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Plasma Technology for the Enhancement of the Agriculture Sector in Nepal

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Abstract

Agricultural applications of cold atmospheric pressure plasma (CAPP) technology have grown significantly during the last few years. Following harvest, using CAPP in agriculture has been the subject of numerous publications and literature reviews. However, pre-harvest plasma use is still in its infancy. Over the past five years, numerous researchers from Nepal have been using plasma technology to promote agriculture domestically and internationally. Their findings, however, are limited to scholarly publications and laboratory work. This paper explores how plasma technology can enhance Nepali agriculture, bringing it from the laboratory to the farm. A topic that has garnered a lot of attention lately is the application of plasma technology in agriculture, which is the focus of this paper. The increased focus on these studies is mostly due to the demand for less pesticide use and more intense food production. An examination of publications, concentrating on studies conducted in the past decade, identified the primary successes of plasma agro-technology as well as the primary challenges to its broad practical implementation. We examined the primary plasma source types utilized in this industry, as well as the benefits and drawbacks that dictate the application areas. Plasma technology has the potential to enhance both the quality and productivity of agriculture throughout the entire production cycle. The conditions of the plasma treatment and the efficiency of the diagnostic methods employed influence how much plasma can enhance agriculture. The possible uses of plasma technology in the field of practical agriculture will be covered in this paper. The application of plasma technology, also known as green technology, in agriculture is being brought to the attention of all stakeholders.

Keywords: Cold plasma, plasma technology, plasma agriculture, physical effect on seed, chemical effect on seed, reactive species

Introduction

Plasma

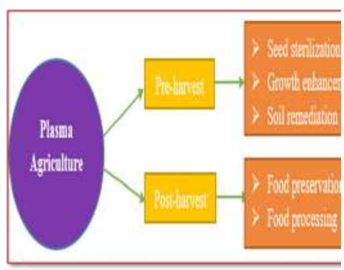
A solid can go from being a solid to a liquid to a gas by adding energy to the system. If the energy input is increased, the electrons will eventually start to separate from their parent nucleus. In contrast to regular neutral gas, this ionization creates a soup of ions and electrons that can react to applied electromagnetic fields [1]. Ionized gases include plasmas; however, not all ionized gases are plasmas. According to the official definition, an ionized gas must satisfy three requirements to be classified as plasma, or the so-called “Fourth state of matter” [2,3] apart from the other three physical states—solid, liquid, and gas. In general, the term “plasma” refers to a medium that contains electrons, radicals, and ionized and excited species under the influence of external energy sources. In nature, plasma is the condition of matter that is most abandoned. 99 percent of the matter in the cosmos that can be observed is thought to be in the plasma state. A broad range of physically feasible scales in terms of energy/temperature, density, and space are observed in plasma systems. Plasma discharges can be classified as thermal or non-thermal (Cold) depending on the energy and temperature of the neutral atoms, ions, and electrons. Thermal discharges occur when the neutral gas temperature (T_{gas}) is close to 5000K, while non-thermal (Cold) discharges occur when the average electron temperature (T_e) is significantly higher than the temperature of the neutral gas. The average electron temperature in a typical cold plasma discharge is between 1 and 2 eV (1 eV = 11,600 K), but the neutral gas temperature can sustain room temperature conditions. Aurora is a well-known illustration of atmospheric non-thermal (Cold) plasma. CAPP has found extensive use in biology in the past few years. It is widely used in biology for a variety of purposes, such as food processing and manufacturing, wound healing, surface cleaning, microbe decontamination, seed germination, and food storage. In this paper, our concern is cold plasma produced at atmospheric pressure and its impact on the agriculture sector.

