12 Electromagnetic Parameters Related to Plants and Their Microbiomes

Ed Moerman

Koppert Biological Systems

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INTRODUCTION

Few people relate electricity or electromagnetism to plants and plant growth, perhaps because the electrotechnical and plant physiological disciplines seem so different. But there are many electrical and electromagnetic parameters that can be measured in plants and in their environment. This chapter describes a number of these parameters and how they can help us to better understand the plant and may even be used to enhance plant growth. Electrophysiology is the discipline that deals broadly with the flow of ions/electrons in biological tissues and, in particular, to the electrical recording techniques that enable the measurement of this flow. Prof. Volkov has edited various books on this subject, collecting work from scientists from all over the world. The latest work is titled *Plant Electrophysiology, Signaling and Responses* (Volkov, 2012: v). Its preface gives a comprehensive description of electrophysiology:

Plant electrophysiology is the study of the electrochemical phenomena associated with biological cells and tissues in plants. It involves measurements of **electrical potentials** and **currents** on a wide variety of scales from single ion channels to tissues to entire plants or trees. Electrical properties of plant cells mostly derive from the electrochemical properties of their membranes. Electrophysiological study of plants includes measurements of the electrical activity of the phloem, xylem, plasmodesmata, stomata and particularly the electrical signal's propagation along the plasma membrane. **Action potentials** are characteristic responses of excitation that can be induced by stimuli such as applied pressure, chemical substances, thermal stimuli, electrical or magnetic and mechanical stimuli, and biotic stressors.

Around 2010, the company I work for started to sell biostimulants to professional growers to improve the resilience of their crops to biotic and abiotic stresses. One of my tasks as knowledge manager was to search for indicators of plants' resilience by asking the following questions: Is there

any method to quantify the condition of the plant and the risk for those stressors causing economic damage? and How can you measure improved resilience after the application of biostimulants? During one of many field visits to greenhouse growers, I experienced a kind of life-changing incident. A top-level Dutch gerbera grower I was visiting had been facing serious problems with his crop from the moment he had installed a combined heat and power (CHP) system in a room next to his new greenhouse. Yearly production figures gradually dropped from 300 to 200 flowers/m², and in addition to that, chemical pesticides showed sub-optimal performance. This had already been going on for more than a year, and no one was able to discover the reason for these problems. While brainstorming during a stroll through the greenhouse, a seemingly simple remark of the grower drew my attention. He said that the irrigation water pipe from the borehole to the greenhouse was installed very close to the CHP's power output cable. This did not feel right, although I could not find any hard evidence against it. Despite this, and desperate to solve the problem, the grower changed the irrigation water supply from borehole to tap water and started using a water vitaliser (a device that improves the molecular structure of water by exposing it to certain vibrations). The result was beyond all expectations: within a week, the grower observed visible change in the plants' appearance, and after some weeks, production returned to the previous high level of 300 flowers/m² on a yearly basis. This broadened my perspective, and I started collecting publications about plants, stressors and electric phenomena and undertook some basic measurements myself in ongoing experiments and with practical growers to become more familiar with the topic.

This chapter is a compilation of what I have learned from publications, participating in experiments and talking to people who are already more familiar with this topic. It has been an interesting journey, one which has perhaps only just begun. To begin with, the following section explains the main electrical terms used.

EXPLANATION OF SOME ELECTRICAL TERMS

For a good understanding of the rest of the chapter, here are some short definitions of terms related to electricity. Electricity is the set of physical phenomena associated with the presence and motion of matter that has a property of an electric charge: electrons, as well as protons (H⁺) and other ions. At the beginning of the nineteenth century, electricity was considered as being unrelated to magnetism. Later on, many experimental results and the development of Maxwell's equations¹ indicated that both electricity and magnetism are from a single phenomenon: **electromagnetism**.

The movement of any moving charged particles through a conductor is known as an electric **current**, measured in (milli)amperes. A simple voltmeter can be used to measure the **voltage (or potential difference)** between two points in a system; often a common reference potential, such as the ground of the system, is used as one of the points. A **voltage** may represent either a source of energy (an electromotive force which can create a **current**) or lost, used or stored energy (**potential drop**). Current can flow through electrical conductors meeting a certain **resistance** (measured in ohms). The resistance is a consequence of the motion of charged particles through a conductor. In metals, for example, resistance is primarily due to collisions between electrons and ions.

