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ELECTRICAL STIMULATION FOR THE GROWTH OF PLANTS: WITH SPECIAL ATTENTION TO THE EFFECTS OF NEARBY LIGHTNING ON MUSHROOMS

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Abstract – Electrical stimulation could trigger biological activities of plants, enhancing their production rate. This paper addresses the application of this technology on mushroom which, possesses unique developmental process that depends on hyphae morphogenesis at growth stages; thus their response to electrical stimulation should be studied separately. The study analyses the information available on electrical environment of mushrooms with the view of investigating the efficiency of external electric stimulation approaches for the enhancement of their progress at various growth stages. Electric treatments at relatively low strengths, applied for a short exposure time have resulted positive impacts on growth rates, yields, length and size of various plants. In the case of mushrooms, the only information available on successful external electrical stimulation technique is the application of high voltage pulses. The technique has shown positive effects on the growth rate of varieties such as shiitake and nameko. This approach has been adopted based on the unconfirmed claims that lightning in the vicinity develops cracks in mushroom hyphae and stimulates their enzyme activities, which in turn boosts the growth rate. Based on the outcomes, we foresee a good economic viability of mushroom production with these modern technologies and methodologies.

INTRODUCTION

Externally applied man-made electrical signals have successfully improved the growth rate and yield of plants in the last few decades, as the available literature claims (Goldsworthy, 2006 and 1966; Pohl and Todd, 1981). However, despite decade long experiments in this regard, there are only few plant varieties that has been studied so far, for their response to electrical stimulation. This paper focuses on the electrical stimulation of a particular agro-product, mushroom, which is not categorised as a plant.

Mushroom is a group of higher fungi that has been classified as a unique biological form since they pose unique cell structure, growth mechanism and biological activities. Mushroom has a large worldwide demand as an agro-commercial product. There are nearly 10,000 identified species of mushroom out of which only a limited number of varieties are edible. Some species such as shiitake (*Lentinula edodes*) are known for both their taste as a food and medicinal properties, where as some, such as tiger's milk mushroom (*Lignosus rhinoceros*) are known only for their medicinal value (Jamil *et al.* 2013). Figure 1 shows pictures of both shiitake and tiger's milk mushroom.

A few sources claim that some mushrooms are able to fast multiply in the presence of lightning (Takaki *et al.*, 2009 and 2010; Tsukamoto *et al.*, 2005). The reason for this response of mushroom to the presence of lightning is still in debate. Perhaps,

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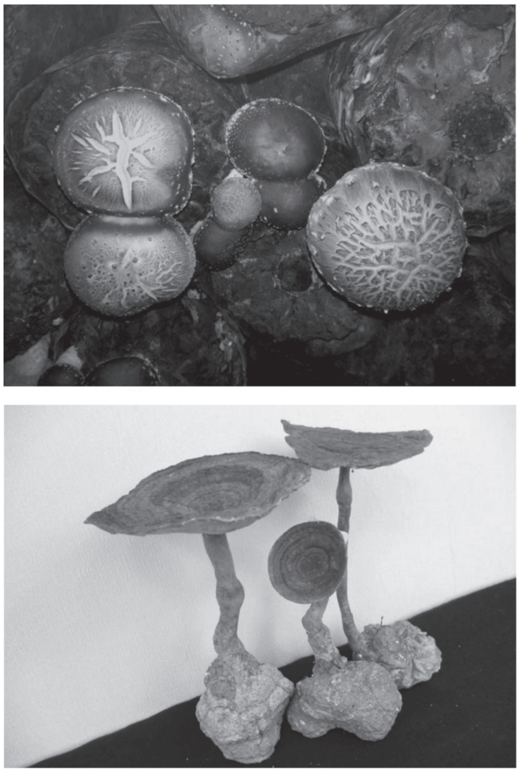

Fig. 1. *a.* Shiitake mushroom. *b.* Tiger-milk mushroom

lightning is considered as a sign of danger or threat to the existence by mushroom. Therefore, mushroom may attempt to boost their reproductive efforts as a way of survival. Several investigations have been conducted to determine the effects of electricity in the form of artificial lightning (or pulsed currents) in mushroom production (Takaki *et al.,* 2009, 2010 and 2014).

So far, the application of external electromagnetic stimulation on mushroom has been limited to a few approaches, which have mostly been done in isolation in several parts of the world. However, the lack of information on electrical stimulation methods and a comprehensive database on the research output stand as a barrier that hinders further progress in the application of external electric means for enhancing constructive processes on mushrooms in an efficient manner. This paper intends to fill this vacuum in the scientific knowledgebase and recommend an appropriate road map in carrying out pertinent research in the future.

