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Explosion of plasma technology in agriculture

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Abstract
Plasma technology is a blazed field for researcher. It can positively modify physical, chemical and biological properties of seed coat through characteristics of surface plasma resonance that enables more imbibitions of water, increase enzymatic activities and improve inherent metabolism of plant. Therefore, it has a potential to improve seed germination, growth and overall agricultural productivity along with food quality and nutritional security by the use of surface sterilization and inclusion of active nutrient in the plant system without any environmental or health hazard issue.

Keywords: plasma technology, surface plasma resonance

Introduction
New technologies often create new challenges to science in addition to their benefits, raise concerns about health and various environmental problems. Plasma science and technology holds an innovative sustainable technology for agriculture sector including an explosive global population which in turn, increases demand for food, water and energy resources. Plasma acts as a standalone technology, provide an innovative solutions for enhancing agricultural productivity. Indiscriminate use of external inputs causes yield stagnation due to declining factor productivity, fertilizer response ratio, micronutrient deficiency, impairing soil as well as environmental health. The understanding of long term role of cold plasma provides a platform to resolve the emerging issues. Plasma is a discharge of gas molecules consisting of energetic ions, electrons and neutral species. Preliminary investigations so far have confirmed that the low-temperature plasma pre-treatment of seeds of important agricultural crops is an effective tool for improvement of germination, shoot and root growth. The plasma treatments provided good fungicidal and bactericidal effects, increased water permeability through surface coat etching and stimulation of germination and seedlings growth. These desirable characteristics have resulted from surface modification by the charged particles and neutral radicals formed in plasma. Such morphological changes on seed surfaces are safe and unlikely to have any genetic impact. Planted seeds require the highest probability of survival to maintain the required plant population and plants also need to grow as efficiently as possible. Plasma treatment of seeds is a new approach that is being proposed to assist fruitful germination of seeds and thereafter a healthy survival of plants.