Plasma Technology

The first attempts to produce electrical luminous effects in evacuated glass bulbs date back to the 17^{th} century, marking the beginning of experimental plasma physics. In 1857, Werner von Siemens created the first technical plasma application when he created an ozone generator that produced ozone using electrical discharge. Nowadays, plasma technology is significantly altering industrial conventional production processes and finding applications in the agriculture and medical technology sectors. Dielectric Barrier Discharge (DBD) for seed treatment [4,5], Radiofrequency (RF) plasma for soil enhancement [6,7], Corona and glow discharge Plasma for water treatment [8], Microwave Plasma for weed control [9], Atmospheric Pressure Plasma Jet (APPJ) for pest control [10], Cold Atmospheric Plasma (CAP) for disease resistance [11], Surface Dielectric Barrier Discharge (SDBD) for post-harvest treatment [12], and Inductive Coupled Plasma (ICP) for elemental analysis in soil [13] are some of the plasma sources used in agriculture. Figure 1 shows the overview of applications of cold plasma. By providing long-term solutions for seed germination, soil fertility, water quality, disease resistance, pest and weed control, and post-harvest preservation, these plasma applications support productive and environmentally responsible farming methods. Numerous researchers from Tribhuvan University and Kathmandu University are working on small-scale projects in Nepal to improve seed germination, seedling growth, agriculture production, etc. using plasma technology.

Figure 1

Overview of Applications of Cold Plasma



Plasma Agriculture

Plasma agriculture is an interdisciplinary field that bridges plasma physics, plasma chemistry, and agricultural sciences, focusing on the application of plasma technology in farming practices. The application of plasma technology to several areas of agricultural cultivation is known as "plasma agriculture. "Figure 2 shows the overview of the effect of cold plasma in the pre-harvest and post-harvest process.

Figure 2

Effect of Cold Plasma in Pre-Harvest and Post-Harvest Process

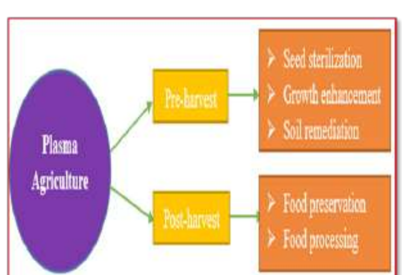
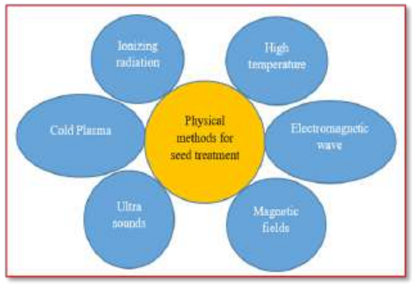


Figure 3 shows the different physical methods used for the treatment of seeds. Different physical methods used for the treatment of seeds are shown in Figure 3. When it comes to agriculture, plasma farming, also known as plasma agriculture, is the practice of applying plasma from pre-cultivation until the point at which the result is served at the dining table. The main goals of investigations on plasma treatment in the field of plant sciences have been to characterize the effects of plasma on plant biochemistry, standardize the treatment, and investigate potential applications [14,15]. The effects of plasma on plant growth and seed germination are mediated by molecular mechanisms that include epigenetics, transcriptome profiling, gene expression analysis, and protein expression analysis [16]. Plant species depend on seed germination to remain viable and survive. Water imbibition initiates a complex process called germination, which, in turn, sets off physiological reactions that break seed dormancy [17]. One essential component of the best crop cultivation is uniform and quick germination [18]. Much research has been done in agriculture to figure out how to get more seeds to germinate, which would eventually increase crop growth, plant biomass, and yield. High crop yields are achieved through seed priming, which shortens the time needed for germination and increases vigor. When seeds are directly treated with plasma, the seed coat is altered, which promotes faster growth and development, enhanced disease resistance, accelerated germination, and shorter germination times [19]. Furthermore, the creation of water through plasma treatment that has a different chemical composition also has antibacterial qualities, which allow for consistent seed germination as well as the activation of germination by its active ingredients, such as reactive species (RS) [20]. Combining the beneficial effects of plasma treatment, which sterilizes seeds, with a decrease in the use of herbicides and pesticides during the pre-cultivation phase is a useful strategy for mitigating the damaging impacts of these substances on the environment [21]. So, we have outlined the latest developments in plasma treatment for plant growth and seed germination in this paper, together with our understanding of the physical and chemical mechanisms that underlie the treatment's effects. We first talked about plasma and its applications in biology, particularly in terms of enhancing plant development and seed germination. We have also discussed the history of plasma treatment, its applications, and the difficulties and discoveries that have recently arisen in technology. We've also talked about our present knowledge of the chemical and physical processes that underpin the growth and germination of seeds in plants. Lastly, the outlook for the future, which includes potential studies, obstacles, and opportunities are discussed.