INFORMATION ANALYSIS

Application of electrical stimuli in agriculture

Exposure of seeds, plants, soil, water or nutrients to strong electric fields, electric currents and magnetic techniques is known as electro-culture. Electro-culture techniques have been claimed beneficial to crops as it can protect the agro system from diseases, insects and frost; reduce the use of fertilizer or pesticides; grow better quality of crops; enhance growth rate; and also reduce the cost (Gandhare and Patwardhan 2014, Sharaf-Eldin *et al.,* 2015). Various types of electro-culture medium have been used so far, including antennas, static electricity, direct and alternating current, magnets, radio frequencies, sounds, electric wires, natural batteries, magnetically or electrically charged rock dust and paramagnetic rock dust (Artem, 2012). The experimental studies in this regard have been started extensively in the 80's, with the injection of low amplitude currents (Hart *et al.,* 1981) and changing of dielectric properties of seedlings (Hart 1983).

Existence of external electric charge could induce action potential that cause short term transient changes to the critical life processes of plant such as water uptake, respiration, photosynthesis and growth (Yan *et al.,* 2009). The action potentials will show no response if the electrical stimulus is below a threshold whereas it exhibits maximum response if the stimulus is in between certain threshold minima and maxima (Davies, 2004). Electrical charges also cause significant influx of calcium ion (Ca^{2+}), a crucial growth and development regulator in living systems including plants and fungi, across the plasma membrane (Lew, 2011). However, as per the basic observations, the response of the plants to the external stimuli depends on its amplitude, frequency, and intensity (Balasa *et al.,* 2011).

Biology of mushroom: The growth development

The kingdom of fungi is different from that of plants even though they are both eukaryotic; A plant cell is developed through splitting of a mother cell wall into two daughter cells whereas the development of fungi is through hyphae (the basic structure of fungi) that branches only at their apex and formation of cross walls which, only occurs at specific angles to the long axis of the hyphae (Moore *et al.,* 2011). Hence, the fungal morphogenesis depends on the position of hyphae branches (Chang and Hayes, 2013). The growth of polarized tip of mycelial fungi is related to their endogenous electric field and ion currents (positive) that flow through and around the fungal hyphae as a result of the polarized distribution of ion channels that pump within the plasma membrane (Rajnicek *et al.*, 1994). However, the position of emergence and growth direction of the branches is controlled by their reaction towards one or more tropisms (Moore *et al.*, 2011; Sanchez *et al.*, 2006). This process, the ability of a plant to direct the outgrowth of neuronal processes through the use of an extracellular electric field, is termed Neuronal Galvanotropism. This phenomenon has been subjected to scientific investigation for nearly a century and the outcomes show that the process could direct the formation of both axonic and dendritic processes in cell culture. However, exposure to exogenous electric field could affect the formation, growth polarity (direction), frequency of branching of the hyphae either towards anode or cathode (Moore, 2005). This reaction has been shown by a variety of fungi when their hyphae responded galvanotropically to exogenous electric fields. One of the fungal systems that have been reported to be influenced by exogenous electric fields is split gill mushroom (*Schizophyllum commune*) where its hyphae orient towards the anode (McGillivray and Gow, 1986).

It should be noted that mushroom is a group of spore-bearing or spore-less fungi that has the main attraction to people as food and medicine. Mushroom morphology and chemical composition are very complex and varies in a large spectrum (Sher *et al.*, 2010). The growth of mushrooms depends on the presence of several physical and chemical properties such as water-holding capacity, air, pH and osmotic potential (Pardo *et al.*, 2010). Mushroom also requires the right amount of moisture content, temperature and high cationic exchange capacity (Ibekwe *et al.*, 2008; Pardo *et al.*, 2010).

Growth of mushrooms and lightning

There are several claims by farmers that the growth of mushrooms is related with lightning as the occurrence of lightning within several tens of meters from mushroom plantation area has caused extraordinary growth enhancement to the mushrooms (Rumack and Spoerke, 1994; Tsukamoto *et al.*, 2005). As per the educated guesses made by the researchers, the electrical stimulation by the charge and current from lightning on mushroom hyphae accelerate the mushroom development through two possible ways (Tsukamoto *et al.*, 2005): 1) generation of more cracks in mycelium hyphae as the mushroom fruit bodies are generated from the crack and; 2) activation of mushroom enzymes by the electrical stimulation.