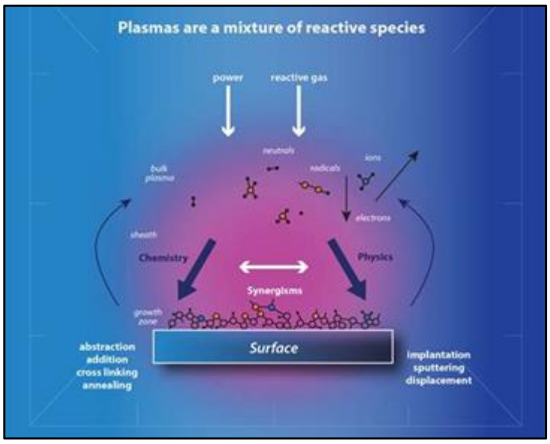

Fig 1: surface plasma resonance phenomenon on seed coat of crop seeds

Effect of atmospheric plasma on germination, growth and yield

Non-thermal plasma has been recently investigated in the field of agricultural science as an alternative to the traditional pre-sowing seed treatment, such as physical scratching or scarification, heat treatment, and chemical treatment (Dhayal, Lee & Park, 2006) [10]. For physical scratching, the seed coat is scratched using a grain feed-mixer at minimal cost. However, this mechanical procedure has a high probability of increasing the number of destroyed or damaged seeds as well as non-uniform treatment. In the case of heat treatment, hot water or a hot surface is used, while the chemical treatment consists in coating the seed with commercial sulphuric acid for 5–10 mins before washing in water and drying, but this process results in environmental pollution and effects are not sustainable (Morison *et al*., 2008, Bodelier *et al*., 2004) [40, 6]. Plasma has the advantage of uniform treatment, there is no destruction of seeds, and plasma does not require chemicals, hence it is harmless for the environment (Selcuk, Oksuz, & Basaran, 2008; Volin, Denes, Young, & Park, 2000) [63, 61]. Recently published works indicate the positive impact of plasma treatment on seed germination and on plant growth and development (Kitazaki, Koga, Shiratani, & Hayashi, 2012; Lynikiene, Pozeliene, & Rutkauskas, 2006; Sera, Sery, Stranak Spatenka, & Tichy, 2009; Sera, Spatenka, Sery, Vrchotova, & Hruskova, 2010; Sera, Stranak, Sery, Tichy, & Spatenka, 2008) [29, 33, 53, 57, 61, 29, 21]. One consequence of the plasma treatment is the sterilization of the seed surface (Basaran & Akhan, 2010; Basaran, Basaran-Akgul, & Oksuz, 2008; Selcuk *et al*., 2008) [21, 4, 3]. It was found that seed germination can be tuned by plasma chemistry; more precisely the germination can be accelerated by creating a plasma-reacted deposit on the surface of seeds (Ling *et al*., 2014) [23]. An important part of the investigations reported on seed treatment was carried out using low-pressure radio frequency (RF) discharges (Bormashenko, Grynyov, Bormashenko & Drori, 2012; Filatova *et al*., 2011; Filatova *et al*., 2013; Kitazaki *et al*., 2012; Puac *et al*., 2005; Volin *et al*., 2000; Zivkovic, Puac, Giba, Grubisic, & Petrovic, 2004) [5, 13, 16, 17, 47, 68] and microwave discharges (Sera *et al*., 2008) [56]. Some studies with atmospheric pressure discharges, such as corona (Lynikiene *et al*., 2006) [33] and diffuse coplanar barrier discharge (Henselova *et al*., 2012) [29] have been published as well. The authors investigated the germination of various types of seeds: safflower (Dhayal *et al*., 2006), radish (Kitazaki *et al*., 2012; Lynikiene *et al*., 2006; Volin *et al*., 2000), lamb's quarters (Sera *et al*., 2008; Sera *et al*., 2009) [29, 55, 57, 29], oat (Sera *et al*., 2010) [56], wheat (Bormashenko *et al*., 2012; Filatova*et al*., 2013; Sera *et al*., 2010) [56, 17], maize (Filatova *et al*., 2013; Henselova *et al*., 2012) [29, 17], blue lupine (Filatova*et al*., 2011; Filatova *et al*., 2013) [16, 17], Paulownia tomentosa (Puac*et al*., 2005; Zivkovic *et al*., 2004) [4, 47] etc. An enhancement in the germination rate of the plasma treated seeds as compared with the control (untreated seeds) was reported by several authors (Mihai *et al*., 2014; Yujuon *et al*., 2017) [36]. For example, Dhayal *et al*. (2006) [10] obtained a 50% higher germination rate of safflower (*Carthamus tinctorium* L.) seeds exposed to RF plasma generated in argon for 130 minutes. Sera *et al*. (2008) [57] obtained almost a three time increase of the germination rate of the lamb's quarters *(Chenopodium album*) after treatment with a microwave discharge for 48 minutes. In contrast, other studies reported no influence of plasma on the germination rate of wheat (Selcuk *et al*., 2008) [57], bean (Selcuk *et al*., 2008), oat (Sera *et al*., 2010) [57, 29] or radish (Kitazaki *et al*., 2012) [29]. In some cases, improved results as compared with the untreated samples were obtained for optimized plasma treatment times (Dhayal*et al*., 2006; Filatova *et al*., 2013; Henselova *et al*., 2012; Puac *et al*., 2005; Sera *et al*., 2008; Zivkovic *et al*., 2004) [10, 57, 47]. Several authors reported enhanced growth parameters of seeds after exposure to plasma (Dhayal *et al*., 2006; Henselova *et al*., 2012; Kitazaki *et al*., 2012; Sera *et al*., 2008) [29, 57]. Sera *et al*. (2008) [10, 57] reported 50% increase in sprouts length of the lamb's quarters after treatment in a microwave discharge. An increase with 60% in the sprout lengths of radish exposed to oxygen RF plasma was reported by Kitazaki *et al*. (2012) [29]. Henselova *et al*. (2012) [29] reported 21% increase in length, 10% increase in fresh weight and 14% increase in dry weight of maize roots treated in a diffuse coplanar surface barrier discharge generated in ambient air. Two times higher length of safflower roots treated by argon RF plasma was obtained by Dhayal *et al*. (2006) [10]. In this work the influence of treatment in a surface discharge generated in air at atmospheric pressure and room temperature on wheat seeds was investigated for the first time. Plasma treated seeds have better vigour index and imbibition rate. The germination rate and growth characteristics, such as roots and sprouts length and dry weight were determined. The modification of wetting properties of seeds by plasma treatment was investigated also.

