journal of Science & Technology*, *40*(4).

Bormashenko, E., Grynyov, R., Bormashenko, Y., & Drori, E. (2012). Cold radiofrequency plasma treatment modifies wettability and germination speed of plant seeds. *Scientific reports*, *2*(1), 741.

Butscher, D., Schlup, T., Roth, C., Müller-Fischer, N., Gantenbein-Demarchi, C., & von Rohr, P. R. (2015). Inactivation of microorganisms on granular materials: Reduction of Bacillus amyloliquefaciens endospores on wheat grains in a low pressure plasma circulating fluidized bed reactor. *Journal of Food Engineering*, *159*, 48-56.

Butscher, D., Zimmermann, D., Schuppler, M., & von Rohr, P. R. (2016). Plasma inactivation of bacterial endospores on wheat grains and polymeric model substrates in a dielectric barrier discharge. *Food Control*, *60*, 636-645.

Chalise, R., Bhandari, P., Sharma, S., Basnet, S., Subedi, D. P., & Khanal, R. (2023). Enhancement of wheat yield by atmospheric pressure plasma treatment. *AIP Advances*, *13*(6).

Chen, H. H., Chang, H. C., Chen, Y. K., Hung, C. L., Lin, S. Y., & Chen, Y. S. (2016). An improved process for high nutrition of germinated brown rice production: Low-pressure plasma. *Food Chemistry*, *191*, 120-127.

Chen, H. H., Chen, Y. K., & Chang, H. C. (2012). Evaluation of physicochemical properties of plasma treated brown rice. *Food Chemistry*, *135*(1), 74-79.

Chen, H. H., Hung, C. L., Lin, S. Y., & Liou, G. J. (2015). Effect of low-pressure plasma exposure on the storage characteristics of brown rice. *Food and Bioprocess Technology*, *8*, 471-477.

Coutinho, N. M., Silveira, M. R., Rocha, R. S., Moraes, J., Ferreira, M. V. S., Pimentel, T. C., Freitas, M. Q., Silva, M. C., Raices, R. S., & Ranadheera, C. S. (2018). Cold plasma processing of milk and dairy products. *Trends in Food Science & Technology*, *74*, 56-68.

Dobrin, D., Magureanu, M., Mandache, N. B., & Ionita, M.-D. (2015). The effect of non-thermal plasma treatment on wheat germination and early growth. *Innovative Food Science & Emerging Technologies*, *29*, 255-260.

Fang, Z., Wang, X., Shao, R., Qiu, Y., & Edmund, K. (2011). The effect of discharge power density on polyethylene terephthalate film surface modification by dielectric barrier discharge in atmospheric air. *Journal of Electrostatics*, *69*(1), 60-66.

Feizollahi, E., Iqdiam, B., Vasanthan, T., Thilakarathna, M. S., & Roopesh, M. (2020). Effects of atmospheric-pressure cold plasma treatment on deoxynivalenol degradation, quality parameters, and germination of barley grains. *Applied Sciences*, *10*(10), 3530.

Fereydooni, M., & Alizadeh, H. H. A. (2022). Microscopic investigation of cold plasma effect on chickpea seed germination. *Journal of Agricultural Machinery*, *12*(2), 231-240.

Filatova, I., Azharonok, V., Goncharik, S., Lushkevich, V., Zhukovsky, A., & Gadzhieva, G. (2014). Effect of RF plasma treatment on the germination and phytosanitary state of seeds. *Journal of Applied Spectroscopy*, *81*, 250-256.

Ghaly, T., & Sutherland, J. (1984). Heat damage to grain and seeds. *Journal of Agricultural Engineering Research*, *30*, 337-345.

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., Pretty, J., Robinson, S., Thomas, S. M., & Toulmin, C. (2010). Food security: the challenge of feeding 9 billion people. *Science*, *327*(5967), 812-818.

Gómez-Ramírez, A., López-Santos, C., Cantos, M., García, J. L., Molina, R., Cotrino, J., Espinós, J., & González-Elipe, A. R. (2017). Surface chemistry and germination improvement of Quinoa seeds subjected to plasma activation. *Scientific reports*, *7*(1), 5924.

