SAARC J. Agri. 22(2): 29-42 (2024) https://doi.org/10.3329/sja.v22i2.73858

SAARC Journal of Agriculture

Journal Homage: https://www.banglajol.info/index.php/SJA

Review Article

Recent Advancement and Future Prospects of Plasma Technology for the Quality and Quantity Enhancement of Agricultural Production

H. K. Shastri[1], V. H. Trivedi[2] and M. T. Thakker[3*]

[1] Research Scholar, Gujarat Technological University, Ahmedabad, Gujarat, India

[2]Assistant Professor, Department of Instrumentation and Control Engineering, L. D. College of Engineering Ahmedabad, Gujarat, India.

[3]Professor, Department of Instrumentation and Control Engineering, L. D. College of Engineering Ahmedabad, Gujarat, India.

Abstract

Innovations in agriculture have greatly enhanced agricultural production, though the global community remains deeply worried about the disparity between food demand and supply. This places a significant burden on agriculture to produce and preserve enough food to feed everyone. Various technological advancements such as forecasting, drones, sensors, big data analytics, blockchain, IoT and plasma technology are playing a vital role in meeting future food demand. Extensive efforts are underway to explore the potential of plasma-based technology across agriculture applications. This includes seed germination, plant growth enhancement, shelf-life extension, preservation, detoxification, decontamination and many more. The transformative potential of plasma technology in agriculture, focusing on its application in enhancing seed germination and promoting plant growth through non-thermal plasma technologies such as, cold plasma treatment (CPT). Additionally, other plasma technologies, such as plasma-activated water (PAW), have shown significant decontamination of chemical and biological contaminants in agricultural produce. This work explores various findings, advancements and opportunities in the plasma technology for its potential application in agriculture for higher productivity and better-quality yields to meet the ever-growing global food demand.

Keywords: Non-Thermal Plasma, Plasma Agriculture, Plasma Activated Water, Plant Growth, Shelf-life

* Corresponding author: dr.mtthakker@gmail.com

Received: 22. 08. 2024 *Accepted:22. 12. 2024*

Introduction

Food is the prime source for survival. No research, automation, skill, art or any kind of innovation can equate the Piece of bread. A report estimated that by 2050 world needs 70% more food, compare to what we produce today (De Clercq et al., 2018). However, looking at current scenario there are lots of hurdles to achieve this target. Degradation of land fertility, global warming and water crises are some of the biggest concerns for agriculture. Several factors affect agricultural production, including limited shelf life, contamination, natural disasters, war, pandemics, and the perception of farming as an unattractive profession. The World Government Summit 2018 focused to emphasize significant transformation agriculture sector by harnessing cutting-edge technologies This summit was emphasized on Unites Nation's Sustainable Development Goals (SDGs) and coined the term "Agriculture 4.0."Agriculture 4.0 encompasses advancements for alternative means of food production and preservation like urban farming, vegan milk and cultured meat by applying novel cutting-edge technologies integrating recent scientific discoveries such as plasma technology.

Plasma known as the fourth state of matter is an ionized gas composed of ions, electrons and neutral particles. While industries have long reaped the benefits of plasma technology, recent research has turned its focus towards exploring its potential in agriculture domain. Plasma technology applications in agriculture offer benefits in seed treatment, plant growth promotion and produce preservation (Attri et al., 2020a; Desai et al., 2024). Both direct and indirect plasma treatments have shown significant improvements in agriculture, as evidenced by numerous studies highlighting enhanced seed germination, robust plant growth and extended shelf life for agricultural products.

Plasma

Solid substances, when heated or provided with energy, they transit into a liquid state. Further application of energy causes the substance to change from liquid to gas, and with even more energy, it can transform into plasma. Plasma can be categorized in various ways, based on its generation methodology, physical properties and behaviours, resulting in several classifications as shown in figure.1.