Figure 3

Overview of Different Physical Methods Used for Treatment of Seeds



The Status of Agriculture in Nepal

Nepal is an agricultural country having 66% of people directly engaged in farming. Agriculture is the backbone of the Nepalese economy (A survey of the economy-080/081). According to the World Bank development indicators in 2018, 28.7% of land area is utilized in the agriculture sector. The agricultural area is decreasing day by day due to rapid urbanization. Therefore, time demands to increase the productivity in the agricultural sector. Based on available data, farmers in the hills and mountains likely utilize integrated crop-animal-tree-based agroforestry systems with farm-derived organic amendments and few external inputs, leading to low but consistent yields. They also likely use native crop and livestock species. While high-yielding cultivars are becoming more and more widespread, the majority of crops in the Terai are based on rice. Wheat, maize, and pulses are cultivated in rotation with low to moderate input use. Climate changes result in problems with food production rates. At the same time, food demand increases as the world's population is growing continuously alongside agrochemical use increases to control pests and diseases to improve productivity. Therefore, the search for a new efficient nonchemical technique is of high importance to improve plant growth, accelerated germination, yields of crops, and resistance against biotic and abiotic stress. CAPP has become a subject of great interest. So far different types of low-pressure systems and few atmospheric pressure systems have been developed. Results of Various works show that many variables are linked for enhancement including the plasma sources but suitable parameters and suitable conditions are still beyond the research. CAPP and its impact on agricultural products are the pioneer fields of research and have lots of potential for innovative works. Several researchers from Kathmandu University and Tribhuvan University are involved in their research for the enhancement of seed germination and seedling growth to promote the agriculture sector. However, their findings are limited to Laboratory and academic papers only. Table 1 shows the summary of findings related to plasma agriculture from Kathmandu University and Tribhuvan University of Nepal. Because of a lack of funding, investments, and collaboration among various stakeholders, it is difficult to transform agricultural plasma technology from lab to farm.

Table 1

Studies of Plasma Agriculture in Kathmandu and Tribhuvan University

Plasma device	Gas used	Seed	Findings of the study	Citation
DBD	Argon (Ar)	Cucumber	Germination and growth	22
DBD	Argon (Ar)	Radish	Growth/ water uptake and antioxidant property	23
GAD	Air	Buckwheat, Barley, Mustard and Rayo	Growth and Physio-chemical	24
DBD	Argon (Ar)	Mustard	Seedling growth and development	25
Plasma Jet	Argon (Ar)	Fenugreek	Growth and metabolism	26
DBD	Argon (Ar)	Radish	Seedling growth and germination	27
DBD	Argon (Ar)	Coriander	Growth and seed dormancy	28
DBD	Argon (Ar)	Soybean	Germination and physio-chemical	29
DBD	Air	Beans	Germination and nutrition absorption	30
GAD	Air	Soybean and wheat	Germination and seedling development	31
DBD	Argon (Ar)	Carrot	Germination and antioxidant property	32
GAD	Air	Cauliflower	Germination and growth parameter	33
GAD	Air	Tejpat	Chlorophyll retention	34
DBD	Argon (Ar)	Wheat	Yield	35
DBD	Argon (Ar)	Tomato	Germination and Growth	36
DBD	Argon (Ar)	Carrot and Radish	Seed germination and growth	37
GAD	Air	Radish, Fenugreek, and Peaक	Physicochemical parameters of PAW and seed germination	38

Plasma Treatment Method

Early in the 1960s, researchers looked into the effects of glow discharge on a variety of grass seeds, cotton, wheat, alfalfa, red clover, sweet clover, beans, and other plants. This was one of the first times plasma was used to treat seeds. It was demonstrated that the plasma treatment affects moisture adsorption, and seed germination, and, presumably, lowers the number of hard seeds in legumes [39,40]. Since then, research on treating seeds with plasma has increased because to the use of various plasma devices, which enable in-depth investigations into the biological, chemical, and physical mechanisms of plasma that can be sparked by the examination of plasma constituents [41,42]. CAPP has created a new area of study in biology and medicine in recent decades [43]. Based on how the plasma comes into touch with the samples, there are two ways to treat seeds with plasma: direct approach (figrure 4) and indirect approach (figure 5).