Gujral, H. S., Sharma, P., Kumar, A., & Singh, B. (2012). Total phenolic content and antioxidant activity of extruded brown rice. *International Journal of Food Properties*, *15*(2), 301-311.

Uncorrected Proof

Guo, J., He, Z., Ma, C., Li, W., Wang, J., Lin, F., Liu, X., & Li, L. (2023). Evaluation of cold plasma for decontamination of molds and mycotoxins in rice grain. *Food Chemistry*, *402*, 134159.

Guo, Q., Meng, Y., Qu, G., Wang, T., Yang, F., Liang, D., & Hu, S. (2018). Improvement of wheat seed vitality by dielectric barrier discharge plasma treatment. *Bioelectromagnetics*, *39*(2), 120-131.

Guo, Q., Wang, Y., Zhang, H., Qu, G., Wang, T., Sun, Q., & Liang, D. (2017). Alleviation of adverse effects of drought stress on wheat seed germination using atmospheric dielectric barrier discharge plasma treatment. *Scientific reports*, *7*(1), 16680.

Hasan, M., Sohan, M. S. R., Sajib, S. A., Hossain, M. F., Miah, M., Maruf, M. M. H., Khalid-Bin-Ferdaus, K. M., Kabir, A. H., Talukder, M. R., & Rashid, M. M. (2022). The effect of low-pressure dielectric barrier discharge (lpdbd) plasma in boosting germination, growth, and nutritional properties in wheat. *Plasma Chemistry and Plasma Processing*, *42*(2), 339-362.

Henselová, M., Slováková, Ľ., Martinka, M., & 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.

Hui, Y., Wang, D., You, Y., Shao, C., Zhong, C., & Wang, H. (2020). Effect of low temperature plasma treatment on biological characteristics and yield components of wheat seeds (Triticum aestivum L.). *Plasma Chemistry and Plasma Processing*, *40*, 1555-1570.

Jiang, J., He, X., Li, L., Li, J., Shao, H., Xu, Q., Ye, R., & Dong, Y. (2014). Effect of cold plasma treatment on seed germination and growth of wheat. *Plasma Science and Technology*, *16*(1), 54.

Kabir, A. H., Rahman, M. M., Das, U., Sarkar, U., Roy, N. C., Reza, M. A., Talukder, M. R., & Uddin, M. A. (2019). Reduction of cadmium toxicity in wheat through plasma technology. *PLoS One*, *14*(4), e0214509.

Keener, K., & Misra, N. (2016). Future of cold plasma in food processing. In *Cold plasma in food and agriculture* (pp. 343-360). Elsevier.

Kikuchi, K., Koizumi, M., Ishida, N., & Kano, H. (2006). Water uptake by dry beans observed by micro-magnetic resonance imaging. *Annals of Botany*, *98*(3), 545-553.

Kusano, Y., Salewski, M., Leipold, F., Zhu, J., Ehn, A., Li, Z., & Aldén, M. (2014). Stability of alternating current gliding arcs. *The European Physical Journal D*, *68*, 1-9.

Lee, K. H., Kim, H.-J., Woo, K. S., Jo, C., Kim, J.-K., Kim, S. H., Park, H. Y., Oh, S.-K., & Kim, W. H. (2016). Evaluation of cold plasma treatments for improved microbial and physicochemical qualities of brown rice. *LWT*, *73*, 442-447.

Lee, K. H., Woo, K. S., Yong, H. I., Jo, C., Lee, S. K., Lee, B. W., Oh, S.-K., Lee, Y.-Y., Lee, B., & Kim, H.-J. (2018). Assessment of microbial safety and quality changes of brown and white cooked rice treated with atmospheric pressure plasma. *Food science and biotechnology*, *27*, 661-667.

Li, Y., Wang, T., Meng, Y., Qu, G., Sun, Q., Liang, D., & Hu, S. (2017). Air atmospheric dielectric barrier discharge plasma induced germination and growth enhancement of wheat seed. *Plasma Chemistry and Plasma Processing*, *37*, 1621-1634.