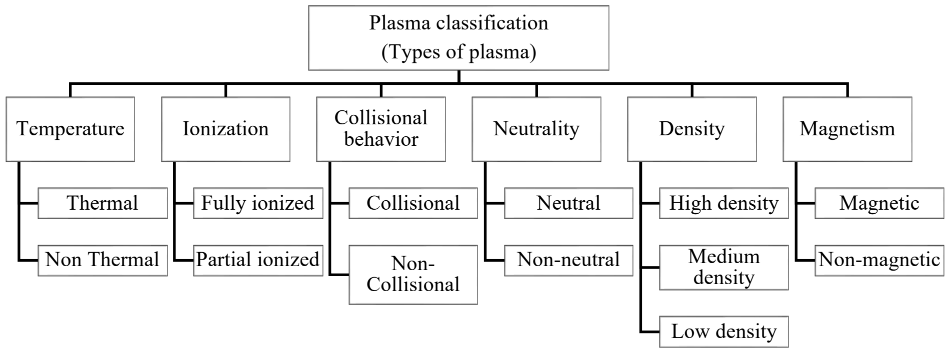

Fig. 1. Plasma Classification

Among all the types of plasma, non-thermal plasma (NTP) also known as cold plasma or atmospheric plasma, is mostly preferred in the field of agricultural research. Plasma is often generated by applying high voltage and high-frequency electricity to various gases through electrical electrodes. This process causes the gas to ionize, creating the plasma state. During this process various parameters like pressure, flow of gas and electrical supply need to be precisely controlled. Most common gases are, Normal air, He, O_2, N_2, Ar, NO and mixture of various gases with the pressure ranges from low, medium pressure or atmospheric pressure (from 10^{-2} to 101325 Pa) (Attri et al., 2022; Bormashenko et al., 2015). The power of the system (from watts to kilowatts) and frequency (from hertz to gigahertz) varies depending on the quality of plasma required for the treatment and the type of plasma to be generated. Barrier Discharge, Gliding arc, Arc Jet, Plasma Torch and some new technology like Microwave driven plasma (Refal Hussain, 2015) are used for the plasma generation.

Plasma technologies are used in the many industrial and medical sectors since many years as shown in figure 2. In last few years, researchers have also found some of the positive results of plasma treatment in the agriculture domain. Plasma and its byproducts have potential to induce alterations in the characteristics of agricultural products. By precisely control mechanism and techniques, some desired quality and quantity improvements of the agriculture products can be achieved.

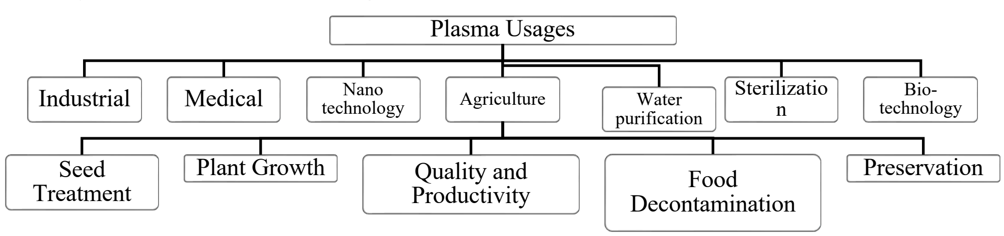

Fig. 2. Applications of Plasma

The NTP can generate the reactive charged species such as electrons, ions, neutral species, with emissions of ultraviolet radiation and electric fields (Attri et al., 2020b). Depending upon the usage of gases, plasma generates reactive oxygen and nitrogen species (RONS) and light. During the plasma treatment on the agriculture products, RONS change various properties like pH, electrical conductivity and oxidation-reduction potential of agriculture produces.

Plasma treatment for the seed germination and plant growth

Germination is the natural process which converts seed to plant. This process needs significant amount of time however, by applying various treatments on the seed, germination time can be reduced to some extent. This treatment can be physical, chemical or biological. Physical therapy encompasses a range of interventions such as temperature, electromagnetic fields, ionization, ultrasound, plasma and more. Plasma treatment changes the physical and biological properties of the seed which gives significant amount of change in seed germination and plant growth (Mildaziene et al., 2022). The treatment on seed basically scratches the outer layer of seeds or deform its structure. This deformation increases the water absorption capacity of the seed, which decreases germination time. The dielectric barrier discharge (DBD) plasma technique is a popular method employed to improve seed germination rates. By subjecting seeds to controlled plasma conditions, this technology stimulates biological processes within the seeds, leading to more robust and vigorous germination.

Seed treatment using non thermal plasma

In this treatment, plasma chambers serve as containers where seeds are strategically positioned for targeted therapy. The schematic diagram of plasma chamber is shown in the figure 3. The gas supply system allows for different gas combinations to be introduced into the chamber, enabling versatile treatment options. The effects of plasma treatment on different seeds can vary depending on the specific combinations of gases utilized during the process. Most preferred gases are He, Ar, N_2, Air, O_2, NO, NO +10% N_2 etc. The flow of gas is carefully regulated by a precise controller, ensuring optimal conditions within the chamber. Pressure is controlled using a vacuum pump. Electrodes play a crucial role, and their placement within the chamber is significant for effective treatment. High-voltage and high-frequency electrical supply applied to the electrodes through variable power supply system. Additional technical functionalities that could be integrated into a plasma generator include mechanism to change distance between electrode and target, or temperature control mechanism. Numerous plasma generators are commercially available, although researchers often prefer customized plasma chambers for specific seed treatment.