Lightning, a flow of transient current from cloud level, brings few tens of Coulombs of charge into ground during the total event. In the phases of return strokes, the main charge transfer processes, impulse currents which approximately follow double exponential wave profiles, flow from cloud to ground. Figure-2 shows a first negative stroke, computed by the current model proposed in Heidler (1985), which is known as Heidler function now. Although lightning impulse currents have somewhat large range of parameters, based on both the randomness and the types of lightning currents (negative first stroke, negative subsequent stroke and positive stroke), the typical range of values could be several tens of kilo amperes of amplitudes and several tens of microseconds of time duration (IEC 62305-1 2010, Rakov and Rachidi, 2009).

The impulse current is most often followed by a relatively small slow varying current, which is termed the continuing current. These continuing currents have magnitudes in the order of few hundred amperes and may be as short as few milliseconds to as long as few hundred milliseconds (Rakov and Rachidi 2009). During the injection of lightning currents to objects at ground level, based on the impedance of the current path large potential gradients may develop along the object. Similar potential gradients may occur along the ground paths where the lightning currents flow before the charge is neutralize. These potential gradients may reach even few Mega Volts per meter (MV/m) along the path of lightning current flow. Apart from the potential rise along the current path, the electromagnetic interaction between the lightning channel and metal parts in the proximity may generate induced voltages as high as many hundred kilo Volts (kV) (Rakov and Rachidi, 2009). These high electric fields and potentials may be the cause

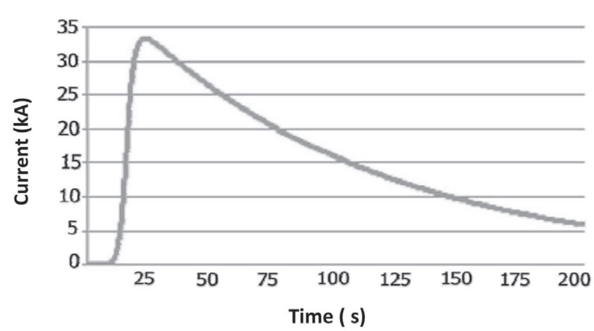

Fig. 2. A typical lightning current waveform that represents the negative first stroke, computed according to the Heidler current function

of mushroom rapidly producing more cells as a way of protection against danger from being harmed or destroyed by the inrush of electric energy (Ryall, 2010). It should also be noted that a lightning strike, too close to the mushroom bed could completely destroy the entire system due to the extremely high temperature rise and the shockwave. Lightning channel is known to raise to temperatures in the order of 30,000 C for a very short period. The high current, potential gradient, arcing, heating effect, shockwave and the intense light emission affect both human beings and animals (Gomes, 2012).

Growth stimulation of mushroom by pulsed electric means

Several researchers have applied electricity at high voltage levels to stimulate the growth of several types of mushrooms as it has been reported in the literature (Tsukamoto *et al.*, 2003; Islam and Ohga, 2012). They have employed pulse power technology as it provides impulse type electrical signals that approximately resemble lightning transients, at high voltage levels and short period of time (both voltage or current impulses). Application of these controlled high voltage impulses to the cultivation system of several crops like tomatoes, lettuce, strawberries, and various flowers has improved the yield (Takaki *et al.*, 2014). Repeated exposure of plant with short pulses (microsecond to millisecond) at high voltage has resulted membrane permealization (Balasa et al. 2011). Permealization of the cell membrane at a certain stage, together with electrophoretic movement of charged species between cellular compartments may cause lethal damage or induction of sub-lethal stress. Induction of sub-lethal stress is very useful for metabolic stimulation. However, suitable conditions have to be considered including pulse shape and polarity, number, width and inter-pulse time in order to obtain effective response (Galindo, 2008). High voltage electrical impulses are known to cause alteration in the electrical properties of plants that affect plant growth, yield and some traits quality (Takaki *et al.* 2014). Yi *et al.* (2012) reported that steady state electric pulses at 4 V to 10 V volts, which has been applied on cultured soil, has given rise to better response on the growth of lettuce and hot pepper plants compared to the observations at 2 V electric field pulses. According to the results and inferences, the electrical pulses have activated geochemical cycle and phosphate solubilisation in the soils that indirectly promotes plant growth. Eing *et al.* (2009) has revealed that exposure of *Arabidopsis thaliana* (an edible flowering plant) to 5 MV/m (or 50 kV/cm) electric field pulses has caused the seedling being destroyed completely when the plant was treated for 100 nanoseconds (ns) which was claimed as due to the electroporation of the plasma membrane of the plant cells. This shows that when the electric field strength in the vicinity is very high (even in the absence of injected current), the possibility of destruction of the plant is much more probable than any positive effect. This destruction may be a result of arcing into the plant bed, as the probability of air-insulation breakdown is very high for electric fields above 3 MV/m, even if the electrodes are plane-plane. It should also be noted that, the electroporation at higher energy and longer pulses causes the stimulating effect to be dominated by necrosis.