Figure 4
Overview of Plasma Devices for the Treatment of Seeds Directly [44]

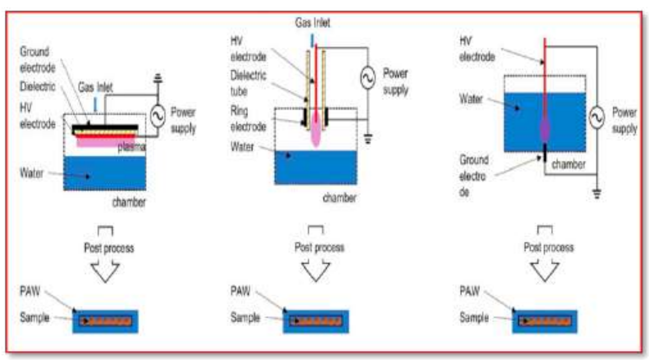
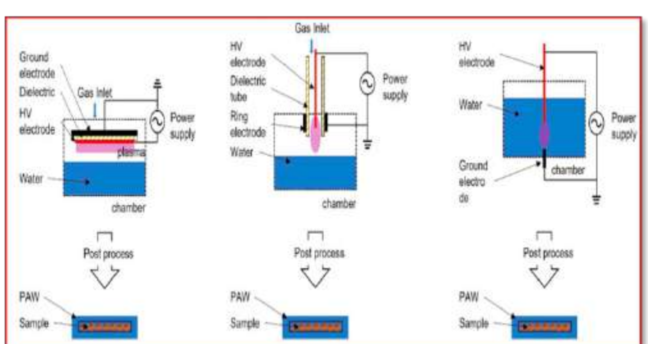


Figure 5
Overview of Plasma Devices for the Treatment of Seeds Indirectly [44]



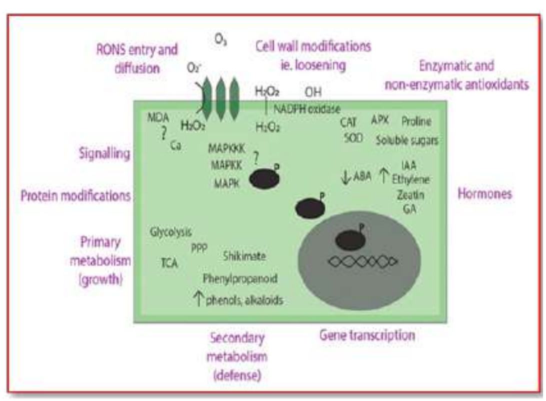
Charged particles, reactive species (including OH radicals, singlet oxygen, ozone, and hydrogen peroxide), electric fields, and photons all have an immediate impact on the exposed seeds in the discharge region. It is thought that a mix of these elements is the primary driver of seed germination and growth. The exposure causes the seed surface to interact with both long- and short-lived radicals that arise from secondary reactions. The sample is not exposed to the plasma directly during indirect treatment. The samples are not directly impacted by the plasma, rather they are impacted by a gas-phase active species that is produced by the plasma and plasma-activated water (PAW). PAW alters its physicochemical characteristics, and PAW engages in a signaling cascade that ultimately encourages root germination and seed germination, root and vegetative growth, and plant reproduction [45]. The modifications in physicochemical components and characteristics like electrical conductivity, pH, nitrite (NO_2^-), nitrate (NO_3^-), ozone (O_3), and hydrogen peroxide (H_2O_2) concentrations, in PAW cause seed germination and plant growth [46]. Furthermore, one of the environmentally favorable nitrogen source substitutes that lessens the drawbacks of using chemical fertilizers is "plasma fertilizer." It follows that it is not unexpected that this will be the main focus of upcoming research on plasma treatment for plant cultivation [47].