Liao, X., Cullen, P., Muhammad, A. I., Jiang, Z., Ye, X., Liu, D., & Ding, T. (2020). Cold plasma–based hurdle interventions: New strategies for improving food safety. *Food Engineering Reviews*, *12*, 321-332.

Liu, J., Wang, R., Chen, Z., & Li, X. (2021). Effect of cold plasma treatment on cooking, thermomechanical and surface structural properties of Chinese milled rice. *Food and Bioprocess Technology*, *14*(5), 866-886.

Liu, Q., Wu, H., Luo, J., Liu, J., Zhao, S., Hu, Q., & Ding, C. (2021). Effect of dielectric barrier discharge cold plasma treatments on flavor fingerprints of brown rice. *Food Chemistry*, *352*, 129402.

Los, A., Ziuzina, D., Akkermans, S., Boehm, D., Cullen, P. J., Van Impe, J., & Bourke, P. (2018). Improving microbiological safety and quality characteristics of wheat and barley by high voltage atmospheric cold plasma closed processing. *Food Research International*, *106*, 509-521.

Los, A., Ziuzina, D., Boehm, D., Cullen, P. J., & Bourke, P. (2019). Investigation of mechanisms involved in germination enhancement of wheat (Triticum aestivum) by cold plasma: Effects on seed surface chemistry and characteristics. *Plasma Processes and Polymers*, *16*(4), 1800148.

Uncorrected Proof

Lutts, S., Benincasa, P., Wojtyla, L., Kubala, S., Pace, R., Lechowska, K., Quinet, M., & Garnczarska, M. (2016). Seed priming: new comprehensive approaches for an old empirical technique. *New challenges in seed biology-basic and translational research driving seed technology*, *46*.

Maghsoudi, H., Balvardi, M., Ganjovi, A., & Amir-Mojahedi, M.-S. (2023). Investigating the Effect of Cold Plasma on some Chemical Properties of Date Fruits (Phoenix dactylifera L.). *Biomechanism and Bioenergy Research*, *2*(1), 56-67.

Mazandarani, A., Goudarzi, S., Ghafoorifard, H., & Eskandari, A. (2020). Evaluation of DBD plasma effects on barley seed germination and seedling growth. *IEEE Transactions on Plasma Science*, *48*(9), 3115-3121.

McDonald, M. B. (1994). Seed germination and seedling establishment. *Physiology and determination of crop yield*, 37-60.

Mendis, D., Rosenberg, M., & Azam, F. (2000). A note on the possible electrostatic disruption of bacteria. *IEEE Transactions on Plasma Science*, *28*(4), 1304-1306.

Meng, Y., Qu, G., Wang, T., Sun, Q., Liang, D., & Hu, S. (2017). Enhancement of germination and seedling growth of wheat seed using dielectric barrier discharge plasma with various gas sources. *Plasma Chemistry and Plasma Processing*, *37*, 1105-1119.

Nalwa, C., Thakur, A. K., Vikram, A., Rane, R., & Vaid, A. (2017). Studies on plasma treatment and priming of seeds of bell pepper (Capsicum annuum L.). *Journal of Applied and Natural Science*, *9*(3), 1505-1509.

Niemira, B. A. (2012). Cold plasma decontamination of foods. *Annual review of food science and technology*, *3*, 125-142.

Nonogaki, H. (2014). Seed dormancy and germination—emerging mechanisms and new hypotheses. *Frontiers in plant science*, *5*, 233.

Park, H., Puligundla, P., & Mok, C. (2020). Cold plasma decontamination of brown rice grains: Impact on biochemical and sensory qualities of their corresponding seedlings and aqueous tea infusions. *LWT*, *131*, 109508.

Park, Y., Oh, K. S., Oh, J., Seok, D. C., Kim, S. B., Yoo, S. J., & Lee, M. J. (2018). The biological effects of surface dielectric barrier discharge on seed germination and plant growth with barley. *Plasma Processes and Polymers*, *15*(2), 1600056.

Penado, K. N. M., Mahinay, C. L. S., & Culaba, I. B. (2017). Effect of atmospheric plasma treatment on seed germination of rice (Oryza sativa L.). *Japanese Journal of Applied Physics*, *57*(1S), 01AG08.