In contrast to the above observations related to plants, fungi have demonstrated different responses and behaviours to electric stimulation. At the right amount of electric energy, the yield of mushrooms has been increased by even 100%. This has been demonstrated when Marx-IES pulsed power generator at voltages of 50 kV to 130 kV with a pulse width of 100 ns (square voltage pulse) were applied to logs of mushroom spores of nameko variety (*Pholiota nameko*) and shiitake variety (*Lentinula edodes*). Application of single pulse of 50 kV and 100 kV has increased the yield of nameko mushroom by 1.7 times compared to the control. The total weight of shiitake fruit body has been doubled compared to the control at single pulsed stimulation of a 50 kV or 100 kV voltage impulses. However, the yield was decreased by about 25% with the treatment of 100 kV to 130 kV. Increment of number of pulses from one time to fifty times at a voltage of 50 kV has further doubled the yield of shiitake mushroom (Takaki *et al.*, 2010, Takaki *et al.*, 2014). The same effect of high voltage pulses on shiitake mushroom has also been reported in another study where application of one time pulse of 90 kV on logs of shiitake spore has increased the weight of the mushroom fruit body.

Application of 90 kV pulsed high voltages on natural logs of shiitake hyphae at different treatment frequencies have found that the spreading ratio was slightly increased (55.9%) compared to that of the control where the spreading ratio of 53.9%, after one time treatment. The ratio remained the same (about 55%) after two time treatment. The spreading ratio of the hyphae was further increased (to 61.2%) after the treatment for three times. Further investigations confirmed that the growth rate of shiitake hyphae could further be increased with higher treatment frequencies (Tsukamoto *et al.*, 2003).

One time pulsed voltages at 50 kV by a generator termed Small Population Lightning Generator (SPLG) on matsutake mushroom (*Tricholoma matsutake*) has resulted in an increment of 67% to 69% of fresh weight and 65% to 113% of growth length (Islam and Ohga, 2012). The SPLG produces 0.5 Joules of energy that generates impulses similar in wave profile to that of lightning (Islam and Ohga 2012; Robbins, 2013). The stimulation has been applied along the ground (Islam and Ohga, 2012). There were some studies that used pulsed high voltage to increase mushroom yield by stimulation at mycelium stage in a sawdust block. The treatment was done on matured mycelium just before the fruiting stage (Ohga, 2012; Takaki *et al.*, 2009; Tsukamoto *et al.*, 2003).

Application of single-pulse at 100 kV on mycelium of fried chicken mushroom (*Lyophyllum decastes*) through a 3 mm diameter and 7 cm length of needle electrode at the centre of the sawdust block has resulted to the increment of 10% to 30% of the mushroom yield (Tsukamoto *et al.*, 2003; Takaki *et al.*, 2009). There were also notable increments on the yield of fruit body for some other edible mushrooms compared to the control such as *Pleurotus ostreatus* (88%), *Pleurotus abalonus* (80%), *Pleurotus eryngii* (64%), *Lentinula edodes* (64%), *Flammulina velutipes* (57%), *Hypsizygus marmoreus* (59%), *Agrocybe cylindracea* (45%), *Pholiota nameko* (25%) and *Grifola frondosa* (25%) (Ohga, 2012).

Electrical stimulation has been observed to cause acceleration on the synthesis of clump connection in fungi and activation of some enzymes such as laccase and protease in several other studies as well (Islam and Ohga, 2012; Takaki *et al.*, 2014). As per the conclusions of the respective researchers, the increment of chemical levels of fungi may contribute to the specific activation of cell division and that helped to increase the weight and height of fruit bodies of treated mushroom (Islam and Ohga, 2012).

Growth stimulation by other electric means

The available information, so far, depicts that the ability of mushroom to boost their growth is due to the presence of cracks on mushroom hyphae or due to the activation of enzyme activity during lightning strike. The limited information in the literature emphasizes that high voltage pulses are the only technique that could produce the same effects as lightning on mushrooms in stimulating the growth successfully. However, the absence of information on the application of electricity by other modes (eg. continuous or pulsed current injection into the growing media at low voltage values) should also be of concern. It is interesting to observe the response of mushrooms to various methods that have successfully been applied in plant growth/yield enhancement. Electric current injection is one of the electrical stimulation techniques that have been used by several researchers in their efforts to improve plant growth. The range of voltage that has been applied varies from several Volts to few kilo Volts in the form of direct current (DC) or alternate current (AC). Figure 3 shows some efforts in increasing the growth rate of mycelium in a petri dish by applying small magnitudes of DC and AC (in milli-ampere to few ampere scales) into the agar medium through two wire electrodes (unpublished data by Jamil *et al.*, 2016). The results are yet to be released.

