Electroculture

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ABSTRACT. Electroculture, the practice of applying strong electric fields or other sources of small air ions to growing plants, has potential to markedly increase crop production and to speed crop growth. The considerable evidence for its effectiveness, and the studies of the mechanisms for its actions are discussed.

I. A Review of Past Research

The use of electricity to affect the growth of plants, although it has had a somewhat stormy history in the earlier decades of this century, has, through the elegant research of Krueger, Bachman, Murr, and many others, become established as having much promise for the practical realization of increasing crop harvests. In view of the urgency for increased food production in our times and in the future, it seems appropriate to bring this subject to the attention of scientists and others who would seek to apply it to the practical enhancement of crop culture, and to further study the basic mechanisms so as to better apply the technique.

There have been many studies on the effects caused by electrical currents in plants, and certain of the functional responses are by now well established. That electrical currents might influence vegetation was early suggested and attempted by Giambatissta Beccaria[1] of the University of Turin in 1775. His suggestion was actively explored by Bertholon,[2] Gardini,[3] and Ingenhouse,[4] Grandeau,[5] and Sturgeon.[6] Lemström[7] observed that an electrical discharge from needle points placed above cereal seedlings produced a detectable growth stimulation. His results were confirmed by Gassner.[8]

Since that time, a spate of papers have appeared. Blackman et al.[9,10] conducted a carefully controlled study of the growth of the coleoptile of barley seedlings and concluded that a maximum effect in enhancing growth occurred when a current of about 50×10^{-12} amperes (50 pa) per plant was passed. An after-effect was also noted, in that an increase in growth rate persisted for several hours after cessation of the current. These experiments were followed by pot-culture and field tests with wheat, barley, and corn. Successes and some failures were carefully reported, with the successes considerably outnumbering the failures. In outdoor pot-culture experiments, barley yield increased 18 ± 2.4%, and corn increased 27 ± 5.8%. In field experiments using thin wires strung 7 feet above soil level and 40 to 80 Kvolts, with barley, oats, and wheat, 14 trials gave positive yield increases, and 4 were negative. Eleven showed increases greater than 10% and nine were qreater than 30%.

Agreement as to the beneficial effects of applied electrical fields to crop growth, however, has not been unanimous. Collins et al.[11] spent several years during the 1920's in laboratory studies on barley and corn seedlings and could detect no appreciable increase in growth due to electric fields. Likewise, Briggs and his co-workers[12,13] during the early 1930's obtained essentially negative results on greenhouse and field studies with carefully controlled experiments. Persistence by more recent workers despite the ups and downs experienced in these very early days has, however, led to a recent large body of convincing evidence that not only does electroculture provide either increased or decreased crop yield at will, but that the fundamental causes are becoming known. This has been at least partly due to the increased sophistication of modern research methods.

Krueger et al.[14] have shown that air ions are the principal mediating agent in electroculture. In particular, iron stress, especially associated with that readily soluble in 1 N HCl, is critical to the growth and to the onset of chlorosis during the presence of applied electric fields. Murr[15,16] showed that although nitrogen or phosphorous levels were hardly affected, applied fields did bring about major changes in several trace element levels, such as Fe, Zn, and Al. He suggested that since these elements are key constituents of certain enzymes in the oxidative pathways, that the relatively large effect by air ions focuses on the controls to these pathways. Krueger et al.[17] were able to readily detect significant biological changes induced by applied electric fields or by the direct administration of air ions. Among these changes, in addition to that noted on Fe levels, were alterations in the increased production of cytochrome C and the acceleration of oxygen consumption. Alterations in the distribution of growth control substances were observed by Clark.[18] Smith and Fuller[19] noted that the release of indole acetic acid paralleled the affect of positive ions. Went[20] had earlier hypothesized that electrical fields were active in bringing about redistributions of auxins.

From this brief discussion of some of the highlights of more important variables in the successful application of electroculture to higher plants, we now turn to a brief summary of the more recent research, looking in particular at the growth accelerating and retarding effects found by various research groups.