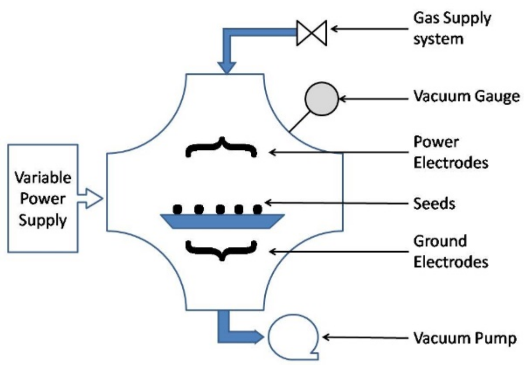

Figure 3. Schematic of NT Plasma Generator

Result analysis for NTP treated seed

After plasma treatment on the various seeds like radish sprouts, wheat, sunflower, pea, bean, maize, rice, pumpkin, cucumber, pepper, barley, spinach, basil, black pine etc., seed germination rate increased by 20% to 25%, details are shown in the Table. 1

Table 1. Results of various seed after Plasma treatment

Treated seeds	Plasma Technology	Result	Reference
Radish Sprouts carrot	Low pressure/ NTP/ O_2	Growth enhancement	(Matra, 2016) (Kitazaki et al., 2012) (Guragain et al., 2023)
Chili pepper	Plasma Jet	Enhancement in seed germination	(Ahmed et al., 2022)
Sunflower	DBD	Seed germination, phytohormone balance, and seedling growth	(Zukiene et al., 2019)
Wheat	Low pressure NTP	Growth and seed germination	(Lotfy et al., 2019) (Jiang et al., 2014)
Soybean	Cold argon plasma	Germination, root length	(Sayahi et al., 2024)
Basil	Radio-frequency (RF) room temperature plasma treatment	Germination increased	(Singh et al., 2022)
Ajwain	Low pressure radio frequency plasma	Improved germination index	(Gholami et al., 2016)

Treated seeds	Plasma Technology	Result	Reference
Tomato	Plasma treatment	Promote seed germination and seedling growth	(Mekarun&Watthanaphanit, 2022)
Barley	80 Watt DBD plasma	Improve seed germination, final germination percentage and vigor index	(Mazandarani et al., 2020)
Pea	Cold atmospheric pressure plasma	Affects Enzymes essential for the germination	(Svubova et al., 2020)
Altaic flax seeds	High-power UV-radiation plasma,	Increase of the germination velocity rate (more than twice).	(Dubinov et al., 2018)
Rice	LPGOD plasma and PAW	Enhanced seed germination percentage, enzymatic activities, yield contributing characters and yield of rice	(Rashid et al., 2022)
Cotton seed	Cold plasma treatment	Improvement in germination	(Groot et al., 2018)

By comparing the seed germination of plasma-treated seeds with untreated ones, an increased germination rate is observed after plasma treatment. In addition to the improvement in germination, researchers have also found increased seed weight and a shorter harvest time as a result of plasma treatment. Table. 1 illustrates that each type of seed treatment requires a specific setup. Plasma treatment that gives positive results for one seed may not work as effectively on other seed. The chemistry of the plasma varies based on gas composition, power levels, timing, positioning of electrodes and seed placement. The treatment process can also be influenced by certain chemicals. For instance, carbon tetrafluoride has been observed to delay germination, whereas cyclohexane can significantly accelerate the germination process. The changed plasma chemistry can also alter chlorophyll, photosynthesis, gibberellin (GA), abscisic acid (ABA) ratio, protein, thiol compound and various stress level of the plant (Volin et al., 2000).

Critical findings and research scope

Literature consistently supports the beneficial effects of plasma treatment on various seeds, although some cases have shown differing outcomes. Cell elongation, DNA damages and protein structure changes are observed by some researchers after plasma treatment (Svubova et al., 2020). In the case of hard-surfaced seeds like Mung beans, researchers have observed that plasma water treatment leads to an increase in the germination rate compare to direct plasma treatment (Zhou et al., 2019). In numerous instances, extending the treatment duration or supplying high power to the electrodes does not offer a cost-effective solution for improving germination rate.

Finding literature on the impact of consuming plasma-treated food on humans or other organisms was quite challenging. The majority of research is on the experimental stage, with limited literature available on real-time field surveys. Some studies also suggest that there is no significant difference in yield when comparing plasma-treated seeds to untreated ones (Ahn et al., 2019). Indeed, this field is relatively new, offering ample scope for further research and exploration.