Physical Effect on Seed Due to Plasma Treatment

The direct treatment of seeds with plasma is supposed to work on a similar principle to seeds that have been etched by plasma on their surface [48]. The summary of the action of plasma treatment to enhance seed germination is shown in Figure 6. It is demonstrated that the type, power, and length of the plasma treatment are likely to have a significant impact on seed coat modifications. using a scanning electron microscope (SEM) technique, several investigations have shown that seed coat disintegration by plasma treatment occurs in a variety of plant seeds, including cotton, wheat, pea, onion, etc. [49,50]. Therefore, when seeds are treated with the proper plasma device and configuration, the effect of plasma treatment on seed germination may be caused by the mechanical elements of the seed coat. The seed coat controls water absorption and shields the seed from the outside environment. Imbibition must take place in the proper ratio; if it happens too quickly or too slowly, seeds may be harmed [51]. In general, a varied setup is required for the ideal treatment setting since plasma treatment impacts seed germination differently in different seeds of different species and plant families, even for distinct varieties and ecotypes. Pleasantly, germination rates were increased in plasma-treated seeds even under osmotic and saline stress conditions due to alterations to the metabolism and lipid component composition and structure [52]. To ascertain the seed wettability, indirect treatment employing plasma-treated water was also carried out. This demonstrated the potential for a combination process including seed perforation and decreased water tension, which raises the surface area and imbibition ability. Water permeability and water affinity on the seed surface, sometimes referred to as seed wettability, are strongly correlated with modifications in the seed coat [53]. Morphologically, we can say that, plasma treatment results in surface erosion or etching, which raises the roughness of the seed surface and raises the seed volume ratio and wettability. The organic polymers in seeds are impacted chemically by the interaction of plasma and seed coat components. It was demonstrated that the increase in germination of seeds treated with plasma is not primarily caused by heat. The tiny increase in temperature in plasma-treated seeds cannot be disregarded, even though it is considered " cold plasma." This is because, when combined with other factors, plasma treatment may still have an impact on the germination ratio. According to certain research, UV radiation from plasma treatment may have unintended consequences in addition to the reactive oxygen nitrogen species (RONS) interaction, rather than improving seed wettability [54]. Furthermore, the UV exposure's nature may cause DNA damage, which may have an impact on seedling germination and growth. When seeds and seedlings are exposed to UV light for a brief period, the stress response may be regulated, which may lead to enhanced cell metabolism and the division, elongation, and differentiation of cells [55].

Figure 6

Schematic Representation of Plasma Treatment on Seed, Resulting Germination Enhancement [56]



Chemical Effect on Seed Due to Plasma Treatment

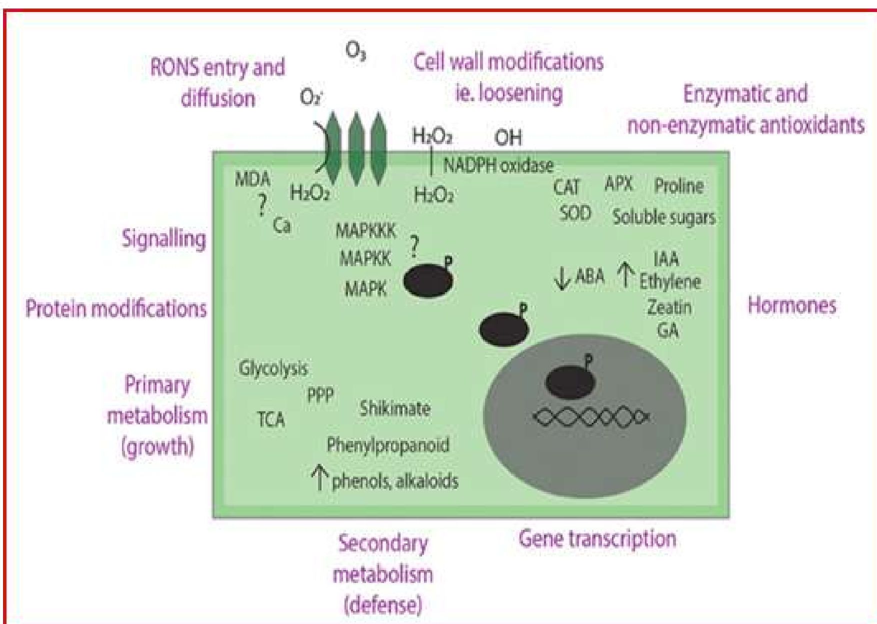
The primary factors influencing plant development and seed germination are due to reactive species (RS) produced during plasma treatment. The overview of the chemical effects of plasma treatment on seed is shown in Figure 7.