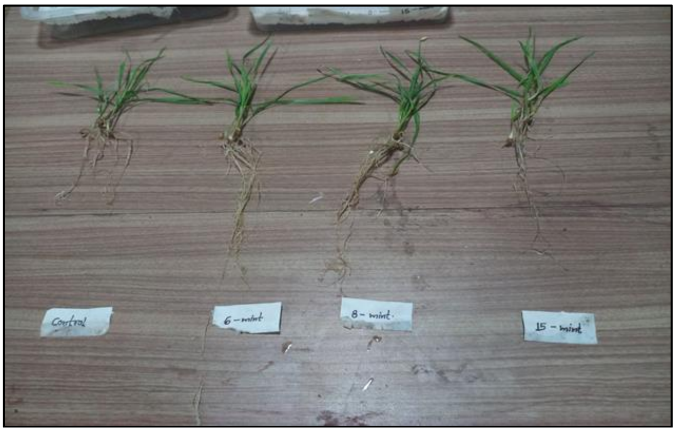

Fig 2: Different response of similar plasma seed treatment at different time duration (control, 6minutes, 8minutes and 15 minutes respectively)

Wetting properties of seeds

It was observed that after placing the seeds on wet filter paper, the plasma treated seeds got wet faster than the control samples. This observation led us to investigate further the wetting properties of the seeds. Wetting of the seed surface is characterized by the contact angle between the tangent to the liquid–air interface and the apparent solid surface as macroscopically observed (Bormashenko *et al*., 2012) [29]. The mechanism responsible for the plasma effect on seed germination has not been entirely clarified till now. Since seeds are an extremely complex system, they can be affected by the plasma treatment in a number of different ways (Hayashi *et al*., 2016) [16]: like by modification of the seed coat, by UV radiation emitted from the plasma, by reactions with electrons, ions and radicals emitted in the discharge, etc. (Ji *et al*., 2016; Randeniya *et al*., 2015) [25, 49]. Therefore, different treatment parameters, such as plasma properties, power values, nature and pressure of the working gas may influence the response of seeds to plasma treatment. The treatment time is an important factor, since too short plasma exposure may insignificantly affect seed germination and growth, while too long exposure may have a negative or harmful effect on the seeds (Filatova *et al*., 2013; Henselova *et al*., 2012) [17, 29]. Another important parameter is the type of seeds, since different seeds may respond differently to plasma treatment. Several authors observed that plasma treatment induces changes on the seed surface (Meng *et al*., 2014; jiayun *et al*., 2014) [19, 26]. Mechanical outside changes in the treated seed coat of Chenopodium album and wheat were confirmed by Sera *et al*. (2008) [57] and Sera *et al*. (2010) [56]. The pictures obtained from scanning electron microscopy (SEM) showed that the plasma treated seeds had an etched/eroded surface. A similar effect was also reported in Filatova *et al*. (2013) [17] for wheat and blue lupine seeds after plasma treatment. SEM images reported by Dhayal *et al*. (2006) [10] showed a "softer" structure of safflower seed surface after RF argon plasma treatment. The authors observed surface modifications of both the seed coat and of the hilum (the opening part of the seed from where the first root comes out during the germination of the seed). Seed surface modification in plasma treated seeds could improve the transmission of oxygen or water through the seed coat this process was confirmed in the case of wheat: obvious changes between the untreated and 10 minutes plasma treated seeds after 10 minutes wetting in water. Cold plasma seed treatment is a modern eco agricultural high-tech that could boost the crop yields. It is somewhat different from space breeding or mutation breeding by particle beam. Based on non-ionizing low level radiation, it could activate the vitality of seed without gene mutation, so there is no genetic risk. (Zivkovic *et al*., 2004) [68] has demonstrated that cold air plasma pre-treatment could significantly improve the germination of Paulownia tomentosa. (Carvalho *et al*., 2005) [8] showed that thin films obtained by plasma polymerization could protect grains and seeds and enhance seed germination. It was reported that magnetized plasma treatment could increase the germination percentage and peroxidase activities of tomato (Meiqiang *et al*., 2005) [35]. (Wu *et al*., 2005) [66] has reported the effect of plasma ion implantation on pea seed. It was found that tomato yield was enhanced after treated with electromagnetic field plasma (Li *et al*., 