THE PLASMA CONNECTION

IEEE NPSS NUCLEAR & PLASMA SCIENCES SOCIETY

FROM THE IEEE NUCLEAR & PLASMA SCIENCES SOCIETY DECEMBER 2021

Plasma Agriculture

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Plasma, also known as the fourth (4th)state of matter, is an ionized gas consisting of electrons and ions (atoms/molecules that lose or gain electrons) as well as neutral reactive species. Plasma can be ignited in air by applying a very high voltage (on the order of tens of kilovolts) to electrodes. Air is (mostly) composed of nitrogen and oxygen and when the nitrogen and oxygen molecules interact with the high energetic electrons in the plasma, they can be dissociated and form reactive oxygen and nitrogen species by reacting with each other. This can also be observed in nature when molecular nitrogen (in the presence of oxygen) is converted to nitric oxide (NO) by lightning, a naturally occurring plasma. Indeed, plants have been observed to "green up" after first spring storms not only due to the water the thunderstorm brought but in particular due to the nitrogen compounds created by lightning that soak into the ground and create nitrates, an important fertilizer for plants.

Figure 1: Lightning, a naturally occurring plasma on Earth. Photo by NOAA on Unsplash.

Nitrogen Fixation—Fertilizer Production with Plasma

This effect of lightning can be recreated at room temperature by applying high voltage to air. An example of a plasma device to convert nitrogen from air into nitric oxides is shown in figure 2. The plasma is a dielectric barrier discharge (the pinkish glow) in direct contact with a water surface (above). Air is flown through the plasma and bubbled into the water to maximize the transport of nitrate into the water. The high voltage applied to the gap underneath the water accelerates electrons that can excite, dissociate, and ionize the surrounding gas. By using air, nitrogen and oxygen molecules are dissociated and form new species, providing the basis for nitrate (NO3-) which can be used by plants as fertilizer.

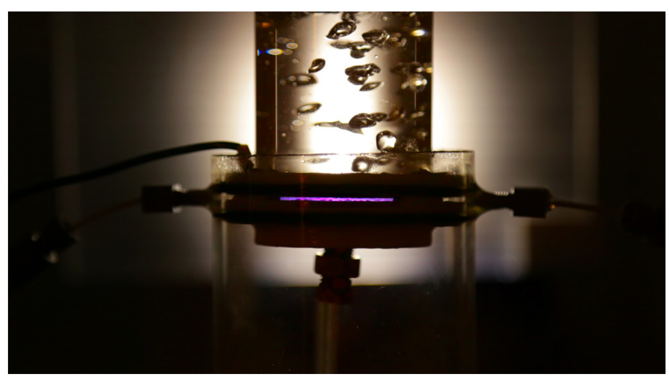

Figure 2: Example of a plasma device for nitrogen fixation in water. The plasma is a dielectric barrier discharge (the pink-ish glow) in direct contact with the water surface above. To increase the residence time and to optimize the transport of nitrogen species into the water, air is flown through the plasma and bubbled into the water column. (courtesy of Plasma for Life Sciences Laboratory, North Carolina State University).

Current fertilizer production focusses on the production of ammonia (NH3) by using the Haber-Bosch process. The Haber-Bosch process converts nitrogen to ammonia via a reaction with hydrogen in the presence of a metal catalyst and under high temperature and pressure. The Haber-Bosch process made mass production of fertilizer possible and changed agriculture tremendously in the early 20th century. However, the process is very energy-intensive and requires a large investment into building new production plants, making it less accessible to some parts of the world. With the strive for a more sustainable agriculture, plasma offers several advantages over the Haber-Bosch process: it can be employed on the farm, creating fertilizer on-demand at the point of use. It can be driven by renewable energy sources, e.g. wind or solar power, and allows farmers to produce their own fertilizer independent of market prices and their fluctuations. The only ingredients needed are water, air, and electricity.

Improved Germination and Plant Growth

In addition to fertilizer production, plasma creates other reactive oxygen and nitrogen species that have been shown to benefit plant growth. Many of the reactive species formed are used by plants as signaling molecules, e.g. hydrogen peroxide and nitric oxide. Further, these reactive species are also known to kill safely such pathogens as bacteria, fungi, and viruses. Researchers around the world have investigated a variety of ways to use plasma in agriculture, beyond the sole production of fertilizer. Plasma can be applied directly to seeds, seedlings, crops, and fields, or plasma-treated water can be used to sanitize seeds and fresh produce, or to “fertigate” plants (fertigation is the combination of irrigation and fertilization). A range of benefits have been reported from scientists to date, from improved germination, to better and faster plant growth, to plants resisting pests. Plasma can be used on demand and it provides some degree of controllability, thus opening the door to manipulating plant productivity precisely, (without genetic modification) while enhancing plant resilience to biotic and abiotic stresses (without the use of pesticides)

Inactivation of Bacteria–Plasma for Food Safety

Another application of plasma in agriculture is the inactivation of bacteria, fungi, and viruses on fresh produce for Food Safety. Plasma can be applied directly to food, or plasma-treated water can be used to wash or mist fresh produce. Both plasma and plasma-treated water have been shown to reduce disease-causing bacteria, such as *Escherichia coli*, *Salmonella* and *Listeria*, or fungi such as *Aspergillus* parasiticus within seconds to minutes on lettuce, tomatoes, mushrooms, apples, peanuts, and many more. Researchers found that plasma and plasma-treated water retains or sometimes even promotes food quality with minimal impact on chemical, nutritional, textural, and sensory attributes of food. Plasma can not only help to make farming more sustainable but also to reduce post-harvest losses.

Suggested Reading:

1. Ranieri P, Sponsel N, Kizer J, Rojas-Pierce M, Hernández R, Gatiboni L, Grunden A and Stapelmann K 2020 Plasma agriculture: Review from the perspective of the plant and its ecosystem *Plasma Process. Polym.* e2000162

2. Puač N, Gherardi M and Shiratani M 2018 Plasma agriculture: A rapidly emerging field Plasma Process. Polym. **15** 1700174

Herianto S, Hou C-Y, Lin C-M and Chen H-L 2021 Nonthermal plasma-activated water: A comprehensive review of this new tool for enhanced food safety and quality *Compr. Rev. Food Sci. Food Saf.* **20** 583–626

4. Varilla C, Marcone M and Annor G A 2020 Potential of cold plasma technology in ensuring the safety of foods and agricultural produce: A review Foods **9**

Text and images by K. Stapelmann; Edited by M. Laroussi.

ABOUT THE AUTHOR

Katharina Stapelmann is an assistant professor in Nuclear Engineering at North Carolina State University. She received her Ph.D. in Electrical Engineering from Ruhr University Bochum, Germany. Her research interest is in the interaction of plasmas with biological substrates and the application of plasmas for life sciences, i.e. plasma medicine and plasma agriculture. The focus of her research program is on plasma device development, plasma diagnostics, the generation and transport of reactive species, and interaction of plasmas with biological substrates and systems.