Plasma treatment for enhancing the quality of agriculture product

Each year worldwide, unsafe food causes 600 million cases of foodborne diseases and 420000 deaths. 30% of food born deaths occur among children under 5 years of age (Food Safety- WHO, 2022). Between one-third to half of all food produced worldwide goes to waste, even developed nations like America dumps around 40 percent of their food produced (Dana Gunders, 2012). In this context, the primary concern revolves around deficiency in technology for preservation and contamination of food either in form of biological contamination (viruses, parasites and bacteria like E coli etc.) or chemical contamination (naturally occurring toxins, heavy metals, organic pollutants, pesticides, fertilizers etc.).

Traditional methods for decontamination are washing, cleaning the product using water and chemicals like chlorine, acid, etc. Coating the outer surface using edible wax is preferred to improve shelf life of agricultural products. Temperature variations are widely used to combat biological contamination. Altering the temperature of food, either by extreme heat or cold, is a simple yet effective way to decontaminate biological substances. This technique affects the food quality like change in the color, fragrance, texture, hardness, crunchiness or degradation of antioxidant, vitamins etc. Overall, using traditional decontamination methods are effective but affect biological, chemical, physical and sensory properties of food. Noval methods for the decontamination of the food are ultra-high pressure, ionizing radiation, including gamma rays (Fatemi et al., 2012) X-ray or electron beam (Shin et al., 2011), ultrasound (Ajlouni et al., 2006), pulsed light, pulsed electric fields (Mañnas et al., 2001) plasma activated water (PAW) etc.

PAW can play vital role for the decontamination of food products having various texture and folds. These places are very difficult to reach and preferred by many micro-organisms to hide. PAW is product of NTP's reaction with water containing a rich diversity of highly reactive oxygen species (ROS) and reactive nitrogen species (RNS), considered as the primary reactive chemical component in food decontamination. First successful study was conducted on the antibacterial activity of PAW in fresh strawberries (Ma et al., 2015). Also, various papers published recently claims that NTP treatment is a chemical-free and eco-friendly method to kill bacteria, bacterial spores, biofilms, viruses and fungi (Xiang et al., 2019; Zhou et al., 2019).

PAW generation method

For PAW generation most preferred plasma technique used by researchers are atmospheric pressure plasma jet (APPJ) and DBD, which are simple to use yet capable of producing richly RONS. The RONS plays key role for the decontamination of the food. The power of RONS depends on the effectiveness of the generated plasma which is influenced by factors such as the source of water, power supply, duration of activation, type of working gas, positioning of electrodes, as well as the techniques and equipment used for generating plasma. Even specialized RONS are produced to address explicit needs, such as targeting specific types of microorganisms or to enhance a particular quality aspect. PAW generation benefits by use of low TDS (low hardness) water, which enhances oxidation reduction potential (ORP) and reduces the pH of PAW, leading to effective antibacterial properties. Values of pH and ORP also depend upon the power and duration of treatment. Increasing these parameters gives lower pH and high electrical conductivity.

Typically, atmospheric air is used as a cost-effective gas source. However, in some cases, Argon gas is preferred as it produces higher levels of Hydrogen Peroxide (H_2O_2), known for its potent antiseptic properties. Additionally, combinations like He and Ar+O_2 are also utilized. The position of the electrode can also affect the PAW generation. Two most common positions of electrodes are, above water (PAW-A) and under water (PAW-B). Underwater electrodes produce more ROS, ORP and electrical conductivity. PAW can be also used with combination of other treatment like combine PAW with mild heat (Choi et al., 2019), ultrasound and blanching treatment (Gracy and Gupta, 2019) shows effective microbial inactivation of food.

Effectiveness of PAW treatment for decontamination

The latest uses of PAW for decontamination of food products or surfaces against biological substances are summarized in Table. 2.

In addition to biological decontamination, PAW can also degrade a wide range of pesticides, including parathion, paraoxon, omethoate, dichlorvos, malathion, azoxystrobin, cyprodinil, fludioxonil, cypermethrin and chlorpyrifos (Mousavi et al., 2016). Overall, this technique offers a potential environment friendly solution for pesticide residue management in agriculture, as it minimizes the need for harsh chemicals and reduces the risk of pesticide runoff into water bodies. However, the efficacy and feasibility of PAW for pesticide degradation may vary depending on factors such as the type of pesticide, crop characteristics and application methods.