Conductivity is expressed in mS/cm and is the inverse parameter of resistance. Liquids show a lower resistance (or higher conductivity) when more ions/electrolytes are dissolved.

Current can be **direct current** (DC) or **alternating current** (AC). DC is a one-directional flow of charge; AC reverses direction repeatedly at a certain frequency (expressed in Hz, fluctuations per second). This is often sinus shaped, but other shapes such as blocks also exist.

The electrical properties of **inductance** and **capacitance** are only observed under AC. **Inductance** describes the tendency of an electrical conductor, such as a coil, to oppose a fluctuation in the electric current going through it. A capacitor is a device which allows electricity to pile up by

¹ Maxwell's equations describe how electric and magnetic fields are generated by charges, currents and changes in the fields.

providing space for it to spread out. A capacitor has a **capacitance**, measured in farads (F), or more often microfarads.

An **electric field** is created by a charged body in the space that surrounds it, and results in a force exerted on any other charges placed within the field. The **electric power** produced by an **electric current** (I) passing through an **electric potential** (V) difference is expressed in watts ($P=I \times V$; work done per unit time).

Many important biological processes involve **redox** reactions. **Oxidation** is the loss of electrons or an increase in oxidation state; **reduction** is the gain of electrons or a **decrease** in oxidation state by a molecule, atom or ion. The **reduction potential** (mostly expressed in millivolts – mV) is a measure of the tendency of the oxidising agent to be reduced.

The **phase angle** is the phase difference between an alternating voltage applied to a conductor or capacitor and the alternating current driven through it. It is expressed in degrees, as shown in Figure 12.1.

Electrical **impedance** is the measure of the opposition or **resistance** that a circuit presents to a **current** when a **voltage** is applied.

ELECTRIC PHENOMENA INSIDE THE PLANT

What drives life is just a little electric current, kept up by the sunshine. All the complexities of intermediary metabolism are but the lacework around this basic fact (Szent-Gyorgyi, 1960).

Photosynthesis is the process that increases the potential energy of electrons as they move from water to sugar. Photosynthesis relies on flows of energy and electrons initiated by light energy, which causes the excitation of electrons in chlorophyll that pushes them out of their orbit. The electrons instantly fall back into place, releasing resonance energy. This energy passes rapidly to the chlorophyll molecules, like the transfer of energy from one billiard ball to another. Photosynthesis thus converts light energy into chemical energy, stored in organic molecules. In terms of redox, reduction takes place (see Table 12.1). Reduction implies an increase of electrons in the plant tissue, enabling the plant to mitigate free radicals and better cope with oxidative stress.

A living plant (or tree) transports electrons from the earth to its top. Electrical engineer Arthur Ramthun (2015) used a digital voltmeter and oscilloscope to measure and record the electric potential between the ground, trunk and branch tips of many different trees. Billions of electrons appear to flow up the trees and outwards to branch tips (e.g. 2.8×10^{11} electrons per second to each Aspen branch tip). His model calculations show that this amount of electrons creates enough repulsive force at the branch tips to direct growth direction and influence plant geometry. This phenomenon he named ‘electrotropism’. From measurements on a specially prepared young corn plant, he learned that electrons came from the water, through the roots and to the stem of the plantlet.

Clark et al. (2013) demonstrated that plants create an electric field with negative potential around flowers. Pollinators (such as the bumblebee *Bombus terrestris*) are able to detect and distinguish these electric fields. Pollinators usually possess a positive electric potential, acquired during their

FIGURE 12.1 Phase angle: alternating current (red line) lags 90° behind alternating voltage (blue line).

TABLE 12.1**Reduction and Oxidation in Relation to Plant Growth**

	Reduction	Oxidation
<i>Electrons</i>	Gained	Lost
<i>Eh value</i>	Decreases	Increases
<i>Takes place in plant processes</i>	Photosynthesis Proteosynthesis Liposynthesis Synthesis of antioxidants, phenols, etc.	Dissimilation: oxidation (of reduced compounds) avails energy, used for metabolic processes in plants
<i>Energy</i>	Increases chemical potential of molecules	Uses energy stored in molecules
<i>Meaning</i>	Antioxidants important for plant defence	Plant stresses have oxidising effect

flight. The potential difference between pollinator and flower is one of the cues that helps pollinators to find flowers that are ready to be pollinated. It is also a driving force for the transfer and adhesion of pollen during the flower visit. The deposition of pollen and the resulting pollination change the flower's electric potential, so the electric field differs according to the pollination status of the flower. This helps pollinators to focus on the flowers that still need pollination, and not to revisit the pollinated ones.

