Plasma agriculture: A century of progress

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Abstract: Plasma agriculture began over 100 years ago, although this is not generally well known. Plasmas of very different character were used for plant growth enhancement and production of N-based fertilizer. These early advances have important implications for modern applications of plasma to various agricultural needs, both today and for the next several decades.

Keywords: Plasma agriculture, plant growth enhancement, fertilizer, nitrogen fixation

1.Plant growth enhancement

The effects of atmospheric electricity on the growth of plants has been studied for centuries and these studies overlap with some recent applications of plasma to agriculture. Krueger et al. [1] cite the 1775 report from Father G. Beccaria of the University of Turin, who wrote: "...it appears manifest that nature makes extensive use of atmospheric electricity for promoting vegetation." In later investigations, other investigators confirm this observation. [1] An important advance occurred in the late 19th century, when the Finnish scientist Lemström observed that an 'electrical discharge' from wires suspended above growing plants induced significant growth stimulation.

In 1904, Lemström [2] describes his initial observations of relatively rapid growth of vegetation in northern regions, postulating that high latitude atmospheric electricity might be responsible. His work is notable mainly because he was the first to systematically test this hypothesis, simulating the effects of atmospheric electricity by setting up dc-powered mesh electrodes suspended above growing plants, illustrated in Fig. 1. The wires had barb-like points, directed downwards, with the idea of directing the electricity towards the plants. Lemström used an electrostatic generating device (an 'influence machine') to power the wires. Lemström [2] detailed results showing significant and consistent plant growth enhancements of up to 100%. He termed this approach to plant growth stimulation 'electro-culture.'

Sidaway [3] notes that Lemström's 1904 book prompted a number of British investigations into electro-culture. The positive results of several of these investigators led to the 1918 establishment of an Electro-Culture Committee, sponsored by the British Board of Agriculture and Fisheries. The research sponsored by the Committee included studies with voltages applied to the wires typically 10-20 kV and currents at the plants only ~ 1mA/ha or ~ 10 pA/cm^2. Enhanced yields were reported to range from ~ 20% - 118%, although results were variable and investigators were hampered by a lack of any fundamental understanding of the effects.

Sidaway [3] notes: "Despite many positive results, the unpredictable nature of the plant response led to a gradual decline in interest and eventually the eclipse of electro-culture during the late 1930s." Sidaway concluded his article with the following observation: "Although often unpredictable and sometimes contradictory, the early experiments in electro-culture gave so many results indicating crop yield enhancement that, at a time of world food shortage, they surely deserve at least a careful re-scrutiny in the light of modern knowledge." [3] It seems that this sentiment is only more strongly justified today.

In the context of modern studies of plasma-aided agriculture, the 2016 review by Ohta [4] concluded: "At present, the studies related to plasma-led growth enhancements in plants are very limited." Puac et al. [5] also report recent results using plasma in agriculture - mainly for enhancing germination of seeds - but with apparently little direct overlap with this early literature on the effects of very low ionic currents on plant growth.

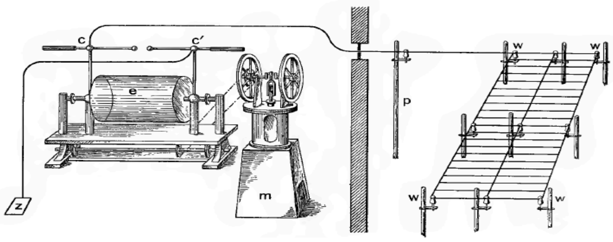

Fig. 1. Illustration of Lemström's electro-culture system, using an electrostatic 'influence machine' (left) to power an electrical discharge via a series of wires with barbs (right), situated about 0.4 m above the growing crops. [2]