Table 2. Biological decontamination of various food using Plasma treatment

Sample	Microorganisms	Technique	Result	Reference
Tofu	S. enterica, L.monocytogenes, and E. coli	PAW A, Plasma Jet, Air	Reduction 0.5-0.8 log CFU/g	(Frías et al., 2020)
Rice cake	S. Typhimurium, L.monocytogenes, and E. coli	PAW A, DBD, Air	Reduction 1.0-2.78 logCFU/g	(Han et al., 2020)
Lettuce	L. innocua and P. fluorescens	PAW B, DBD, Air	Reduction 2.4 logCFU/g	(Ajlouni et al., 2006)
Fresh cut Fruits	Natural microflora	PAW B, Micro plasma array, Air	Reduction ~1 logCFU/g	(Bagheri and Abbaszadeh, 2020; Liu et al., 2020; Zhao et al., 2019)
Mung bean sprouts	Natural microflora	PAW A, Plasma Jet, Air	Reduction ~2.5 logCFU/g	(Xiang et al., 2019)

Critical findings and research scope

PAW produced through NTP technology has shown effectiveness in reducing pesticide residues, as evidenced by various studies like Strawberries, grapes (Sarangapani et al., 2020) and tomatoes (Gracy and Gupta, 2019). However, most research outcomes are based on laboratory experiments, with limited literature on continuous process system development. For instance, DBD plasma can generate 520 L/hr. of PAW, which can be stored and utilized as needed, making it an economical and readily available option for potential commercial use. While PAW technology offers safe and efficient pesticide residue reduction, careful control is crucial to prevent undesirable outcomes like color changes, sensory deterioration, or increased toxicity levels. Although progress has been made in removing target pesticides to major extent, complete pesticide degradation is still area of research.

Thin walled Gram Negative bacteria (e.g., Salmonella and E. coli) are less resistant to Plasma treatment compared to thick membranes Gram Positive (e.g., L. monocytogenes). (Mai-Prochnow et al., 2014). There are various perspectives for the bacterial killing mechanism. One perspective is that, plasma radicals such as OH and NO are absorbed by the bacteria's surface, leading to the formation of volatile compounds like CO_2 and H_2O. This process may potentially inflict irreparable damage to the cell surface, ultimately causing cell death (Misra and Jo, 2017). While other perspective (Mai-Prochnow et al., 2014; Ryu et al., 2013), is that, the toxicity effect of Hydroxyl radicals (OH) within plasma is accountable for the bacteria demise, attributing it to the damaging effects on lipids and proteins. The findings also states that reactive protein species interact with amino acid chains, resulting in changes to protein structure, harm to nucleic acids and damages the cell. Despite the differing perspectives for decontamination methods, all share a common conclusion that plasma treatment has the potential to prevent food from microbes which enhance the shelf life.

Conclusion

Plasma technology especially CPT and PAW is having potential to boost seed germination, seedling as well as plant growth and shelf life improvement. It is a modern approach that effectively eliminates both pathogenic and non-pathogenic microbes. Choosing the right plasma technology is critical. In seed germination, it depends on factors like seed type and physiology. Similarly, for decontamination, it varies based on the type of bacteria and chemicals that need to be removed. Plasma treatments have shown positive results for decontaminating agricultural products. However, the challenge of achieving 100% decontamination while preserving product quality remains to be addressed. Increased seed germination using plasma technology offers substantial potential for rapid plant growth, resulting in faster yield and increased profitability for farmers. Comparing the quality and quantity of yield between traditional farming and plasma-treated farming is also an area of research for various plants and treatments. The toxicity of plasma residuals and potential adverse effects resulting from interactions with food chemistry are also under investigation. Plasma technology is an emerging research area in agriculture, as most available research still in the experimental stage. Implementing it in real-time field applications could revolutionize agricultural practices, making them more sustainable and efficient to meet global food demand while minimizing environmental impact and resource usage.

References

Ahmed, N., Masood, A., Siow, K. S., Wee, M. F. M. R., Haron, F. F., Patra, A., Nayan, N., and Soon, C. F. (2022). Effects of Oxygen (O2) Plasma Treatment in Promoting the Germination and Growth of Chili. *Plasma Chemistry and Plasma Processing*, *42*(1), 91–108. https://doi.org/10.1007/s11090-021-10206-2

Ahn, C., Gill, J., and Ruzic, D. N. (2019). Growth of Plasma-Treated Corn Seeds under Realistic Conditions. *Scientific Reports*, *9*(1), 4355. https://doi.org/10.1038/s41598-019-40700-9

Ajlouni, S., Sibrani, H., Premier, R., and Tomkins, B. (2006). Ultrasonication and Fresh Produce (Cos lettuce) Preservation. *Journal of Food Science*, *71*(2). https://doi.org/10.1111/j.1365-2621.2006.tb08909.x