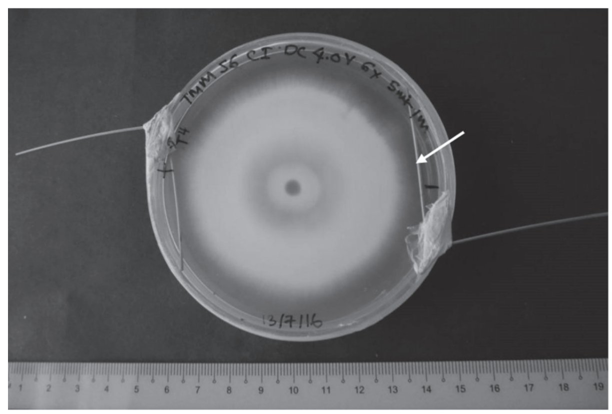

Fig. 3. Attempts to enhance the growth rate of mycelium by the application of small DC and AC into the growing medium (agar layer) through two stainless steel wire electrodes (Jamil *et al.* 2016).

Poole (2010) has found a growth increment up to 4.5% when 5 V DC voltage is applied for 7 minutes to bean sprout in water. Application of 1.5 V DC voltage for 40 days to sweet pepper seedlings has resulted in 35% increment of its stem length (Gabdrakhmanova and Qussiny, 2011). The effect of these steady voltage may be related to the activation of plant hormones that stimulates the seedling metabolism and also related to the increment of nutritional cation uptakes (Artem, 2012).

Another technique that has been used to stimulate plant growth was through uniform or sinusoidal alternating electric fields. Exposure of alternating electric field at 50 Hz on tomato seeds at 12 kV/cm for 15s exposure time has double its germination rate (Eing *et al.*, 2009). This information justifies the ability of external electrical stimulation to manipulate plant activities even at non-pulsed field variation.

Experiments on other plants with electric fields in the form of pulses reveal that it could also alter metabolism processes that lead to modification of cell activities (Balasa *et al.* 2011; Yi *et al.*, 2012). Low amplitude pulses may generate small pores of plasma membrane (1.5 nm in diameter) that reseal in a very short time (nanosecond). Larger pores (about 50 nm) are generated by stronger pulse electric field and will be resealed slowly or left permanently opened. This causes the reestablishment of vital functions of the cell (Balasa *et al.*, 2011). Opening of pores allow the efflux and influx of polar molecules. Resealing of the plasma membrane after treatment has results to several responses such as energy release from the movement of ionic species, hydrolysis of ATP to rebuild gradients of charges across cell membranes and other physiological events (Galindo, 2008). Therefore, electrical parameters through various techniques such as current injection, electric field and corona discharge for both short and long time exposures especially at low strength should also be considered to look for effective growth enhancement on mushroom. As low voltage is more viable than high voltage applications, the feasibility of upscaling the successful techniques to commercially producible level is also of concern to the industrial sector. This should also be an important point of concern in developing new methodologies for triggering mushrooms growth in the future.

DISCUSSION

The nature of applied electrical energy

It is evident that the observation of the rapid enhancement of mushroom growth following a lightning strike in the vicinity or a thunderstorm in the area has prompted the researchers to select the wave profile of the applied electric stimulation. The pulsed power signals could be treated as transients that approximately resembles the lightning impulse. It should be noted that lightning is a current generator (an electrical generator which produces a current of which the parameters remain the same irrespective of the impedance of the path through which it flows), which produces voltage waveform along the object that it flows based on the electrical properties of the object (known as the load). For good conductors, such as copper tapes, the resistance (*R*) along the current path may be as low as $10^{-4}\Omega$/m whereas for bad conductors such as dry wood, the value may be as high as $10^{6}\Omega$/m. Note that the actual value of resistance of an object depends on its resistivity and dimensions. The voltage waveform also depends on the self-inductance (*L*) of the path which is in the order of 10^{-6} H/m for a copper tape of typical cross-section. The value of inductance does not vary much based on the materials.