Pérez-Pizá, M. C., Cejas, E., Zilli, C., Prevosto, L., Mancinelli, B., Santa-Cruz, D., Yannarelli, G., & Balestrasse, K. (2020). Enhancement of soybean nodulation by seed treatment with non–thermal plasmas. *Scientific Reports*, *10*(1), 4917.

Radjabian, T., Saboora, A., Hhasani, B., & Fallah-Hosseini, H. (2007). Effects of GA3 and chilling on seed germination of Ferula assa-foetida, as a medicinal plant. *Researches on medicinal and aromatic plants of Iran*, *23*(3).

Ranieri, P., Sponsel, N., Kizer, J., Rojas- Pierce, M., Hernández, R., Gatiboni, L., Grunden, A., & Stapelmann, K. (2021). Plasma agriculture: Review from the perspective of the plant and its ecosystem. *Plasma Processes and Polymers*, *18*(1), 2000162.

Rasooli, Z., Barzin, G., Mahabadi, T. D., & Entezari, M. (2021). Stimulating effects of cold plasma seed priming on germination and seedling growth of cumin plant. *South African Journal of Botany*, *142*, 106-113.

Ray, D. K., Mueller, N. D., West, P. C., & Foley, J. A. (2013). Yield trends are insufficient to double global crop production by 2050. *PloS one*, *8*(6), e66428.

Roy, N., Hasan, M., Talukder, M., Hossain, M., & Chowdhury, A. (2018). Prospective applications of low frequency glow discharge plasmas on enhanced germination, growth and yield of wheat. *Plasma Chemistry and Plasma Processing*, *38*, 13-28.

Saberi, M., Sanavy, M., Zare, R., & Ghomi, H. (2019). Improvement of photosynthesis and photosynthetic productivity of winter wheat by cold plasma treatment under haze condition. *Journal of Agricultural Science and Technology*, *21*(7), 1889-1904.

Uncorrected Proof

Sabularse, V., Liuzzo, J., Rao, R., & Grodner, R. (1991). Cooking quality of brown rice as influenced by gamma irradiation, variety and storage. *Journal of Food Science*, *56*(1), 96-98.

Sajib, S. A., Billah, M., Mahmud, S., Miah, M., Hossain, F., Omar, F. B., Roy, N. C., Hoque, K. M. F., Talukder, M. R., & Kabir, A. H. (2020). Plasma activated water: The next generation eco-friendly stimulant for enhancing plant seed germination, vigor and increased enzyme activity, a study on black gram (Vigna mungo L.). *Plasma Chemistry and Plasma Processing*, *40*, 119-143.

Sarangapani, C., Devi, Y., Thirundas, R., Annapure, U. S., & Deshmukh, R. R. (2015). Effect of low-pressure plasma on physico-chemical properties of parboiled rice. *LWT-Food Science and Technology*, *63*(1), 452-460.

Sarangapani, C., Keogh, D. R., Dunne, J., Bourke, P., & Cullen, P. (2017). Characterisation of cold plasma treated beef and dairy lipids using spectroscopic and chromatographic methods. *Food Chemistry*, *235*, 324-333.

Selcuk, M., Oksuz, L., & Basaran, P. (2008). Decontamination of grains and legumes infected with Aspergillus spp. and Penicillum spp. by cold plasma treatment. *Bioresource Technology*, *99*(11), 5104-5109.

Sera, B., Spatenka, P., Šerý, M., Vrchotova, N., & Hruskova, I. (2010). Influence of plasma treatment on wheat and oat germination and early growth. *IEEE Transactions on Plasma Science*, *38*(10), 2963-2968.

Shi, H., Ileleji, K., Stroshine, R. L., Keener, K., & Jensen, J. L. (2017). Reduction of aflatoxin in corn by high voltage atmospheric cold plasma. *Food and Bioprocess Technology*, *10*, 1042-1052.