Attri, P., Ishikawa, K., Okumura, T., Koga, K., and Shiratani, M. (2020a). Plasma agriculture from laboratory to farm: A review. In *Processes* (Vol. 8, Issue 8). https://doi.org/10.3390/PR8081002

Attri, P., Ishikawa, K., Okumura, T., Koga, K., and Shiratani, M. (2020b). Plasma agriculture from laboratory to farm: A review. In *Processes* (Vol. 8, Issue 8). https://doi.org/10.3390/PR8081002

Attri, P., Okumura, T., Koga, K., Shiratani, M., Wang, D., Takahashi, K., and Takaki, K. (2022). Outcomes of Pulsed Electric Fields and Nonthermal Plasma Treatments on Seed Germination and Protein Functions. *Agronomy*, *12*(2), 482. https://doi.org/10.3390/agronomy12020482

Bagheri, H., and Abbaszadeh, S. (2020). Effect of Cold Plasma on Quality Retention of Fresh-Cut Produce. *Journal of Food Quality*, *2020*, 1–8. https://doi.org/10.1155/2020/8866369

Bormashenko, E., Shapira, Y., Grynyov, R., Whyman, G., Bormashenko, Y., and Drori, E. (2015). Interaction of cold radiofrequency plasma with seeds of beans (Phaseolus vulgaris). *Journal of Experimental Botany*, *66*(13), 4013–4021. https://doi.org/10.1093/jxb/erv206

Choi, E. J., Park, H. W., Kim, S. B., Ryu, S., Lim, J., Hong, E. J., Byeon, Y. S., and Chun, H. H. (2019). Sequential application of plasma-activated water and mild heating improves microbiological quality of ready-to-use shredded salted kimchi cabbage (Brassica pekinensis L.). *Food Control*, *98*, 501–509. https://doi.org/10.1016/j.foodcont.2018.12.007

Dana Gunders. (2012). *Acknowledgments About NrDC*. http://uliwestphal.com/mutates.html.

De Clercq, M., Vatz, A., and Biel, A. (2018). World Government Summit. In *World Government Summit* (pp. 4–25).

de Groot, G. J. J. B., Hundt, A., Murphy, A. B., Bange, M. P., and Mai-Prochnow, A. (2018). Cold plasma treatment for cotton seed germination improvement. *Scientific Reports*, *8*(1). https://doi.org/10.1038/s41598-018-32692-9

Desai, M., Chandel, A., Chauhan, O. P., and Semwal, A. D. (2024). Uses and future prospects of cold plasma in agriculture. *Food and Humanity*, *2*, 100262. https://doi.org/10.1016/j.foohum.2024.100262

Dubinov, A. E., Kozhayeva, J. P., and Zuimatch, E. A. (2018). Scarification of Altaic Flax Seeds With High-Power UV Radiation Generated by Plasma of Nanosecond Electric Discharges. *IEEE Transactions on Plasma Science*, *PP*, 1–7. https://doi.org/10.1109/TPS.2018.2844213

Fatemi, F., Asri, Y., Rasooli, I., Alipoor, Sh. D., and Shaterloo, M. (2012). Chemical composition and antioxidant properties of γ-irradiated Iranian *Zataria multiflora* extracts. *Pharmaceutical Biology*, *50*(2), 232–238. https://doi.org/10.3109/13880209.2011.596208

Food safety. (n.d.). Retrieved March 6, 2024, from https://www.who.int/news-room/fact-sheets/detail/food-safety

Frías, E., Iglesias, Y., Alvarez-Ordóñez, A., Prieto, M., González-Raurich, M., and López, M. (2020). Evaluation of Cold Atmospheric Pressure Plasma (CAPP) and plasma-activated water (PAW) as alternative non-thermal decontamination technologies for tofu: Impact on microbiological, sensorial and functional quality attributes. *Food Research International*, *129*, 108859. https://doi.org/10.1016/j.foodres.2019.108859

Gholami, A., Safa, N. N., Khoram, M., Hadian, J., and Ghomi, H. (2016). Effect of Low-Pressure Radio Frequency Plasma on Ajwain Seed Germination. *Plasma Medicine*, *6*(3–4), 389–396. https://doi.org/10.1615/PlasmaMed.2017019157

Gracy, R. T., and Gupta, V. (2019). Effect of plasma activated water (PAW) on chlorpyrifos reduction in tomatoes. *International Journal of Chemical Studies*, *5000*(3), 5000–5006.