2.Role of small air ions

A relatively recent development (ca. early 1960s) is the study of the role of small air ions, both positive and negative, on various biological systems. It should be stressed that this literature addresses the effects of very low ions densities - usually orders of magnitude less than 0.1% of neutral molecule density. This is consistent with observations of plant growth enhancement via electro-culture with very low current densities, noted above. Krueger appears to have been the major pioneer in these studies of air ions, e.g. [1]. By 1985, a summary editorial based on Krueger's work, published posthumously, summarized the situation as follows [6]:

1. Negative air ions are moderately lethal for bacteria and fungi, positive ions less so.
2. Ions of either charge influence the motility of certain protozoa
3. Both positive and negative ions stimulate the growth of a wide variety of plants
4. Ions of either charge induce early hatching of insect eggs, accelerate larval growth, augment biosynthesis of important enzymes.
5. Negative air ions improve the learning ability of rats - especially older animals and exert a definite effect in allying anxiety.

Finally, Krueger notes that the effects of air ions on humans was less well established, but that it appeared at that time that very few air ions could stimulate the release of the hormone serotonin. [7]

Plasmas will generate ions, under reduced or at atmospheric pressure. The documented degree of plant growth enhancement following plasma exposure, as well as the effects of applied plasma on seed germination and early seedling growth may well be related to plasma generation of air ions. More recent papers support the earlier work. [8, 9] The role of air ions in plant growth, studied for decades, appears to deserve considerable additional study in the context of plasma agriculture.

3. Air plasma for nitrogen fixation

The importance of nitrogen-containing fertilizer has been known since at least the early 1840s. Justus von Liebig is credited by Smil with the observation: "Agriculture's principle objective is the production of digestible N." [10] Traditional methods to supply nitrogen to plants included biological nitrogen fixation from certain leguminous plants (e.g. Rhizobium bacteria); reactive nitrogen from the atmosphere from lightning; decaying plant and animal material; and animal (including human) manure and urine. By the mid-19th century, farmers in industrialized nations learned to utilize other forms of inorganic N-containing fertilizers such as fossilized bird excrement ('guano') and fertilizer from mined deposits of sodium nitrates, found in South America.

However, by the late 19th century, growing populations in the industrialized world made it clear that new sources of N-fertilizer were needed. in 1898, William Crookes, the president of the British Association for the Advancement of Science, famously called for chemists to develop methods to develop technologies to fix nitrogen from the air in order to alleviate this threat.

One approach developed about this time utilized air plasma to form nitric oxide (NO), followed by oxidation to nitrogen dioxide (NO_2) NO_2 dissolves in water to form nitrate and nitrite anion (NO_3 and NO_2) or nitric acid (HNO_3). Aqueous solutions of nitric acid were mixed with calcium carbonate ('limestone') or aqueous calcium hydroxide ('milk of lime') to form calcium nitrate, the desired fertilizer product.

Although this process worked and was developed commercially, mostly notably by Birkeland and Eyde in Norway [12], this approach was abandoned by the early 1920s in favor of the less expensive Haber-Bosch (HB) process making NH_3 from H_2 and N_2 via a high temperature, high pressure catalytic process.

The successes and problems associated with the rapid rise of HB-generated NH_3 for fertilizer have been detailed elsewhere. [13] The key problem is that most of the N deposited on fields is lost before making its way into food, creating serious environmental problems.

It was only recently recognized that plasma-generated aqueous NO_x could be used to treat organic waste, allowing valuable recycling of otherwise polluting N and increasing the value of organic waste as fertilizer. [14, 15]

4. Organic waste acidification minimizes NH_3 volatilization

Organic waste such as manure and urine contain nitrogen that plants can assimilate, but it is prone to evaporation in the form of ammonia. In his 1840 book, von Liebig [11] wrote: "In Paris, for example, the excrements are preserved in the houses in open casks...The mass when dried by exposure to the air has lost more than half of the nitrogen which the excrements originally contained;...Nevertheless, it is still a very powerful manure, but its value as such would be twice or four times as great, if the excrements before being dried were neutralised by a cheap mineral acid."