Reactive species are classified as reactive nitrogen species (RNS) like NO, NO_2, ONOO−, etc.) and reactive oxygen species (ROS) like O_2^-, OH^- H_2O_2, O_3, etc.). Ozone (O_3), hydrogen peroxide (H_2O_2), superoxide anion, peroxyl, nitric oxide, hydroxyl, nitrogen dioxide, and peroxynitrite are a few examples of frequent reactive species [57]. Even so, there is still much to learn about the mechanisms underlying how ROS and RNS affect seed germination and development. Regarding the impact of ROS on seed germination, there aren't many theories. According to one theory, the cells in seeds that cause signal transduction from the outer layer of the seed detect and perceive external ROS. The alternative theory holds that water plays a crucial role in allowing ROS to enter the seed cells during imbibition. As a result, it causes a spike in seed respiration and sets off a series of events involving the oxidation of sugars, which releases ATP, the metabolic energy [58]. Consequently, the role that ROS play in the respiration pathway is thought to be a main as well as a secondary trigger in seeds that initiates the shift from dormancy to biomass. The possible use of RNS generated by PAW as a liquid fertilizer for plant development is another topic of interest in plasma treatment. Numerous strategies have been investigated to identify the best tool and course of action for producing large quantities of RNS in the solution. For example, a plasma jet has been used for plasma-assisted nitrogen fixation for corn [59], a large volume of glow discharge has been tested as a liquid fertilizer in radish, tomatoes, and marigolds [60], and bubble discharge has been studied in the cultivation of spinach, radish, Brassica Rapa, and strawberries [61]. All of these studies show that plasma fertilizers can be used as a more sustainable and eco-friendly supply of nitrogen for plant cultivation. However, the low pH or elevated acidity of the plasma-treated fluid poses a problem for plasma-assisted nitrogen fixation since it harms the exposed seeds and plants. An acidic atmosphere restricts the growth of plants [62]. In the plasma sector, research on maintaining equilibrium and strategies for overcoming the acidity of plasma-activated fluids is therefore prioritized. A crucial part of germination is also played by microbial inactivation, which happens when seeds are treated with plasma. Normally, the surface of the seed is exposed to the environment, which is full of various particles, toxins, and microorganisms that may hinder the germination of the seed. For instance, Fungal growth on the seed surface influences germination in grain crops such as rice, wheat, oats, and barley

[63]. It is well known that fungi frequently harm seeds, possibly lowering their viability and yield. Furthermore, a fungal pathogen on seeds might result in an infection that spreads to other seeds, causing a significant loss in yield. It has been demonstrated that the plasma treatment of seeds improves seed sterilization by getting rid of fungus spores on the seeds. When rice is directly treated with micro corona discharge, the microorganisms on the husk are rendered inactive, resulting in better germination than in untreated seeds [64]. The addition of Ar and air to plasma, which would produce reactive oxygen species (ROS) and reactive oxygen species (RNS), which degrade and inactivate fungus on seed surfaces.

Figure 7

Overview of Chemical Effects of Plasma Treatment on Seed [65]