In 2015, Koppert Biological Systems performed greenhouse trials with tomatoes grown in rock-wool substrate with different additions of biostimulants and biochar to stimulate the development of the root microbiome (Moerman, unpublished research, 2015). Orienting measurements of potential differences between the rockwool slabs and the stem base of tomato plants in these greenhouse trials showed a potential difference between 0.5 and 0.6 V, the stems having the lower value. These values, and the polarisation, correspond with what other researchers, Ramthun (2015) and Rajda (2004), found in trees and herbaceous plants.

USING THESE ELECTRICAL PARAMETERS TO BETTER UNDERSTAND AND MONITOR PLANTS' STATUS, DEVELOPMENT AND PROCESSES

In this section, I discuss a range of examples of how various electrical parameters can help to better understand and monitor the plant. The examples given are just a snapshot of the huge amount of work done in this field. They are selected on the basis of their simplicity and potential to provide answers to my search for a method to quantify the condition of the plant and its resilience. The equipment needed to undertake the measurements should be affordable to growers/advisors and simple to operate.

Rajda (2004) measured the electric current flowing between the ground (measured in the soil at some distance from the stem base) and the stem base of hundreds of individual trees. Stems always showed a negative potential compared to the earth. Measurements showed different values for different tree species, positively correlated with stem diameter (and showing a typical seasonal pattern), and lower values for unhealthy trees. With this information, he was able to predict health problems by frequently checking the seasonal current and benchmark this value against the same values of similar trees. Table 12.2 shows the range of values measured in different groups of plants. Frequent measurements of these parameters helped to predict which trees were going to have health problems, before the symptoms were visible.

Vivent,² a Swiss-based bio-signal company, is developing an innovative device for exploring and monitoring electrical signals in plants. These devices capture the bio-signals that plants themselves

² <http://www.phytlsigns.com/>.

TABLE 12.2**Range of Currents and Potential between Ground and Stem Base in Different Types of Trees or Plants**

Type of Plant/Tree	Maximum Current (μA) Related to Stem Diameter (cm) ($\mu\text{A}/\text{cm}$)	Potential (V)
<i>Deciduous trees</i>	200–500	1.2
<i>Conifers</i>	100	1.0
<i>Vegetables and ornamental plants</i>	8–117	0.4–0.7

Source: Rajda (2004).

are transmitting. The device (PhytSigns) measures potential differences between the root zone, stem base and leaves. Measured values (voltage) are recorded at very short time intervals. Deep analysis (with the help of artificial intelligence) of the voltage line patterns comparing plants with and without known biotic and abiotic stressors reveals that different types of plant/stressor combinations show a typical pattern. At present, the device is already used by a Swiss research station and had demonstrated that a pesticide spray can put plants ‘on hold’ for hours to days, depending on the type of pesticide (Personal communication with N. Wallbridge, 2019). The company claims that this device ‘can be used to investigate plant responses to diseases, pests, crop protection treatments and environmental conditions’.³ In time, this device could provide an intelligent monitoring system to detect stressors early on in order to help the grower anticipate potential problems.

The investigation of plant roots is inherently difficult and therefore often neglected. Being out of sight, roots are often out of mind. Nevertheless, roots play a key role in the exchange of mass and energy between soil and the atmosphere, and therefore, it is useful to be able to better monitor root growth and root activity.

The size and activity of the plants’ root system are good predictors for plant condition, but difficult to assess. Cseresnyés et al. (2013) did a lot of work on how to use electrical impedance spectroscopy⁴ to measure root systems and stressed the usefulness of measuring the phase angle between alternating potential (voltage) between the stem and root zone and resulting AC, for the rapid *in situ* investigation of the root system size and root activity without any intrusion into plant life functions.

Dietrich et al. (2013) report that electrical capacitance, measured (with an LCR meter⁵) between an electrode inserted at the base of a plant and an electrode in the rooting substrate, is often linearly correlated with root mass. Electrical capacitance has often been used as a proxy for root mass and is conventionally interpreted using an electrical model in which roots behave as cylindrical capacitors wired in parallel. However, recent experiments in hydroponics show that this interpretation may not be correct and a newer model has been proposed by Dietrich in his doctoral thesis (2013), in which he revised the existing model of resistance–capacitance circuits in plants and which is tested in solid substrates. The results were consistent with the new physical interpretation of plant capacitance. Substrate capacitance and plant capacitance combine according to standard physical laws. For plants growing in wet substrate, the capacitance measured is largely determined by the tissue between the surface of the substrate and the electrode attached to the plant. While the measured

³ From the company website <https://www.phytlsigns.com/product-solutions> (accessed 1 July 2020).

