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# 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, especially in Asia, is directly supplied from grains, and nearly 70% of the cultivated area of the world, which is one billion hectares, is used for growing grains. Therefore, non-destructive methods must be found and developed to increase seed quality in agriculture and industry. Cold plasma is a novel and efficient method that can be used in the agricultural and food sectors for the inactivation of surface microorganisms and the 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, 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 length, growth efficiency, shoot and root weight, and metabolic activity. This review can provide insight into the promising trends in utilizing plasma as a method to decrease the prevalence of harmful plant diseases transmitted through seeds and reduce the dormancy of hard seeds.

**Keywords:** Biological feature, Cereal grain, Cold plasma, Seed treatment

## Introduction

Cold atmospheric plasma, has gained significant popularity in recent years. In the last few years, cold plasma has been extensively used 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).



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The use of different plasma devices has enabled extensive research on the 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 method, 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 method, the treated product is positioned relatively close to the plasma production point. This method produces a higher concentration of reactive species. At high voltages, it induces electrical conductivity in products with 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 produced 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 are also 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 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 with small edible seeds. In many Asian and African countries, grains provide more than 80% of people's food. 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, the supply of cereals must be increased by 70-100% (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 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 across arable lands. Therefore, to improve crop yield, 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 (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 could ensure food security. Given the increasing attention to plasma treatment in 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 objectives of our review are summarized in Fig. 1.

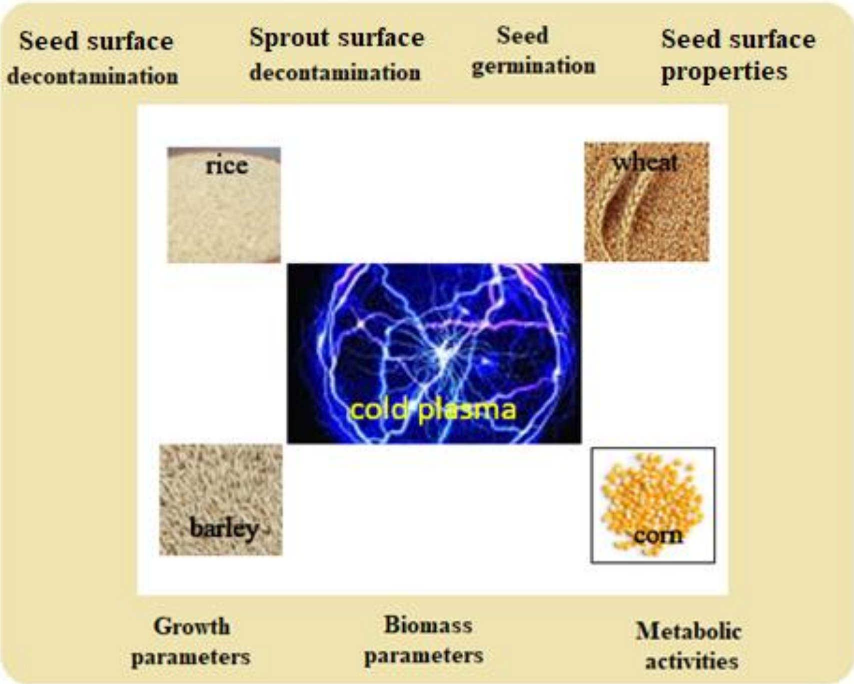


**Fig.1.** Schematic overview of the effects of cold plasma on cereal grains

**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 *Bacillus amyloliquefaciens* bacteria on wheat seeds could be effectively deactivated using this method. 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 of 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, and 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 with 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, and von Rohr (2016) conducted a study to investigate the impact of atmospheric pressure on the deactivation of bacterial cells in 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 were reported*. In a study conducted by Shi, Ileleji, Stroshine, Keener, and 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 200 W 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 (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's performance can be increased to further reduce Deoxynivalenol by adjusting various process factors such as voltage and frequency, type of feed gas, relative air humidity, 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 20 minutes of treatment of DBD plasma at 80 kV voltage showed promise in controlling both native microflora and pathogenic microorganisms on the wheat and barley seeds. 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 the seed's 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 both 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, hydro, osmose, hormonal, chemical, physical, and biological priming (Ali *et al.*, 2017). Recently, cold plasma seed treatment has gained 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).

So far, much research 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 stimulation for 75 s resulted in a notable increase (84%) in germination rate. A study carried out by Amnuaysin, Korakotchakorn, Chittapun, and 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-minute treatment of low-pressure plasma exposure. They attributed this enhancement to the increased a-amylase activity. Penado, Mahinay, and 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 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 seconds. The speed of germination begins to decline after treatment times exceed 30 seconds. 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 on wheat seeds with two types of operating gases, air, and $SF_6$, 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, and Ionita (2015) reported that germination was less affected by treatment compared to growth parameters.