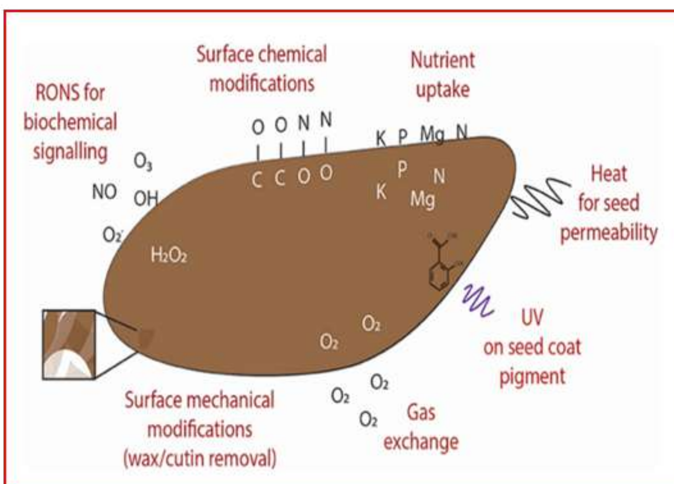
Key Components of Plasma Agriculture

Seed Treatment

There are various ways that plasma exposure enhances germination and development. Plasma exposure improves the hydrophilicity of the seed surface and slightly erodes it, which results in improved absorption of water, oxygen, and nutrients—all essential for germination. Within, it produces species of reactive oxygen and nitrogen that pierce the seed coat and serve as signaling molecules to activate the cellular mechanisms necessary for germination. Enzymatic activity is also altered by this treatment, most notably by raising amylase activity for effective mobilization of feed that has been stored. Furthermore, plasma primes seeds to undergo a stress response that boosts their resistance to environmental stressors and improves growth and disease resistance. Because of its sterilizing qualities, which are obtained from reactive species and UV radiation, surface pathogens are successfully rendered inactive, shielding seeds from illness. Furthermore, seed cell membrane permeability is altered by plasma exposure, encouraging the use of reserves that have been accumulated. Additionally, it affects hormonal balances, specifically those related to gibberellins and abscises acid, which are necessary for germination and dormancy. Furthermore, it may affect the expression of genes related to stress resistance and growth. Figure 8 shows the potential interaction between plasma constituents and seed surfaces.

Figure 8

Overview of Interactions Between Plasma and Seed Surface [65]



Pest and Disease Control

In agriculture, cold plasma technology uses an intricate web of interconnected processes to manage diseases and pests. Pathogens and pests undergo oxidative stress due to reactive oxygen and nitrogen species (RONS) produced by plasma, such as hydroxyl radicals and ozone, which compromise their cellular integrity and metabolic processes. In addition, direct damage to DNA caused by ultraviolet (UV) light from plasma renders dangerous microorganisms inactive. The generated electromagnetic fields have an impact on the physiology and behavior of pests, possibly upsetting their reproductive cycles. In addition to their mild heat effects, these fields weaken pests and pathogens, making them more vulnerable to UV and oxidative harm. Thus, plants are more equipped to fend against future threats. Furthermore, plasma can alter the surface features of plants, deter insect colonization, and stop the spread of infections. It is also capable of breaking down aflatoxins and mycotoxins, which are crucial for the safety of crops after harvest. In keeping with sustainable agronomic methods, plasma agriculture provides a comprehensive, ecologically friendly option for disease and pest control because of these focused operations.

Promotion of Plant Growth and Yield

Irrigating adult plants and seedlings with plasma-activated water causes a complicated cascade of physiological and biochemical reactions. Rich in species including nitrates, nitrites, and peroxides, plasma-activated water catalyzes to improve plant metabolism and nutrient uptake. These reactive species interact at the cellular level, altering the rhizosphere's chemical dynamics and increasing the efficiency with which roots absorb nutrients. As a result, vital nutrients and water are transported more effectively, which boosts photosynthetic efficiency and speeds up the growth of seedlings and mature plants. Additionally, plants' defensive mechanisms against free radicals are heightened when they come into contact with plasma-activated water. This is distinguished by the activation of enzyme-based antioxidants, such as catalase and superoxide dismutase, which are essential in reducing oxidative stress.

Enhanced Nutrition Uptake

It is possible to increase the amount of vital nutrients that are available in the soil by using plasma technology. Plasma helps plants absorb essential components more effectively by generating conditions that improve nutrient solubility, resulting in healthier and more nutrient-rich crops.

Weed Management

Plasma technology has shown promise in managing weed growth. By precisely targeting unwanted, vegetation, plasma can offer a more selective and environmentally friendly approach to weed control. This not only reduces the reliance on herbicides but also minimizes the impact on beneficial plants and biodiversity.

Plasma agriculture offers a possibility to maximize water use in areas where water is scarce. Plants that receive plasma treatment on their seeds and soil may be better able to tolerate drought conditions, leading to more consistent agricultural yields even in water-stressed situations.

Friendly Environment

Plasma Agriculture is in line with the increasing desire for environmentally benign and sustainable farming practices because it uses fewer chemical inputs. This method helps to maintain biodiversity, increase the quality of the water, and conserve soil.

Energy Efficiency

Energy efficiency is a well-known feature of plasma technology. In contrast to certain traditional farming methods that could necessitate significant energy inputs, Plasma Agriculture provides a more efficient and environmentally friendly technique, reducing the farming's environmental impact.