⁴ Electrical impedance (EI) and electrical capacitance (EC) measurements in a plant–soil system offer good opportunities of rapid *in situ* investigation of the root system size and root activity. By fixing an electrode at the plant stem and embedding the other one in the soil and connecting them by an LCR instrument, the measured root EI and EC are directly correlated with root mass, root length or root surface area (Chloupek, 1972; Ozier-Lafontaine and Bajazet, 2005; Rajkai et al., 2002).

⁵ An LCR meter is an electronic test equipment used to measure the inductance, capacitance and resistance of an electronic component.

capacitance can, in some circumstances, be correlated with root mass, it is not a direct assay of root mass (Figure 12.2).

In 2015, Koppert Biological Systems performed a dedicated propagation trial with cucumbers grown in perlite to validate the findings of Dietrich (2013) and Cseresnyés et al. (2013) in a greenhouse situation (Moerman and Weber, unpublished research, 2015). Measurements of the phase angle and dry root weight of 2 groups of 25 plants taken on 4 and 9 March 2015 confirmed the

FIGURE 12.2 Resistance–capacitance (RC) circuits according to the revised model: (a,c) diagrams of barley plants with five root tips, (b,d) electrical equivalent networks of the root systems showing the location of the RC components, (a,b) RC circuits for a completely submerged root system and (c,d) RC circuits for a partly submerged root system. The sub-circuit that largely determines the capacitance is ringed to emphasise its importance. Note that the individual RC components can have different values.

correlation between phase angle and dry weight of the root system and showed that a non-destructive measurement of phase angle has the potential to replace the destructive and time-consuming measurement of root dry weight (Figures 12.3 and 12.4).

Postic and Doussan (2016) compared various electrical methods to estimate root mass. The parallel measurement using a clamp as a stem electrode of capacitance and a hand-held LCR meter at an alternating current gave the most reliable results. They found that the frequency of the AC current used plays a role in the accuracy of the outcome.

Benada (2017) described his investigations on variable resistance in wheat plants as a starting point for considering the nature of variable disease resistance of cereals against obligate

FIGURE 12.3 Correlation between gram dry root weight per plant (X-axis) and phase angle (Y-axis).

FIGURE 12.4 Simple LCR meter (a) and voltmeter (b) used for measurements of cucumber plants in pots. (c) The grounding probe and (d) a crocodile clamp on a needle inserted into the stem at the plant base.

parasites⁶ such as powdery mildew and rust, in which redox potential and pH measurements in leaf sap were the main observations. He developed a simple and quick method for redox measurements in the tissue of detached leaves and formulated a hypothesis for why the biophysical status of a plant plays such an important role in resistance, and plant physiology in general. He found that the principle of resistance lies in the ability of the parasite to gain the energy from the host cell. The parasite uses the terminal oxidase of the host plasmalemma (the plasma membrane of the cell wall) as its energy source.

Plant roots generate electric currents and associated electric fields as a consequence of electrogenic ion transport at the root surface. van West et al. (2002) demonstrated that swimming zoospores of oomycete plant pathogens⁷ to plant roots are partly attracted by electrotaxis (the movement of an organism in an electric field) in natural root-generated electric fields. The zones of accumulation of anode- or cathode-seeking zoospores adjacent to intact and wounded root surfaces correlated with their *in vitro* electrotactic behaviour (either attracted to the anode or the cathode). Manipulation of the root electric field was reflected in changes in the pattern of zoospore accumulation, and imposed focal electric fields were capable of overriding endogenous signals at the root surface. Data suggested that electrical signals from a potential difference (voltage) between root and rhizosphere/rhizoplane can augment or override chemical cues in mediating short-range tactic responses of oomycete zoospores at root surfaces. These findings may help in the future to better assess risks for infection of root-borne diseases.