PAW can impact water consumption during the germination phase and lead to the production of hybrid cereal seeds with superior germination rates. In a study conducted by Chalise *et al.* (2023), the effectiveness of PAW created by gliding discharge plasma was examined concerning 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. Similarly, 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. Similarly, a study conducted by Wang, Cheng, and 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, and 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 seeds were 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 the 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, and Bourke (2019); Meng *et al.* (2017); Roy, Hasan, Talukder, Hossain, and 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 process of wheat seeds. They generated plasma using glow and afterglow discharge techniques, with oxygen feed gas, under low-pressure conditions. Their findings indicated that plasma treatment had no significant impact on the germination rate, except for the seeds treated under 90 s 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, and 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 reached 24.78% and was observed after 5 h of soaking. The increase in water uptake ratio was associated with a decrease in cooking time. The plasma treatment altered the microstructure of the rice bran layers, making it easier for water to penetrate 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, and 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 the 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, and 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 the water absorption rate, weakening the protein network, and speeding up starch gelatinization. Thirumdas, Deshmukh, and 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 seed coats 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 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, and 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, and 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 a 2-hour treatment with coplanar surface DBD, the water uptake ranged from 6.41 to 9.60 mg, and after 8 hours 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 the metabolic process by breaking down the 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 ultraviolet 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 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. Additionally, 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 the seedlings. A study by Chen *et al.* (2016) determined that low-pressure plasma increased the length of brown rice seedlings by 37% compared to the control. However, there were no significant differences between the samples treated with plasma and the control group, as per the 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, 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 to 7 minutes) of surface DBD in air, nitrogen, and argon were observed in terms of the germination rate, water absorption, and 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. The 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 research. In a study conducted by Selcuk *et al.* (2008), it was demonstrated that the germination percentage, shoot height, and root length of the treated seeds were not affected by either air or $SF_6$ gas plasmas. Wheat roots and sprout length improvement were also reported 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 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. Although not significant, the 6-minute treatment showed some improvement in root volume, average root diameter, and germination percentage. Similarly, Mazandarani, Goudarzi, Ghafoorifard, and 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. Investigating the effect of three types of plasma including RF, microwave, and DBD in a 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 acted as fertilizers, which 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. Moreover, the 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. Furthermore, Saberi, Sanavy, Zare, and Ghomi (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 only affects the growth parameters during long-term treatment. Additionally, when exposed to hot air, temperatures below 70 °C do not have a significant impact on the seedling mass (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, and 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, a 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 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 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 efficiency compared to the control group (Amnuaysin *et al.*, 2018; 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 and 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 were recorded after a 24-hour germination time. Similarly, Park *et al.* (2020) also reported positive changes in 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 compound contents after 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 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.

Chen, Hung, Lin, and Liou (2015) suggested that the improvement of brown rice quality during the 3-month storage is related to the reduction of fatty acid and α-amylase of samples treated with 3–kV plasma. The 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 by 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 research by Wang *et al.* (2023), a 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 types of cereals and the parameters studied after plasma treatment.

**Table 1-** Summary of studies conducted on 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)

| Cereal | Plasma source/device | Studied parameters | 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, and 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, and chlorophyll b | (Amnuaysin *et al.*, 2018) |
| Brown rice, cultivar: 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, and 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, and 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, and germ lengths | (Penado *et al.*, 2017) |

| | | | |
|---|---|---|---|
| Brown rice, cultivar: not specified | Jet (0-40 W, 50 -600 kHz, 10 kV, RF, argon) | Colony count of *Aspergillus flavus* | (Suhem, Matan, 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, and 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, and gluten | (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, and 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, and chewiness | (Chen *et al.*, 2012) |
| Brown rice, cultivar: Nan-jing 46 | DBD (40-50 kV, 90-180 s, air) | Major volatile organic compounds, fatty acids, and color change | (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, and chalky rice rate | (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, and 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, and 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 *Penicillium spp. and 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, and contact angle | (Dobrin *et al.*, 2015) |
| Wheat seeds, cultivar: not specified | PAW (high voltage DC, 0–15 kV, 5-15 minutes, air) and DBD (50 Hz, 0–45 kV, 1-5 minutes, air) | Germination rate, contact angle, wettability, growth rate, germination potential, total number of fruits, root length, and spike length | (Chalise *et al.*, 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, and 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, and 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, and 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, and 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, and SEM | (Los *et al.*, 2019) |
| Wheat seeds, cultivar not specified | DBD ($3\times10^9$ MHz, 60-100 W, 150 Pa, 15 s, helium) | Seed germination, yield, plant height, root length, fresh weight, stem diameter, leaf area, and 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, and 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, and 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, and 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, and yield | (Roy *et al.*, 2018) |
| Wheat seeds, cultivar: Jimai 23 | PAW generated by plasma jet (high voltage AC, 7.0 kV, 600 W, 1-5 minutes, 98% Ar and 2% $O_2$) | Seed germination, pH, total soluble solids, color, vitamin C, soluble protein contents, pigments contents, enzyme activities of SOD, PPO and POD, TPC, DPPH, free amino acids, and mineral contents | (Wang *et al.*, 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, and 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*, and *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, and 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, and germination rate | (Feizollahi *et al.*, 2020) |
| Barley seeds, cultivar: not specified | DBD (40-120 W, 15 s, air) | Germination parameters, SEM, water penetration, and 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, and quality properties | (Los *et al.*, 2018) |

