Primer of Plasma Agriculture

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Contributor: Dayun Yan

Nonthermal plasma (NTP) is a tunable source of reactive species and other physical factors. It exerts luxuriant biological effects on plant seeds. To date, NTP has shown promising application in modern agriculture.

nonthermal plasma | plasma agriculture | seed germination

1. Nonthermal Plasma (NTP)

As a phase of matter, plasma can easily be found in many places. From household objects to deep space, plasma is present in fluorescent lamps, lightning, nuclear fusion, the ionosphere, the sun, and all other stars. The first definition of plasma was introduced by Irving Langmuir, who described plasma as an ionized gas containing ions and electrons with a roughly equal charge as a whole. In other words, plasma is an ionized gas with a quasi-neutrality.

Ionizations can be achieved by particle collisions with energies higher than their ionization thresholds. Heating and applying an electric field are two common ways of energizing collisions. The former strengthens the random motion of particles, while the latter accelerates naturally existing “seed” electrons to knock out additional electrons from atoms. However, the electrons with lower mass are usually accelerated prior to ions at the beginning of applying an external electric field. The higher drift motion of these electrons causes a higher random motion during collisions, resulting in a different temperature distribution from other species. Such plasma is called thermal non-equilibrium plasma.

Nonthermal plasma (NTP) is a nonequilibrium plasma with all heavy particles at near room temperature (average temperature). The collision frequency of electrons with other particles or species is not high enough to make the plasma reach thermal equilibrium before those free electrons are lost during the diffusion, the recombination, or the attachment with atoms.

NTP has been studied for many years, and multiple generators have been invented. The most popular hardware includes plasma jet, dielectric barrier discharge (DBD) reactor, radiofrequency (RF) reactor, and surface DBD reactor [1]. To avoid arc discharge, either the anode or cathode will be covered by a layer of dielectric materials such as glass, quartz, ceramic, or others [2]. Noble gases such as helium (He) and argon (Ar) are used to trigger the stable and nonthermal glow-like discharge in NTP sources [3]. For the plasm jet, the samples do not involve the discharge process. Therefore, the plasma jet is an indirect discharge source [4]. In contrast, the DBD source is a direct discharge source, in which samples such as seeds are involved in the discharge process [5]. The DBD reactor is more suitable for a large area treatment compared to the plasma jet. Similarly, surface DBD is a unique DBD configuration, in which two electrodes have been integrated into one surface [6]. Even a large volume sample can also be treated by a surface DBD source. The discharge in a radiofrequency (RF) plasma reactor is based on the RF power input between two electrodes [5]. Typically, RF plasma is generated in a chamber, where samples, such as seeds, are set in the gaps between electrodes.

An abundance of reactive species is formed in NTP. Due to the emission, many excited species can be identified from spectra, such as an Optical Emission Spectrum (OES). It is generally understood that reactive species build the foundation for the interaction between plasma and plant cells. The initial mole fraction of He, N_2, and O_2 can be controlled by the flow rate of a carrying gas such as He and the geometry of the nozzle. In addition, the humidity of air is another key, yet hardly controllable, factor for the formation of reactive species in NTP. Reactive species in the gas phase will have complex plasma-aqueous solution interactions when plasma touches the solution. The main reactive species in plasma can be divided into short-lived and long-lived. Short-lived reactive species, such as $OH^{\cdot}$ and $^1O_2$, may only affect the cells near cold plasma over a short-time scale. In contrast, long-lived reactive species, such as H_2O_2, O_3, NO, and NO_2^-, may even be capable of affecting cells from a site far from plasma through the diffusion in aqueous environments over a long timescale. In addition, many aqueous components, such as amino acids in the medium, are modified during plasma treatment. The pH in the plasma-treated solutions may also be changed. All of these chemical changes may finally contribute to the biological impact of plasma on plants.

2. Plasma Agriculture

The chemical effect of NTP builds the foundation for plasma agriculture [7]. The pathogen-based disease therapy, the resistance to abiotic stress, food sterilization during storage, as well as the improvement of germination rates are all challenges in modern agriculture. NTP may help humans to overcome all of these challenges through an abundant and controllable reactive species generation [8].

Pathogen-based plant diseases are profoundly affecting crops worldwide. Naturally, H_2O_2 production in plants can kill pathogens directly or induce defense genes to limit the infection [9]. NTP is a powerful source of ROS including H_2O_2 and others. A plasma jet could cure the fungus-infected plant leaves and inhibit the spread of infection [10]. The leaves with small black spots are infected with fungal cells and could be completely recovered from the infection. A plasma jet with a relatively high plasma density could completely kill the tomato pathogen and decrease the rotting rate of the infected tomato seeds within a short treatment time [11].

Furthermore, NTP is a safe tool for food decontamination. Diverse pathogens are threats to the food industry. The abundant reactive species components in plasma make it a flexible and low-cost food processing technology for fruits, poultry, meats, as well as vegetables [12]. NTP treatment is also desirable for in-package decontamination. NTP significantly eliminated the post-process contamination, while retaining the essential quality characteristics of strawberries [13]. The foods’ cross-contamination from persistent pathogen reservoirs is a risk in processing environments. NTP rapidly decontaminated the food surface with *salmonella* biofilms [14].

Additionally, NTP treatment triggers the tolerance of plants to various abiotic and biotic stresses. Plasma was used to help oilseed rape seedlings resist the damage caused by the drought-stressed tomato seeds [15]. Under drought stress, a direct treatment significantly improved seeding growth characteristics, including shoot and root dry weights, lengths, and the lateral root number in a drought-sensitive oilseed [16]. ROS and RNS in NTP may mainly contribute to the tolerance of plants to diverse stresses. Naturally, the H_2O_2 production in plants also induces resistance to various stresses, including ultraviolet (UV) radiation, salt stress, drought stress, light stress, metal stress, and high or low temperatures [17]. H_2O_2 is involved in the abscisic acid (ABA)-induced stomatal opening and closing [9]. NO has been identified as an important signaling molecule in plant immune response [14]. NO is also involved in the ABA-induced stomatal closure in epidermal peels and can strongly counteract many ROS-mediated cytotoxic processes in plants [18].

More importantly, as a controllable ROS/RNS source, NTP treatment has drastically improved the seed germination rate, speed, water update, seed vigor, as well as several key characteristics of seedling growth, including the shoot length, shoot dry weight, root length, and root dry weight of several seeds [19]. These effects have been observed in the seeds of rice, cotton, soybean, mung bean, wheat, spinach, tomato, watermelon, and cultivar. Obvious, NTP is an alternative to conventional pre-germination modalities.

In addition to the direct NTP treatment on plants or seeds, aqueous solutions particularly water have been used as the carriers for the NTP-originated reactive species through NTP treatment on these solutions [20]. Plasma-stimulated solution (PSS) can be widely used in many circumstances independent of generators. PSS was also named as a plasma-activated solution (PAS) or water (PAW) in some references [21]. With promising applications in agriculture, PSS contains an abundance of reactive species. Additionally, PSS has been shown to have a strong killing effect on bacteria and viruses [22].

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