Guragain, R. P., Baniya, H. B., Shrestha, B., Guragain, D. P., and Subedi, D. P. (2023). Non-Thermal Plasma: A Promising Technology for the Germination Enhancement of Radish (Raphanus sativus) and Carrot (Daucus carota sativus L.). *Journal of Food Quality*, *2023*, 1–15. https://doi.org/10.1155/2023/4131657

Han, J.-Y., Song, W.-J., Kang, J. H., Min, S. C., Eom, S., Hong, E. J., Ryu, S., Kim, S. bong, Cho, S., and Kang, D.-H. (2020). Effect of cold atmospheric pressure plasma-activated water on the microbial safety of Korean rice cake. *LWT*, *120*, 108918. https://doi.org/10.1016/j.lwt.2019.108918

Jiang, J., He, X., Li, L., Li, J., Shao, H., Xu, Q., Ye, R., and Dong, Y. (2014). Effect of Cold Plasma Treatment on Seed Germination and Growth of Wheat. *Plasma Science and Technology*, *16*(1), 54–58. https://doi.org/10.1088/1009-0630/16/1/12

Kitazaki, S., Koga, K., Shiratani, M., and Hayashi, N. (2012). Growth Enhancement of Radish Sprouts Induced by Low Pressure O_2 Radio Frequency Discharge Plasma Irradiation. *Japanese Journal of Applied Physics*, *51*(1S), 01AE01. https://doi.org/10.1143/JJAP.51.01AE01

Liu, C., Chen, C., Jiang, A., Sun, X., Guan, Q., and Hu, W. (2020). Effects of plasma-activated water on microbial growth and storage quality of fresh-cut apple. *Innovative Food Science and Emerging Technologies*, *59*, 102256. https://doi.org/10.1016/j.ifset.2019.102256

Lotfy, K., Al-Harbi, N. A., and Abd El-Raheem, H. (2019). Cold Atmospheric Pressure Nitrogen Plasma Jet for Enhancement Germination of Wheat Seeds. *Plasma Chemistry and Plasma Processing*, *39*(4), 897–912. https://doi.org/10.1007/s11090-019-09969-6

Ma, R., Wang, G., Tian, Y., Wang, K., Zhang, J., and Fang, J. (2015). Non-thermal plasma-activated water inactivation of food-borne pathogen on fresh produce. *Journal of Hazardous Materials*, *300*, 643–651. https://doi.org/10.1016/j.jhazmat.2015.07.061

Mai-Prochnow, A., Murphy, A. B., McLean, K. M., Kong, M. G., and Ostrikov, K. (Ken). (2014). Atmospheric pressure plasmas: Infection control and bacterial responses. *International Journal of Antimicrobial Agents*, *43*(6), 508–517. https://doi.org/10.1016/j.ijantimicag.2014.01.025

Mañas, P., Barsotti, L., and Cheftel, J. C. (2001). Microbial inactivation by pulsed electric fields in a batch treatment chamber: effects of some electrical parameters and food constituents. *Innovative Food Science and Emerging Technologies*, *2*(4), 239–249. https://doi.org/10.1016/S1466-8564(01)00041-8

Matra, K. (2016). Non-thermal Plasma for Germination Enhancement of Radish Seeds. *Procedia Computer Science*, *86*, 132–135. https://doi.org/10.1016/j.procs.2016.05.033

Mazandarani, A., Goudarzi, S., Ghafoorifard, H., and Eskandari, A. (2020). *Evaluation of DBD plasma effects on barley seed germination and seedling growth*. *August*. https://doi.org/10.1109/TPS.2020.3012909

Mekarun, J., and Watthanaphanit, A. (2022). In-situ plasma treatment of tomato and rice seeds in-liquid to promote seed germination and seedling growth. *Plasma Processes and Polymers*, *19*(6). https://doi.org/10.1002/ppap.202100238

Mildaziene, V., Ivankov, A., Sera, B., and Baniulis, D. (2022). Biochemical and Physiological Plant Processes Affected by Seed Treatment with Non-Thermal Plasma. In *Plants* (Vol. 11, Issue 7). MDPI. https://doi.org/10.3390/plants11070856

Misra, N. N., and Jo, C. (2017). Applications of cold plasma technology for microbiological safety in meat industry. In *Trends in Food Science and Technology* (Vol. 64, pp. 74–86). Elsevier Ltd. https://doi.org/10.1016/j.tifs.2017.04.005

Mousavi, S. M., Imani, S., Dorranian, D., Larijani, K., and Shojaee, M. (2016). Original Article. Effect of cold plasma on degradation of organophosphorus pesticides used on some agricultural products. *Journal of Plant Protection Research*, *57*(1), 25–35. https://doi.org/10.1515/jppr-2017-0004

Rashid, M., Alam, M. S., and Talukder, M. R. (2022). *COLLECTIVE IMPACTS OF LPGOD PLASMA AND PLASMA ACTIVATED WATER TREATMENT IN RICE (Oryza sativa L.)*. *20*(2), 17–30. https://doi.org/10.3329/sja.v20i2

Refal Hussain, and S. N. (2015). Research Journal of A Review of Microwave-Induced Plasma for Production of High Value Products from Waste Glycerol. *A Review of Microwave-Induced Plasma for Production of High Value Products from Waste Glycerol*, *6*(1842), 1842–1848.