II. A Summary of Recent Research

Research on electroculture of plants during the period following World War II has, as noted above, established that applied electric fields can controlledly accelerate or inhibit the growth of higher plants. Moreover, some of the basic processes responsible have been pin-pointed. Nyrop[21] examined the killing effects of applied electric fields on bacteria and on foot-and-mouth virus. Smith and Fuller[19] indicated that positive air ions, especially CO_2^+, accelerated plant growth in the blue-green alga, *Microcoleus vaginatus*, by releasing indole acetic acid. Krueger, Kotaka, and

Andriese[22] examined the effect of added positive and negative air ions on the growth of oat seedlings (*Avena sativa*), and showed that ions of either sign could accelerate growth. In a subsequent paper they showed similar results for oats and for barley (*Hordeum vulgaris*), and found that an increase of 30% to 60% in dry weight could be obtained. An encapsulated tritium source was used to supply ions in various gases supplied, and the dominance of ion charge was controlled by passing the effluent gases over appropriately charged grids. Ion densities in the plant growth chambers gave currents of 6×10^{-12} to 9×10^{-13} amperes per plant during growth acceleration, while the (background) current in the control chambers was about 10^{-13} amperes per plant. Krueger et al.[23] observed effects of the electric field upon the iron, cytochrome C and chlorophyll levels, in barley. Although Smith and Fuller[19] had suggested that the applied fields were affecting the indole acetic acid (IAA) levels, Krueger et al.[23] found no significant shift in the free or bound levels of IAA in barley seedlings, but substantiated their air-ion results. Krueger et al.,[24] using their tritium-source ion generator, showed that O_2^- or O_2^+ ion accelerated growth of barley seedlings, but that CO_2^- or CO_2^+ inhibited the plant growth, and also the production rate of chlorophyll. Moreover, the added presence of O_2^- or O_2^+ stimulated the production of cytochrome C and of Fe-containing enzymes. The role of $CO_2^{\pm}$ was not explained, and still remains a mystery. The role of Fe as affected by air ions was much clarified by their finding that there are three types of iron in young seedlings; (1) Constitutional Fe, destined for cytochromes and other Fe-containing enzymes, and which is not extractable by 1 N HCl from mascerated plants. (2) Fe destined for chlorophyll synthesis in the first and second leaves. This iron is extractable by 1 N HCl. (3) Free-state iron (easily soluble).

They suggest that the air ions in some way enhance or guide the synthesis of cytochrome C and other Fe-containing enzymes. It is suggested that the distribution of the iron among the various metabolic pathways is then affected by ions of either charge, by the action of the ions upon certain "governors" of the iron distribution pathways in the mitochondria and chloroplasts. These as yet unknown "pathway governors" are then the site of the more important actions of air ions upon growth pattern.

Pratt[25] on working with black mustard seedlings (*Brassica nigra*) observed that air ions of either sign when produced at a rate of 9.5×10^6 ions cm^{-1} sec^{-1} in the air above the seed plant caused delay in the emergence of shoots in these seedlings, but also noticed that by the fifth day an acceleration in shoot length occurred compared to that of the controls. Murr[26] observed tip damage to orchard grass seedlings by applied electric fields, and at first suggested that a possible mechanism to explain the effects would be an ionization phenomenon involving the migration of polarized salts which initiated cell bursting by catastrophic osmosis. He later[15] concluded that this mechanism was incorrect, and that the mechanism was more properly one concerned with biochemical transformations involving enzyme constituents of cell metabolism. Spectroscopic and micro-Kjeldahl analyses of the leaf tips showed that the elemental N and P contents were rather little affected, but that the levels of the trace elements, Fe, Zn, and Al were demonstrably affected. It seemed reasonable then to ascribe the effects of the applied field to mechanisms involving the metallo-enzymes. Further studies[16,27,28,29] on orchard grass and grain sorghum showed that Ca, Mg, and Mn levels were also affected by applied fields. The weight response curves obtained by Murr[29] for sweet corn (Pennlewis) as affected by various intensities of the applied electric field reversed at 100 kV/m and for yellow bush bean at 60 kV/m.[27,28] There is a rather wide region of field strengths for which the weight gain is positive, and that above this (circa 1 kV/cm) region of field intensities the plant is inhibited in its growth. Interestingly, Murr[30] showed that plants grown in very low magnetostatic fields were also stimulated. Krueger et al.[31] showed that air ion depeltion to lower than normal levels resulted in lowered growth rates.