Sidik, M. A. B., Buntat, Z., Nawawi, Z., Jambak, M. I., Buntat, Y., & Musa, F. N. (2018). Effects of cold plasma treatment on the growth rate of corn and eggplant plants. 2018 International Conference on Electrical Engineering and Computer Science (ICECOS),

Sivachandiran, L., & Khacef, A. (2017). Enhanced seed germination and plant growth by atmospheric pressure cold air plasma: combined effect of seed and water treatment. *RSC advances*, *7*(4), 1822-1832.

Sookwong, P., Yodpitak, S., Doungkaew, J., Jurithayo, J., Boonyawan, D., & Mahatheeranont, S. (2014). Application of oxygen-argon plasma as a potential approach of improving the nutrition value of pre-germinated brown rice. *Journal of Food and Nutrition Research*, *2*(12), 946-951.

Starič, P., Grobelnik Mlakar, S., & Junkar, I. (2021). Response of two different wheat varieties to glow and afterglow oxygen plasma. *Plants*, *10*(8), 1728.

Starič, P., Mravlje, J., Mozetič, M., Zaplotnik, R., Šetina Batič, B., Junkar, I., & Vogel Mikuš, K. (2022). The influence of glow and afterglow cold plasma treatment on biochemistry, morphology, and physiology of wheat seeds. *International Journal of Molecular Sciences*, *23*(13), 7369.

Suhem, K., Matan, N., Nisoa, M., & Matan, N. (2013). Inhibition of Aspergillus flavus on agar media and brown rice cereal bars using cold atmospheric plasma treatment. *International Journal of Food Microbiology*, *161*(2), 107-111.

Ten Bosch, L., Pfohl, K., Avramidis, G., Wieneke, S., Viöl, W., & Karlovsky, P. (2017). Plasma-based degradation of mycotoxins produced by Fusarium, Aspergillus and Alternaria species. *Toxins*, *9*(3), 97.

Thirumdas, R., Deshmukh, R., & Annapure, U. (2015). Effect of low temperature plasma processing on physicochemical properties and cooking quality of basmati rice. *Innovative Food Science & Emerging Technologies*, *31*, 83-90.

Tian, S., Nakamura, K., & Kayahara, H. (2004). Analysis of phenolic compounds in white rice, brown rice, and germinated brown rice. *Journal of agricultural and food chemistry*, *52*(15), 4808-4813.

Velichko, I., Gordeev, I., Shelemin, A., Nikitin, D., Brinar, J., Pleskunov, P., Choukourov, A., Pazderů, K., & Pulkrábek, J. (2019). Plasma jet and dielectric barrier discharge treatment of wheat seeds. *Plasma Chemistry and Plasma Processing*, *39*, 913-928.

Wang, J., Cheng, J.-H., & Sun, D.-W. (2023). Enhancement of wheat seed germination, seedling growth and nutritional properties of wheat plantlet juice by plasma activated water. *Journal of Plant Growth Regulation*, *42*(3), 2006-2022.

Uncorrected Proof

Wang, Y., Thorup-Kristensen, K., Jensen, L. S., & Magid, J. (2016). Vigorous root growth is a better indicator of early nutrient uptake than root hair traits in spring wheat grown under low fertility. *Frontiers in plant science*, *7*, 865.

Yodpitak, S., Mahatheeranont, S., Boonyawan, D., Sookwong, P., Roytrakul, S., & Norkaew, O. (2019). Cold plasma treatment to improve germination and enhance the bioactive phytochemical content of germinated brown rice. *Food Chemistry*, *289*, 328-339.

Yong, H. I., Lee, S. H., Kim, S. Y., Park, S., Park, J., Choe, W., & Jo, C. (2019). Color development, physiochemical properties, and microbiological safety of pork jerky processed with atmospheric pressure plasma. *Innovative Food Science & Emerging Technologies*, *53*, 78-84.

Zahoranová, A., Henselová, M., Hudecová, D., Kaliňáková, B., Kováčik, D., Medvecká, V., & Černák, M. (2016). Effect of cold atmospheric pressure plasma on the wheat seedlings vigor and on the inactivation of microorganisms on the seeds surface. *Plasma Chemistry and Plasma Processing*, *36*, 397-414.

Zulfiqar, F. (2021). Effect of seed priming on horticultural crops. *Scientia horticulturae*, *286*, 110197.

Uncorrected Proof