Indeed, waste acidification is currently utilized in some countries in Europe and is known to be one of the most effective ways to reduce volatile ammonia loss from organic waste to be used as fertilizer. [16] In recent years, typically sulfuric acid is used because it is generally the cheapest acid. As we will see below, the same idea has been proposed recently in the context of air plasma nitrogen fixation, using nitric acid (nitrate anion) as the acidifying component. [17]

The basic idea has been described in detail elsewhere, but briefly, effluent from air plasma can be mixed into aqueous slurries of decaying waste, trapping most of the otherwise volatile NH_3. In addition, a molecule of nitrate (NO_3) is added for each NH_3 retained, thus considerably increasing the N-content of the organic fertilizer. The concept is illustrated in Fig. 2. It was, in part, precisely because organic fertilizer had too little nitrogen that the HB process was developed and rapidly spread around the world, greatly increasing agricultural productivity and allowing the growth of human population. [10]

The idea is to displace some of the demand for HB-generated fertilizer by recycling some of the otherwise volatilized NH_3. It is virtually certain that the electricity needed to power the plasma and overall process will come from locally generated renewable sources such as wind turbines, solar photovoltaic cells and biogas conversion. The steady drop in the cost of renewable energy is clearly favorable for future economic adoption of the technology.

There are potential advantages in treating waste by generating reactive N in the form that plants can most readily assimilate it - mainly NO_3. This allows farmers to apply less fertilizer to a field since they can be more certain of delivering sufficient quantities. Tthere may be reduced overall emission of global warming gases such as CH_4 and N_2O, although this remains to be proven in field tests. [15]

Initial reports on plasma treated organic waste indicate that treatment greatly reduces or eliminates objectionable odors. [15] It is also likely that the well-known ability of plasma treatment to inactivate bacteria could be of value for fertilizer to be applied to crops intended for human consumption.

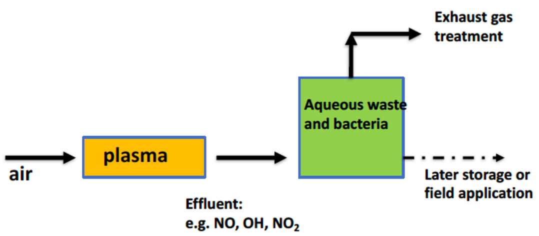

Fig. 2. Schematic of air plasma treatment treating decaying waste for organic fertilizer. [14]

5. Energy efficiency of air plasma for NO_x creation

By the early 1900s, it was clear that a commercially successful application of air plasma for nitrogen fixation hinged on plasma energy efficiency in addition to other issues. The early investigators concluded that the effect of the plasma on NO_x generation is primarily to create thermally-generated chemical equilibrium in air, thus implying that rapid quenching of the heated neutral gas, in order to retain the highest possible NO concentration, is key to high efficiency. For example, Birkeland [12] wrote:

"We can apply here a thought that was evolved by Nernst, which clearly shows the importance of a rapid cooling of the gases treated. As the temperature from the axis of the arc falls very quickly towards the peripheral parts, the partial pressure of nitric oxide answering to the central parts of the section of the arc will be considerably higher than that answering to the periphery. It follows, therefore, that a continuous and rapid diffusion of NO will take place from the central, hottest parts of the arc, out towards the colder parts."

Modern research in this area has still not fully resolved the fundamental question of the optimal pathways for most efficient NO_x creation via air plasma.

6. Concluding remarks

There is much to be learned from a careful reading of the historical literature - much of it unfortunately largely forgotten - associated with applications of plasmas and electrical discharges for agricultural applications. The situation in plasma agricultural applications is therefore analogous to that recently described for generally forgotten historical biomedical applications of plasma. [18]

Not all 'received wisdom' contained in the historical literature is correct, but it stimulates current research as well as provide contrast with more recent ideas. The resulting critical comparisons should be healthy in our pursuit of the most effective ways to develop these promising technologies.

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