As the lightning current flows down an object of height *h*, the potential (*V*) along the object is given by the following equation.

$$V = R\,h\,i(t) + Lh\,\frac{di(t)}{dt}$$

where $i(t)$ is the time dependent lightning current and $di(t)/dt$ is the time derivative of the current. If the lightning current enters a good conductor the first part in the right hand side becomes negligible and the second part with current derivative dominates. Thus for one meter of the object the voltage (voltage gradient) becomes about 50 kV/m (or 0.5 kV/cm) with typical value of lightning current derivative for first negative stroke. For a very poor conductor the first term in the right-hand side dominates giving rise to voltage gradients in the order of 50 GV/m (500 kV/cm). Therefore for a wet log or moist soil/saw dust, which is poor but not very bad conductor, an electric field in the order of 5 - 50 kV/cm is quite representative of the lightning environment, considered that only a partial lightning current flows into the mushroom bed. For a log or sawdust bag of length 10 cm, this electric field represents a voltage of 50 – 500 kV. However, considered the breakdown voltage of air, 30 kV/cm or 300 kV for a 10 cm distance the 100 kV threshold or 10 kV/cm is a viable voltage or voltage gradient respectively to be applied to any plant/mushroom bedding system to ensure no arcing in the vicinity.

The impulse voltage width of nano-second range, commonly adopted in most of the studies, is a total deviation from the characteristics of lightning impulse voltage. Figure 4*a* shows the voltage gradient calculated for a wet log of length 1 m (with resistance of 10Ω) applied with the current waveform depicted in Figure 1. It could be seen that the time duration of voltage in this case is in the order of few hundred microseconds (half width approximately 100 μs). Even for an object of quite low resistance, say 0.01Ω, the voltage waveform will last for over 20 μs (neglecting the low voltage tail) with half value width about 8-10 μs (Figure 4*b*). For objects with larger values of resistance the voltage waveform follows the profile of the current waveform as the '*R h i(t)*' term becomes significantly dominant over '*L h {di(t)/dt}*' term. Therefore, if the researchers plan to follow the lightning impact on the growth enhancement of mushroom, it is suggested that they follow the above waveforms. However, it is reasonable to assume that the energy content of the applied waveform should be much less than that of the total-current-generated voltage, as only a fraction of the lightning current may enter a log of mushroom nearby. The fractioning of the energy content of the lightning impulse could be achieved in two ways. The first is to reduce the impulse amplitude and the second is to shrink the time duration. By considering nano-second range time scale for impulse duration, the scientists have adopted the second option so far. One may suggest that the first option is more realistic as plant metabolism processes take place in the time scales much larger than nano-second scale, thus micro-second scale impulses may be more effective. The following equation may be used to scale down a nano-second scale square impulse of voltage *V0* to microsecond scale square impulse of voltage *V1* with same energy dissipated in an object of same resistance value.

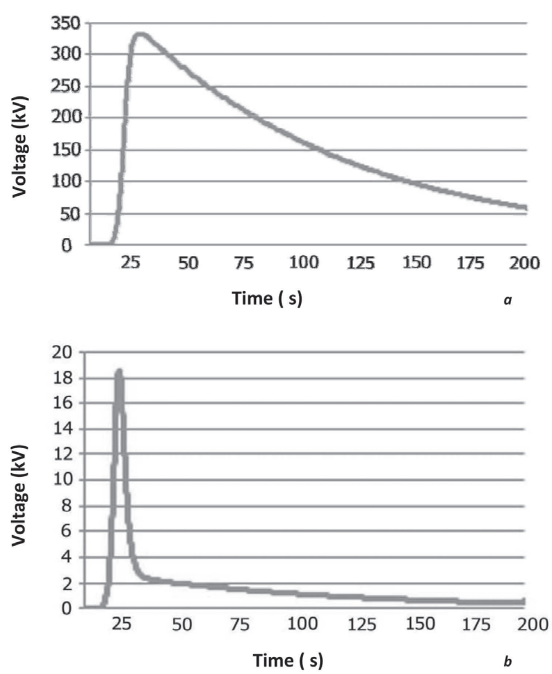

Fig. 4. *a.* Time dependent voltage generated during the passage of lightning current waveform given in Figure-2, along a wooden log of resistivity 10 (a wet wood). *b.* The same simulation for a log of wood having resistivity 0.01 (a hypothetical material)

$$V_1 = V_0 \sqrt{\frac{T_0}{T_1}}$$

Where *T0* and *T1* are the time durations of nano-second scale and micro-second scale square waveforms respectively. For an example, an impulse of 50 kV magnitude and 10 ns duration becomes a waveform of magnitude approximately 0.8 kV at 40 μs.