Akay and Kara (2006) investigated quality parameters that can be measured by different methods. One of them is Vincent's bioelectronic method (BEV). The *P*-value is measured in sap pressed from fruits or vegetables. It is based on three factors: pH (acidity), rH (redox potential) and *R* (resistivity). The *P*-value integrates the three parameters to a parameter of quality and is calculated as $[30 \times (rH - 2pH)]/2/R$ (Hoffmann, 1991), which is expressed in microwatts (μW).

These electrochemical parameters can tell us something about the production conditions and the effects on humans after consumption. Products with low *P*-value are supposed to be health promoting. Good foods give us more power than bad ones and are good for our health. Life processes in plants and animals can be described as chains of electrochemical or redox reactions. The *P*-value is used in the areas of environment, human medicine and food research. Food with low redox values provides many electrons that counteract free radicals (in other words have an anti-oxidising effect) and hence contribute to health. Good examples of these 'curing foods' are beetroot, (organic) carrots and fermented cabbage.

Hoffmann et al. (2007) worked on electrochemical quality assessment, using the redox potential (rH in mV), resistivity (ohm) and pH of a liquified, homogenised sample. In his book, Hoffmann explained the relationship between redox value and entropy: a lower redox potential coincides with lower entropy, which means less chaos or more organised tissue.

Northolt et al. (2004) investigated the usefulness of electrical parameters to assess carrot quality and the development of the inner quality concept and concluded that these measurements can be valuable. Their report presents a comprehensive explanation of the meaning of the different parameters, as provided in Box 12.1.

EFFECTS OF APPLIED, EXTERNAL, ELECTRICAL (ELECTROMAGNETIC) FACTORS ON PLANTS AND THEIR MICROBIOMES

This section explores a number of experiments aiming to influence plant growth to the benefit of the grower/farmer. Although this work started in the beginning of the twentieth century, to the author's

⁶ An obligate parasite is a parasitic organism that cannot complete its life cycle without exploiting a suitable host. If an obligate parasite cannot exploit a host, it will fail to reproduce.

⁷ Oomycetes, also known as 'water moulds', are a group of several 100 organisms that include some of the most devastating plant pathogens. The diseases they cause include seedling blight, damping-off, root rot, foliar blight and downy mildew.

BOX 12.1 EXPLANATION OF THE USEFULNESS OF DIFFERENT ELECTRICAL PARAMETERS (NORTHOLT ET AL., 2004: 56)

Life processes in plants and animals can be described as chains of electrochemical or redox reactions. Hoffmann (1991) explains how Haas developed a bioelectric theory to derive an electrical energy value for food from measurements of pH, redox potential and electrical resistance. He suggested that food with high reducing power, later expressed as low *P*-value, promotes health. The *P*-value is calculated from the three stated parameters which are affected by the growth conditions of the product. The pH value is the best known electrochemical parameter to measure proton concentration or acidity. The pH is measured by potentiometry using suitable electrodes. The measured mV value is logarithmically transformed to the pH value. The potentiometric equilibrium is at pH 7 and 0 mV. A difference in pH of 1 (at 25°C) equals 59 mV. In plants, proton activity has energy aspects. The redox potential *Eh* (mV) reflects the gradient of electrons which life processes utilise for their cellular work (Kollath, 1978). The redox potential represents the equilibrium between oxidising and reducing substances. When redox potential is low, plant cells have more energy for their activity. Traditionally, the flow of electrons is considered to be the main form of respiratory energy transport in an organism with oxygen as the terminal electron acceptor. Electrical resistance *R* (ohm) gives an indication of the dissipation of electrolytes in plant cells. High values of electrical resistance indicate that electrolytes are more integrated in membranes and cell organelles. Low values indicate free-moving electrolytes, which might be a sign of deterioration in plant cells and tissues.

knowledge only a few patents have been filed and none of them are as yet applied on a commercial scale. Undoubtedly, there may be many more examples.

Blackman et al. (1923) performed detailed research on the effect of a positively loaded discharge point just above the top of grounded cereal plants, showing it had a lasting effect on the growth rate of barley sheaths. Similar trials in which the direction of the current was reversed did not give the same positive effects, and in some cases results were even negative. So the direction of the current appeared to be important.