## Limitations and future of cold plasma in the 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 the day-to-day pressure of staying competitive (Keener & Misra, 2016). Therefore, for atmospheric cold plasma to be successfully adopted in the food industry, it is important to consider several non-technical factors. The primary focus should be on the consumers' needs, as they desire to consume fresh and high-quality food without added chemical preservatives. Food safety and maintaining the consumers' confidence in a particular food category is established gradually 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 the needs of consumers. 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 the elimination of pesticide and chemical residues; and (6) Environmentally friendly technology that promotes sustainability, as generation of efficient plasma requires only air and electricity. 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).

## Conclusion

Thanks to its capability to operate in low-temperature conditions without causing any harm to the surface of the seed, cold plasma has gained significant popularity as a seed treatment method. 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 concerning applications for cereal seeds. Based on the reviewed works, 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. 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. Probably, cold plasma could effectively alter the dormancy of hard seeds by influencing seed permeability. Cold plasma can also have a positive impact on seed germination, growth, and the characteristics of seedlings. In addition, cold plasma can be used to decontaminate the surfaces of cereal seeds effectively. 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, etc. Furthermore, assessing the long-term effectiveness of plasma treatment is crucial for controlling pests in stored grains.

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## Author Contribution Statement

**Maryam Pourbaghe:** Investigation, resources, data curation, writing (original draft), writing (review and editing). **Roghayeh Pourbagher:** Conceptualization, methodology, formal analysis, investigation, resources, data curation, writing (original draft), writing (review and editing), visualization. **Mohammad Hossein Abbaspour-Fard:** Conceptualization, project administration, writing (review and editing), data curation.

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**مقاله مروری**

جلد ؟، شماره ؟، آماده انتشار، ص ؟-؟

# تکنیک پلاسمای سرد در کنترل آلودگی و بهبود فرآیندهای فیزیولوژیکی غلات (مروری)

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## چکیده

امروزه تقریباً نیمی از کل نیازهای غذایی انسان به‌ویژه در آسیا مستقیماً از غلات تأمین می‌شود و نزدیک به ۷۰ درصد از سطح زیرکشت جهان که یک میلیارد هکتار است را غلات اشغال می‌کنند. بنابراین یافتن روش‌های غیرمخرب برای افزایش کیفیت بذر در کشاورزی و صنعت باید توسعه یابد. پلاسمای سرد روشی جدید و کارآمد در بخش کشاورزی و غذایی است که می‌توان از آن برای غیرفعال کردن میکروارگانیسم‌های سطحی و تحریک بذر استفاده کرد. این بررسی خلاصه‌ای از اثربخشی درمان با پلاسمای سرد بر ویژگی‌های چهار گیاه مهم غلات: گندم، برنج، ذرت و جو را ارائه می‌کند. تمرکز بر روی اثرات این تیمار بر روی جوانه زنی بذر، تغییرات خواص سطحی و جذب آب بذر، پارامترهای رشد ریشه، طول ساقه و نهال، پارامترهای زیست‌توده و فعالیت‌های متابولیکی است. با بررسی تحقیقات انجام‌شده توسط محققان مشاهده می‌شود که بذر غلات تیمارشده با پلاسمای سرد دارای قدرت جوانه‌زنی، جذب آب، طول ساقه و اندام هوایی، راندمان رشد، وزن اندام هوایی و ریشه و فعالیت متابولیکی بهتری بودند. این بررسی می‌تواند روندهای بالقوه امیدوارکننده‌ای را در استفاده از پلاسما به‌عنوان روشی برای کاهش شیوع بیماری‌های مضر گیاهی که از طریق بذر منتقل می‌شود و خواب دانه‌های سخت را کاهش دهد، ارائه دهد.

**واژه‌های کلیدی:** پلاسمای سرد، تیمار بذر، دانه غلات، ویژگی بیولوژیکی

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