If it is required to calculate *V1* in such a way that the energy of the square waveform at micro-second scale is a fraction of the energy of the lightning impulse, then the following equation could be applied.

$$V_1 = \sqrt{\frac{F\int_0^{\tau} V^2(t)\,dt}{T_1}}$$

Where τ is the time duration of the lightning impulse and *F* is the fraction of the lightning current assumed to be entering the mushroom bed. Typically, *F* could be taken as 0.01. Figure-5 shows the square waveform of width 40 μs having 1% of the energy dissipated in the same resistor by the voltage waveform given in Figure 4*a*.

Effects of injected voltage impulse

Several biological effects of the applied impulse that may enhance plant growth has been discussed in the previous sections. As the current due to the applied voltage pulses grow along the growing media rather than through the plants itself, it is reasonable to expect that the changes observed in plant

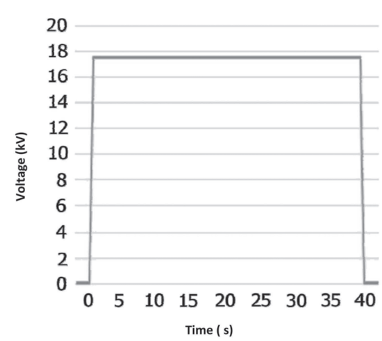

Fig. 5. A square voltage waveform that generates the same energy per resistance as that is generated by the waveform given in Figure-4*a*.

morphology may be caused by the strong transient electric field generated in the vicinity of the current path. Figure 6 shows a simulation done in ANSYS-Maxwell software which shows the electric field distribution along a long of wood as the current waveform given in Figure-1 is applied axially into it. The height, diameter, resistivity and relative permittivity of the log has been considered as 1 m, 0.1 m, 100 & Ωm and 2 respectively. It can be seen that the electric field strength on the surface reaches to about 360 kV/m during the passage of impulse current. The effects of such high electric fields on the plant or mushroom morphology has not been studied in details yet.

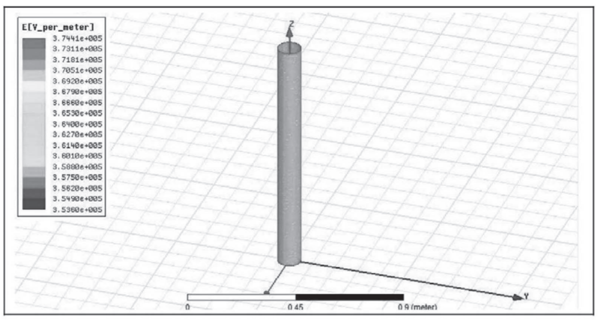

Fig. 6. The electric field distribution as the lightning current (given in Figure-2) enters a log of wood of resistivity 100 & Ωm

Other effects of lightning that may influence the growth enhancement

Although the popularly observed growth enhancement of mushroom due to lightning (note that still there are no published scientifically proven evidence for such) is attributed to the electric fields/potentials generated by the lightning current, one should not overlook other possibilities as well. The most prominent such lightning caused effects are the ionization of the growing medium, NOx generation, emission of ultraviolet radiation and corona emission.

Ionization of the growing medium: Usually the growing medium of mushroom is soil, clay or wood. The passage of large transient current through this medium changes the chemical and electrical properties of this medium due to thermal ionization (Ala *et al.*, 2009; Burhanuddin *et al.*, 2016, Gonos and Stathopulos 2004). Sometimes, the medium may even form fulgurites or fulgurite like material which has totally different physical structure to the original material (Burhanuddin *et al.*, 2016). The new material formed may provide better growing media and nutrients for the mushroom to grow faster. A detailed study on the composition of ionised medium needs to be conducted to fully understand the effects of ionization on the mushroom growth.

NOx generation: The generation of large amount of thermal energy during the passage of the lightning current triggers many chemical reactions out of which the fixation of atmospheric nitrogen plays an important role.

During the return stroke and continuing current phases of the lightning, thermal dissociation of carbon dioxide occurs leading to the formation of atomic oxygen and carbon monoxide.

$CO_2 \rightarrow O + CO$

In the presence of a third body M some of these oxygen atoms recombines to form molecular oxygen

$O + O + M \rightarrow O_2 + M$

Some oxygen atoms, at high temperatures (typically above 1500 C) associates with molecular nitrogen to form NO. The production of NO enhances in the presence of CO_2.

$O + N_2 \rightarrow NO + N$

$N + CO_2 \rightarrow NO + CO_2$

In the presence of atmospheric ozone, NO is converted to NO_2

$NO + O_3 \rightarrow NO + O$

A fraction of this NO_2 dissociates into NO by releasing energy.