Rajda (2004) managed to enhance plant growth by putting a DC voltage on positive and negative electrodes on opposite sides of the substrate in a growing table. However, the mode of action was not explained and could be caused directly by the potential difference or by electrolytic effects on the dissolved nutrients. Wawrecki and Zagorska-Marek (2007) demonstrated that even a weak (1 V/cm) DC electric field with a horizontal direction disturbed the pattern of cell divisions in plant root meristems of maize. This in turn changed the global organisation of the root apical meristem: it influenced the direction of apical root growth. A field of slightly higher strength also damaged root cap initials, terminating their division. This implies that care should be taken when applying this technique and not to apply too high an intensity of treatment. It is not clear if and how this phenomenon could be used to the benefit of growers/farmers. But one could image that stray current⁸ could not only affect farm animals but also crops in a way that is not yet understood.

Gasner (2013) demonstrated a positive effect of grounding the root medium of pepper plants grown in pots. Devices were inserted into the plants' growing medium at an angle towards the centre of the pot and connected to earth. Grounded plants grew better and produced more fruits than ungrounded plants. The measure of grounding provided the plants with a continuous stream of electrons from the earth, which could also be measured. The voltage between grounded plants and

⁸ Stray current refers to the electricity flow via buildings, ground or equipment due to electrical supply system imbalances or wiring flaws. It refers to an existence of electrical potential that can be found between objects that should not be subjected to voltage.

earth varied between 200 and 300 mV, which is in the same range as in herbaceous plants (Rajda 2004) and also concurs with the author's own (unpublished) trials in 2015 of tomatoes grown in rockwool. Unfortunately, while there are many publications about the positive effects of grounding on human health, this is the only publication showing the positive effects of grounding on plant growth, and the grounding devices for plants that the author has developed may have a commercial potential. There is a patent filed for grounding rods for plants,⁹ but it is unclear if this has yet been commercialised.

Olyslaegers (2012) states that electroculture has been investigated for a long time, but with inconsistent results. He defines electroculture as any electrical stimulation of plants. His research focused on the question of whether young tomato plants (*Solanum lycopersicum*) could be electrically stimulated in a manner that would be practically feasible in commercial greenhouses. As well as the attempt to demonstrate the 'proof of principle' and investigate possible mechanisms, attention was paid to the possibilities of this technique with regard to a decrease in the costs and quantities of nutrient usage in intensive greenhouse cultivation. He worked with a low DC voltage (0.1–0.2 V/cm) and two polarities, applied via a piece of felt underneath rockwool blocks. The results were inconsistent.

A recent publication from India (Patil, 2018) describes experiments to study the effect of electricity on germination and growth of radish (*Raphanus sativus*). Here, plants were only briefly exposed to low DC voltage: 3, 6 and 9 V for 10 minutes per day. This helped increase germination rates from 85% in the control sample to 95% in the treated sample.

A very promising method to stimulate plant growth with electricity is described in PJJ van Zyl's thesis (2012) on radio frequency energy for bioelectric stimulation of plants. This principle uses electromagnetism. The study is about utilising low power radio frequency (RF) energy signals from leaky transmission lines for the benefit of plant growth and production in hydroponic systems. The way it works is that plant cell walls are covered with tightly bonded, positively charged calcium ions that affect the inflow of nutrients into the cell. As calcium ions have a mass twice that of the potassium ion, the fundamental harmonic of calcium is equal to the first harmonic of potassium (32 Hz). Thousands (10k:1) fewer positive potassium ions also exist around the cell wall, and when stimulated at their resonance frequency (16 Hz), they will bounce against the bonded calcium ions so that these calcium ions become dislodged from the cell wall. When this happens, more nutrients can enter the cell causing an acceleration in plant growth. However, it is important to control the process, because if too many calcium ions are released it would cause plant stress and a breakdown in the plant structure. The amplitude modulated (block, as opposed to sinus) wave allows sufficient time for the calcium ions to return to the cell walls during the period without externally applied energy. One medium to apply radio energy to a plant is to transmit the energy into two leaky transmission lines to cause standing waves, which can then be absorbed by plants placed between these transmission lines. The energy from the radio waves is then used to create window periods during which the calcium ions are dislodged, allowing additional nutrients to enter the plant cell, enhancing plant growth and production. In the thesis, van Zyl also refers to a US patent from Kertz (1995) where principles of electronic stimulation of plants are described extensively and illustrated with trial results. Van Zyl himself performed some trials to validate the principle. In these trials, treated plants were healthier and produced significantly more biomass and tomato yield than the control plants.