Ryu, Y.-H., Kim, Y.-H., Lee, J.-Y., Shim, G.-B., Uhm, H.-S., Park, G., and Choi, E. H. (2013). Effects of Background Fluid on the Efficiency of Inactivating Yeast with Non-Thermal Atmospheric Pressure Plasma. *PLoS ONE*, *8*(6), e66231. https://doi.org/10.1371/journal.pone.0066231

Sarangapani, C., Scally, L., Gulan, M., and Cullen, P. J. (2020). Dissipation of Pesticide Residues on Grapes and Strawberries Using Plasma-Activated Water. *Food and Bioprocess Technology*, *13*(10), 1728–1741. https://doi.org/10.1007/s11947-020-02515-9

Sayahi, K., Sari, A. H., Hamidi, A., Nowruzi, B., and Hassani, F. (2024). Application of cold argon plasma on germination, root length, and decontamination of soybean cultivars. *BMC Plant Biology*, *24*(1). https://doi.org/10.1186/s12870-024-04730-4

Shin, J., Harte, B., Harte, J., and Dolan, K. (2011). The Effect of Low-dose X-ray Irradiation on the Quality of Fresh-cut Asparagus in Microwaveable Vacuum Skin Packs. *HortScience*, *46*(1), 64–69. https://doi.org/10.21273/HORTSCI.46.1.64

Singh, R., Kishor, R., Singh, V., Singh, V., Prasad, P., Aulakh, N. S., Tiwari, U. K., and Kumar, B. (2022). Radio-frequency (RF) room temperature plasma treatment of sweet basil seeds (Ocimum basilicum L.) for germination potential enhancement by immaculation. *Journal of Applied Research on Medicinal and Aromatic Plants*, *26*, 100350. https://doi.org/10.1016/j.jarmap.2021.100350

Švubová, R., Kyzek, S., Medvecká, V., Slováková, Ľ., Gálová, E., and Zahoranová, A. (2020). Novel insight at the Effect of Cold Atmospheric Pressure Plasma on the Activity of Enzymes Essential for the Germination of Pea (Pisum sativum L. cv. Prophet) Seeds. *Plasma Chemistry and Plasma Processing*, *40*(5), 1221–1240. https://doi.org/10.1007/s11090-020-10089-9

Volin, J. C., Denes, F. S., Young, R. A., and Park, S. M. T. (2000). Modification of Seed Germination Performance through Cold Plasma Chemistry Technology. *Crop Science*, *40*(6), 1706–1718. https://doi.org/10.2135/cropsci2000.4061706x

Xiang, Q., Liu, X., Liu, S., Ma, Y., Xu, C., and Bai, Y. (2019). Effect of plasma-activated water on microbial quality and physicochemical characteristics of mung bean sprouts. *Innovative Food Science and Emerging Technologies*, *52*, 49–56. https://doi.org/10.1016/j.ifset.2018.11.012

Zhao, Y., Chen, R., Liu, D., Wang, W., Niu, J., Xia, Y., Qi, Z., Zhao, Z., and Song, Y. (2019). Effect of Nonthermal Plasma-Activated Water on Quality and Antioxidant Activity of Fresh-Cut Kiwifruit. *IEEE Transactions on Plasma Science*, *47*(11), 4811–4817. https://doi.org/10.1109/TPS.2019.2904298

Zhou, R., Li, J., Zhou, R., Zhang, X., and Yang, S. (2019). Atmospheric-pressure plasma treated water for seed germination and seedling growth of mung bean and its sterilization effect on mung bean sprouts. *Innovative Food Science and Emerging Technologies*, *53*, 36–44. https://doi.org/10.1016/j.ifset.2018.08.006

Zukiene, R., Nauciene, Z., Januskaitiene, I., Pauzaite, G., Mildaziene, V., Koga, K., and Shiratani, M. (2019). Dielectric barrier discharge plasma treatment-induced changes in sunflower seed germination, phytohormone balance, and seedling growth. *Applied Physics Express*, *12*(12), 126003. https://doi.org/10.7567/1882-0786/ab5491