Anderson and Vad[32] demonstrated the inhibition of bacterial growth by the application of fields of approximately 3 kV/cm (*Serratia marcescens* and *E. coli*). Sidaway[33] reported on observing lettuce germination (*Lactuca sativa*, var. Cluseed Borough Wonder) that the sign of the applied field made a difference in the growth response and that with a positive electrode above the seed a slight inhibition occurred. [His tabulated results appear to show the opposite, however, (sic).] Sidaway and Asprey[34] studied the influence of electrostatic fields upon the respiration of beets (*arum maculatum*), and of *Triticum vulgare, Vicia fabia, Castanea sativa, Ulmus glabra,* and found measurable effects on the O_2 and CO_2 respiration. Sharp[35] found a strong correlation between the concentration of small air ions and the germination rate of the uredospores of *Puccinia striiformis*, the causal agent of stripe rust of wheat. Sale and Hamilton[36] observed killing effects of strong fields (25 kV/cm) on various bacteria and yeasts, noting that yeasts were more sensitive than bacteria. Bentrup[37] rather than using electrodes placed in the air above the growing organisms as in most other studies, used an electrochemical gradient produced by electrodes immersed in the culture medium which produced transcellular potential differences of about 1 to 10 mV corresponding to about 0.1 to 1 V/cm in the medium. Their studies with the horsetail *Equisetum*, moss (*Funaria*) and with zygotes of brown alga (*Fucus*) showed that growth of the cells was oriented towards either the anode or cathode, depending upon the growth stage. Kotaka, Krueger, and Andriese[38] were able to correlate the effect of air ions upon the light-induced swelling and dark-induced shrinking of isolated spinach chloroplasts (*Spinacia oleracea L.*). With the light on, either positive or negative ions induced swelling; but induced shrinking in the dark.

An excellent detailed review and discussion of possible mechanisms concerned with the effect of air ions appeared in a long paper by Kotaka and Krueger[39]. It is interesting to note that Feder and Sullivan[40] observed that ozone depressed frond multiplication and floral production in duckweed (*Lemmna perpusilla* #6746). The presence of only 0.1 ppm of O_3 reduced frond number by a factor of 4 and flower number by a factor of 6.

Krueger[17] in commenting on electroculture and related experiments notes that air ions play a large role, but that other factors such as ozone and nitrogen oxides, humidity, and air pollutants can be expected to affect the results and must be monitored in good experiments. The normal concentration of small air ions in "normal" air is about

10^3 to 4×10^3 ions cm^{-3}, and that because of rapid recombination mechanisms, the upper practical limit inducible by external means is about 10^6 ions cm^{-3}. That such small concentrations (air contains about 2.7×10^{19} molecules cm^{-3}) can markedly affect physiological processes such as the growth of higher plants or of mammals is remarkable, but must now be regarded as factual. The small ions readily unite with nuclei and pollutants in air to form large ions (high mass per charge) which have only relatively small effects on organisms. The dominant positive small ions in air are present as the hydrated forms of H^+, or as the negative ions O_2^-, OH^-, CO_3^- and CO_4^-, with possible contributions of ON^-. The principle ionic reactions, according to Krueger[17] are:

$$CO_2^+ + O_2 \Rightarrow O_2^+$$

$$O_2^+ + H_2O \Rightarrow H^+$$

$$N_2^+ + O_2 \Rightarrow O_2^+$$

$$O_2^- + H_2O \Rightarrow OH^-$$

$$CO_2^- \Rightarrow O^- + CO$$

$$O^- + CO_2 \Rightarrow CO_3^-$$

Stersky, Heldman and Hedrick[41] used applied fields of 6 to 20 kV/m to kill air-borne *Pseudomonas fragi*, *Serratia marcescens*, *Candida lipolytica*, *Penicillum roqueforti*, and *Bacillus subtilis* and observed 40% to 60% kills. Wheaton, Lovely, and Bockhop[42] found small but positive effects on the germination upon exposing seeds of corn and soybeans to static or 60 Hz fields of 500 to 5500 volts across 1.5 inch (3.8 cm) air gaps for quite short periods (up to 20 sec.). Bachman and Hademenos and Underwood[43] examined the effects of intense fields at the tips of barley, measuring the presence of ozone, air ions, and corona current. Among some thirty varieties of plants examined in their preliminary studies, wax beans were observed to be outstandingly sensitive. When an upper electrode plate at 15 kV positive was maintained at a distance of 5 cm above a planting of wax beans, the wax beans germinated faster, grew taller, and grew heavier, and in all ways maintained a lead over control planting which was not exposed to the applied electric field. Their study focused mainly on the behavior of barley seedlings. Ozone appeared (0.01 ppm) in the air when a critical current of 2×10^{-7} amperes per plant tip was reached.

Direct insertion of electrodes into tomato plants and application of currents of 3 to 15 microamperes per plant produced linear increases of growth, according to the Canadian workers, Black, Forsythe, Fensom and Ross[44]. Kotaka and Krueger[45] noted an effect of air ions on RNAase activity in green barley leaves (*Hordeum vulgaris*, var. Mariout). Development of Fe-chlorosis in barley grown in Fe-free nutrient was seen to be accelerated by air ions of either charge. As the concentration of chlorophyll dropped with the onset of chlorosis, there was marked rise in the concentration of cytochrome C. When Fe was added to the nutrient, typical ion-induced acceleration of growth occurred, accompanied by the stimulation of cytochrome C synthesis, but no chlorosis developed, and there was no difference in the concentrations of chlorophyll in exposed and normal plants. As in earlier results, ions of either charge reduce the "active" Fe content of seedlings but the content of residual Fe increases in cytochrome C and other Fe-containing enzymes. Air ions increased the uptake of exogenous Fe and increased O_2 consumption. Both EDTA and air ions decreased the concentration of RNAase[46]. A general survey of electropotentials in cells, by Higinbotham[47] reviews present views of the normal distribution of electric fields in cells, and how it is affected by applied fields.

Bachman and Reichmans[48] closely examined tip-burning on barley resulting from the application of high electric fields, finding the damage, D, obeying $D = k(V^2/R)t$, where V is the applied voltage, R is the resistance, and t is the time of exposure and k is a constant. In careful experiments with barley, electric fields were found to not only enhance growth for field strengths of less than about 2kV/cm, but that enhancement of growth could be produced by some by-products of the corona occurring above the plants. In the latter case, air moved from above electric field-exposed plants was observed to accelerate growth in plants remote from the electrical exposure. Recent summaries of electroculture studies were presented by Krueger, et al.[49]

Recent preliminary green-house experiments on electroculture[50] here at Oklahoma State University, done with 60-plants plots of green bush beans (cultivar, Provider), planted in clay pots containing 1:1:1 soil, perlite, and peat moss mix. The pots were set out on a wetted blanket atop a metallic screen serving as a grounding connection. Watering was normal except on the 20th day when 300 ppm of K^+, NO_3^-, and PO_4^{3+} (Peters 20-20-20-) was used, and on the 24th and 32nd days when 250 ml per pot of Fe chelate solution (28 g Fe per 80 liters) was added. An increase of 61% and of 85% in crop weight by DC and by AC (60 Hz) respectively over the controls was observed at harvest (60 days total). (Plot to plot variation was known to be 10 to 20% in this greenhouse.) Electrode height, with 12kV applied was adjusted (at about 80 cm above plant tips) to maintain a relatively constant DC current density of 7 to 20 picoamperes per plant, from seed-planting to harvest. 6kV rms was simultaneously supplied to the AC electrode adjusted to the same height. In view of the known Fe-stress evokable by electroculture, the plants were given supplemental Fe chelate (0.1g per plant) during the 3rd and 4th weeks. The positive results obtained here confirm the earlier observations of Murr[16,27], and of Bachman et al.[43] and suggest the desirability of trace element metal supplement feed during electroculture.

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