DON'T FORGET THE ROOT MICROBIOME

From what has been described above, plants need electrons to aid all kinds of metabolic processes. This is also the case for microorganisms (which make up the plant microbiome, part of the soil food web). These microbes also need and give electrons for and through everything they do. They need

⁹ <https://patents.google.com/patent/US20140020294A1/en>.

electrons to consume nutrients or spew out methane or expel carbon dioxide, or any other biological process. It is often observed that the microorganisms that make up the root microbiome thrive in the presence of biochar. There had been no clear explanation for this, but scientists from Cornell University (Sun et al., 2017) have now discovered that biochar provides high-definition electron pathways in the soil that allow electrons to travel through the soil farther and more efficiently.

Field trials undertaken by Koppert Biological Systems demonstrated that the addition of a liquified stable carbon source to rockwool enhances *Trichoderma* (fungal) growth, resulting in at least a 10-fold colonisation of the fungus on the roots in the rockwool slabs that had been treated with liquid carbon. *Trichoderma harzianum* T22 acts as a biological fungicide against *Pythium*, *Fusarium* and *Rhizoctonia* in many crops. It also has plant growth-promoting features. Growers often struggle to get this beneficial fungus established on the plant roots in rockwool substrate. But the addition of a liquid biochar-like carbon gave remarkable improvements. The mode of action has not been investigated. It is unlikely that the *Trichoderma* fungus uses the carbon as a food source, since it is a very stable form that cannot further be digested. This is confirmed by Sun et al. (2017) who note that the use of biochar as a food source can be discarded because microorganisms cannot consume much of it. So the effect may be explained either in that it provides a more friendly place for *Trichoderma* to grow than the 'hostile' rockwool substrate or in that high-definition pathways for electrons are created by the carbon.

DISCUSSION AND CONCLUSIONS

The above is a snapshot of the research undertaken to better understand the role of electromagnetic phenomena in plants. The matter has many facets and is quite complicated, and the results are not always consistent. Many methods have been tried. Some look promising, and certainly, the rapid developments in the domain of sensors, artificial intelligence and the Internet of things will help to develop systems that enable growers to better monitor plant growth and have more comprehensive information to support their decision-making. Bioelectric methods could also help with simple and cheap comparisons of fruit and vegetable products and their internal quality.

The same holds true for the methods investigated that promote various types of electromagnetic effects on plant growth. Many approaches have been tried, yet none have really shown a breakthrough so far. The notion that plant growth concerns more than particles at least has started to be accepted in some quarters. There is a need for more in-depth and systematic analysis as to whether – and to what extent – the elements of energy and information connected to electricity can be applied and managed to benefit plant growth.

As a common thread running through all that has been presented above, I am beginning to see a lot of similarities between water and electrons. Both must be able to flow freely from the root zone, upwards through the plant, partly leaving the plant through the leaves and partly stored in the plant tissue. They need electrons to be present in a free and available form, to help flowers to be more visible for pollinators, to facilitate metabolic processes throughout the rhizosphere and the rest of the plant, to store energy in an excited form to help plants cope with oxidative stress and to contribute to the health of those who eat the parts of the plant harvested for food or feed. Similarly, water has to be available in the root zone, be taken up and transported via the root system, carry water-soluble components up and down and be part of many metabolic processes. Water must also be amply available in the leaves for evaporation to regulate leaf temperature, but sufficiently kept in the plant tissue to maintain turgor.

The question arises that if these concepts have been worked on for almost a century, why have there not been more major commercial breakthroughs and uptake? Several factors are at play here. It is curiosity that has driven many researchers and others (including myself) to dive into this topic. For farmers and growers, the combination between the disciplines of electro(magnetism) and (plant) physiology may not be sufficiently attractive. In the area of monitoring, practical people may prefer direct or visible (e.g. morphological or symptomatic) observations above indirect or invisible

(electromagnetic) ones. My own search only started when I wanted to measure plant resilience against stresses, something you cannot see on the outside of a plant. Further, in terms of influencing plants and their microbiomes, the results of experimental electromagnetic interventions are not always as obvious and consistent as chemical and biological interventions, which are also more trusted because they fit with current practices.

At the company where I work¹⁰, we encounter this in terms of growers' and advisors' acceptance of new bioprotection systems: new systems based on beneficial arthropods are more easily accepted than those based on beneficial microbes. Visibility plays a role here: what you see and can manage helps learning and builds trust quicker than something invisible, what you believe or hope to happen.

I hope that this chapter contributes to an improved understanding of plant growth beyond the plant physiological principles that are commonly known and accepted and encourages further research and experimentation in this field.

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