2002) [30]. Similarly, (Wang *et al*., 2007, Wang *et al*., 2007, Zhou *et al*., 2011., He *et al*., 2011) [42, 42, 66, 22] also demonstrated that the growth and yield of lettuce, cucumber, tomato, *Andrographis paniculata* were improved after treated with atmospheric pressure plasma. Seed dormancy is an inherent seed property that enables the species to reproduce generatively to survive (Finch *et al*., 2006) [13]. Cold plasma is known as a recent stimulation treatment to break down dormancy (Sera *et al*., 2008) [57]. Plasma treatment could generate UV radiation, radicals and chemical reactions, which played a significant function in breaking dormancy. Cold helium plasma might function in dormancy breaking, and it was in accordance with Sera's, 2008 [57]. Previous studies have reported that cold plasma treatment could improve the growth of wheat and oat, with the weight of shoots significantly increased (Sera *et al*., 2009) [55]. Since the hydrophilic property of seeds was improved by cold plasma treatment, and the ability of plants to absorb water and nutrition was relatively enhanced, that led to a better growth. (Satoshi *et al*., 2012) [59] also reported that cold plasma treatment could improve the growth of radish sprouts. At the same time, we found that chlorophyll content of the treated wheat was higher than that of the control, indicating that cold plasma treatment could increase the physiological activities of wheat. This is in agreement with (Guo *et al*., 2017) [19]. Because of the advantages, as the ability to large-scaling, low costs, no needed expensive vacuum systems and high processing speed, the cold atmospheric pressure (in the sense nonequilibrium) plasmas (CAPPs) have been used for a wide range of technological applications (Roth *et al*., 2001) [50]. The plasma treatment influences properties of the surface, leading to a change in the surface energy, chemical composition and roughness of the surface. In recent years bio-applications of the Cold air pressure plasma are done for sterilization, bio decontamination, preparing of the biocompatible surfaces, direct treatment of hardly healing wounds (Gadri *et al*., 2000) [7]. In the last years also many physical methods have been used to influence a germinating power of seeds and reduce germination time, as well as to interfere with growth, development and yield of plants (Marinkovic *et al*., 2009) [44]. Seed germination starts with imbibition and ends with radicle protrusion (Abebe *et al*., 2009) [1]. The amount of water to be imbibed for seed germination depends on species. The results with wheat seed showed, that the water content increased with CAPP exposure time and uptake of water was more intensive after 2-h than 8-h imbibition. The water imbibed by the treated plant seeds activates hydrolytic amylase enzyme and facilitates metabolism of a stored starch and also a protein in beans seed (Kikuchi *et al*., 2006) [27]. Thus, water absorption or imbibition is the most important event to ensure a nutrient supply to the germinating embryo and to produce energy for the commencement of active germination and seedling growth (Jiafeng *et al*., 2014) [23]. Cold plasma effects have been presented for many domains starting with material science. Plasma treatment could improve hydrophobic property of a polymer surface not hydrophilic and a good hydrophobic property could modify polymer surface (Chen K.S. *et al*., 2008) [9]. Recently, there has been considerable interest in investigating various physical properties of quantum plasmas since the quantum plasmas have been achieved in semiconductor devices and as well as in dense laser produced plasmas. Moreover, the quantum plasmas have been found in different dense astrophysical environments (Jung Y.D, Murakami I., 2005) [42].