Carbon Reduction

Because plasma agriculture reduces the carbon impact of conventional agricultural methods, it is in line with environmental aims. When combined with efficient resource management, a decreased need on chemical inputs results in a more environmentally friendly agriculture industry.

Soil Fertility

The overall productivity of agriculture can be increased by using fertilizers or water that has been plasma-treated.

Challenges and Prospect

Even though plasma agriculture has a lot of potential, there are still issues that need to be resolved, like the scalability of plasma technology and its widespread acceptance. So far, it has been demonstrated that a variety of plasma device geometries, treatment techniques, and seed types can change the characteristics of the plant. While this variation results from different academics taking into account what matters to their community and local economy, it also makes it challenging to standardize the body of current research. By releasing only positive results, we may be creating the impression that finding these setups is easy and that optimizing the treatment conditions just requires trial and error. However, it appears that we have reached a point where this technology has potential as a proof of concept. Air plasma generates a rich chemistry and is a useful material. It is still up for dispute, though, how important humidity is in these plasma seed treatments. It is yet unclear how it happens—by mechanical, chemical, or both—and whether the plasma treatment, the kind of seed, or both matters. To get these effects, how much energy must be delivered into the plasma? To tackle this, subsequent research has to persist in linking surface alterations with variations in germination using a methodical approach, while accurately documenting the electrical properties. It appears that the majority of writers also concur that RONS are primarily in charge of the impacts on plant growth that have been noted. It's unclear at this point if it's the combined effect of RNS, ROS, or both. If additional research is done on the expression of genes and proteins, it will at least shed light on whether the same genes are triggered in response to various plasma treatments and seed kinds. Furthermore, it is unclear how long-lasting these effects will be and when they would be deemed genotoxic or detrimental to plant growth. Here, the restriction on gene expression research to plant genomes that have already undergone sequencing will act as a bottleneck. Nonetheless, these findings might be relevant to closely related species. To make it easier to regulate the output, it would be helpful to know how each plasma treatment parameter influences the result as a next step. When a seed has numerous layers that require scarification, plasma can aid in mechanical erosion by etching it or by using the heat generated as a byproduct of plasma creation to melt the wax. If the seed has a rather porous surface, it may functionalize the surface by adding chemical groups to make it more hydrophilic and improve gas exchange, which will subsequently have an impact on the biochemistry of the seed. The main questions are:

- Which treatment parameters are required to see a repeatable beneficial effect on seeds?
- Can parameters of a single be applied to a wide variety of seeds?
- What is the molecular impact of the plasma treatment on the seed?
- Can the biological effects of the plasma treatment be reliably replicated?
- Can the plasma treatment be scalable for industrial applications?
- How is the plasma treatment different from currently used techniques like mechanical or acid scarification?

In order to achieve the solution of such questions, biologists, chemists, and physicists need to work together in concert on a continuous basis. It is our expectation that technology that will benefit the agricultural community of Nepal will be plasma technology.

Conclusion

Plasma agriculture represents a paradigm shift in the way we cultivate and harvest our food. With its multiple benefits, from boosting crop yields to fostering environmental sustainability, this innovative approach has the potential to shape the future of agriculture. As we continue to explore the possibilities of plasma technology, we move closer to a more resilient, efficient, and sustainable agricultural future that can meet the demands of a growing global population. There are several benefits to plasma agriculture. It lessens reliance on chemical pesticides and fertilizers by providing an eco-friendly substitute for conventional chemical treatments in agriculture. In the context of organic and ecological farming methods, this element of plasma technology is especially intriguing. The efficacy and efficiency of plasma treatments set them apart as well, providing a flexible option that can be tailored to a range of farming operations, from large-scale agriculture to small-scale gardens. Research and development is still being done in plasma agriculture to determine the precise processes through which plasma interacts with biological systems in an agricultural setting. Scholars are currently exploring the ideal parameters and techniques for plasma treatment to optimize its agricultural benefits. A state-of-the-art method for addressing some of the most important issues in sustainable food production is plasma agriculture. Farming techniques can be made more environmentally friendly, increase crop yields dramatically, and help to agriculture development strategy (2015 to 2035) made by the Ministry of Agriculture, the government of Nepal by incorporating plasma technology.

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