Fig 3: Water imbibition capacity of plasma treated seeds (a) and control (b)

Stress Hardening

According to some authors the plasma induces not only structural changes on the seed surface (Volin *et al*., 2000; Zahoranova *et al*., 2016) [63] but also changes in some biochemical parameters (Meiqiang *et al*., 2005; Dubinov *et al*., 2000) [43, 12]. Physiological parameters modify as a result of exposure of seeds to plasma have been reported also.(Henselova, Slovakova, Martinka &Zaharanova, 2012; Ling *et al* 2016; Pulinundla *et al*., 2017) [20, 23]. Based on the previous results of (Henselova *et al*., 2012) [20] the effect of CAPP on maize seeds showed an increase in activity of some anti-oxidative enzymes SOD, CAT and G-POX in roots what is connected with the production of ROS by germinating seeds due to CAPP stress. Moreover, we determined an increase of dehydrogenase activity in embryos of the treated maize seeds in comparison with untreated seeds, what could depend on the intensive respiratory activity at an initial stage of the germination process. Similarly, the results on CAPP treatment of pea showed the rapid germination and hormonal activities related to plant signalling and development during early growth of pea seedlings (Stola *et al*., 2015) [58].

Food security and quality enhancement

In recent years, promotion of healthier lifestyles and consumer demands for greater food variety and availability has led to increased consumption of fresh produce (Thirumdas *et al*. 2016) [52]. Consumers are seeking for more nutritious, less processed foods, while simultaneously expecting microbial-free products of superior quality and long shelf life (Fernandez *et al*. 2013) [18]. The applications of CP for food industries have been demonstrated for food decontamination (Misra *et al*., 2011) [37], enzyme inactivation (Misra *et al*., 2016) [38], toxin removal (Misra, *et al*., 2015) [39], food packaging modifications (Pankaj *et al*., 2014) [45] and waste water treatment (Sarangapani *et al*., 2016) [52] Particularly for food processing, Cold plasma has been shown to be effective against major food-borne pathogenic microorganisms such as Escherichia coli (Bermudez *et al*., 2013) [2], Salmonella typhimurium (Fernandez *et al*., 2013) [18], Staphylococcus aureus (Kim *et al*., 2014) [28], and Listeria monocytogenes (Ziuzina *et al*., 2014) [69]. Plasma, a quasi-neutral gas, is referred to as the fourth state of matter. It contains versatile type of active particles, such as ions, radicals, electrons, metastable excited species, and vacuum ultraviolet radiation that have sufficient energy to break covalent bonds and initiate some reactions and form volatile compounds (Şhapira *et al*. 2017). Practically, active species disappear immediately once the plasma power is turned off; therefore plasma processing is environmentally safe and can be fulfilling all ecological standards (Misra *et al*. 2011) [22]. Plasma technology is one of the novel green technologies, used now a days for various industries mentionably food industry. This technology has shown the promising applications for retaining the nutritional, functional, and sensory properties, thus ensuring the fresh appearance. The technology helps in desirable structural modification of food and packaging material as well as in controlling the microbial load. The effect of CP on polysaccharides has been mainly focused on starch in legume and grain products. An increase in the water uptake rate in black gram was reported by Sarangapani, Devi, Thirumdas, Trimukhe, Deshmukh and Annapure (Sarangapani *et al*., 2017) [51], decrease in cooking time of brown rice, indicating the incorporation of polar groups between the starch molecules (Thirumdas *et al*., 2016) [52]. The antioxidant effects of phenolic compounds could be due to their redox properties, which include possible mechanisms such as free-radical scavenging activity, transition metal-chelating activity and singlet-oxygen quenching capacity (Shan *et al*., 2005) [53].

Conclusion

Plasma technology is a very useful technology. Application of plasma in agriculture has versatile positive impacts besides being environmentally safe. It plays significant role starting from stimulation of better seed germination by improving water imbibition, stress hardening to enhanced plant growth, development and also many more. So, this high-tech is going to have a very bright prospect in near future. It will lead to boost the agricultural production along with quality products to meet the ever increasing global hunger in a sustainable way.

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