$NO_2 \rightarrow NO + CO_2$

In the presence of a third body, a part of NO_2 associates with OH to form nitric acid which dissolves in rain water and reach ground.

$NO_2 + OH + M \rightarrow HNO_3 + M$

(The above equations have been adopted from Mvondo *et al.*, 2001 and Drapcho *et al.*, 1983). This HNO3 provides the required nitrogen based nutrients for plants. It is of interest to investigate quantitatively, the correlation between the amount of NOx received by a bed of mushrooms due to a nearby lightning and the growth rate enhancement of the relevant bed. If the distance and the current parameters of the lightning strike could be obtained (by interferometric techniques or by a sensitive and accurate lightning detection system), an empirical formula could be developed to relate the lightning charge, distance and growth rate.

In addition to NOx, the presence of Ozone, a product emitted during the lightning process as per the reactions given above may affect the biochemistry of plants. Ozone may penetrate the leaves of trees in the proximity through stomata during normal gas exchange. Being a strong oxidant, ozone may give rise to several plant anomalies such as chlorosis and necrosis (Felzer *et al.*, 2007; Krupa *et al.* 2001; Matyssek *et al.*, 2008). Additionally, there may be other plant health issues as well such as flecks, stipples, bronzing, and reddening of the leaves which deteriorate the metabolism of the cells (Ainsworth *et al.*, 2008; Booker *et al.*, 2009). Similar to the case of NOx, in this regard too, no research has been done so far to find the effects of O_3 on the growth rate of mushroom, although such studies are numerous with respect to plants and other living organisms.

Emission of ultraviolet radiation: In the chemical reactions taking place in the lightning current channel, energy is released most often in the form of electromagnetic radiation. For an example in the reaction where NO_2 dissociates into NO and O_2, energy is released with wavelength less than 420 nm. This is the violet and UV-A range. As per the extremely high temperatures (about 30,000 C) that has been observed in the lightning channel during the return stroke phase, even UV-B and UV-C radiation (with smaller wavelengths) is also emitted into the space. It has been shown that high levels of UV radiation (especially UV- (B) threatens the well-being of plants as the radiation is capable of damaging DNA, proteins, lipids and membranes (Frohnmeyer and Staiger 2003, Hollósy 2002, Stapleton, 1992; Zuk-Golaszewska *et al.*, 2003). Thus, the threat of extinction may prompt the plants to enhance the growth rate and reproduction. Interestingly, no research has been done to investigate the effects of abnormally high exposure of mushrooms to UV light (at least UV-A). Such study could bring vital information on the growth enhancement of mushrooms by non-electrical and non-chemical means.

Corona Emission: The emission of charged fluid particles (gases or liquids) from sharp points in the presence of a high electric field is termed corona. The presence of both the overhead thunder cloud and the nearby lightning strikes may give rise to partial discharges in various objects including the tips and edges of plants, which produce corona. For a long time this corona produced is known to the scientific community as an effective chemical catalyst (McMahon, 1968). The corona plays this role by generating numerous free radicals that mediate chemical reactions. Out of many chemical changes that corona may make, only the effects of ozone produced by corona on the plants have been studied so far. Thus, it is another area that needs to be payed attention with regard to both plants, in general and mushroom.

Economic viability of growth enhancement due to electric stimulation

A new technology or techno-methodology may give rise to high yield in production output at laboratory level. However, it could be treated as a successful commercial outcome only if the set up could adopted feasibly at mass production level. The analysis of the methods adopted by many researchers in increasing the yield of mushrooms raises doubts on the practicality of equipment and conditions needed for the observed output enhancement, at mass production level. A custom made impulse generator of nanosecond width pulse trains needs high voltage supply and the operation should be done in an EMI-free environment. Such equipment may cost nearly USD 100,000 at current rates in the market, which will be prohibitively high capital investment for the farmer. The limitation of the number of mushroom beds that can be treated in parallel by such equipment is another constraint that is added on the issue. The equipment also need operators specifically trained for the purpose. All workers in the farm and outsiders who may visit the premises should be given strict advises on safety requirements. The mechanical and electrical safety of the equipment, which should continuously be operated in the field is another concern.

Application of a small DC or AC signal to the growing medium may be more practical, if such method shows reasonable productivity enhancement. Through a mesh network of electrical connection, a medium size power supply could provide current injection to a large number of mushroom beds without raising any significant safety issue. However, such technique is not yet proven to be successful in enhancing the growth or fruiting notably.

It is of interest to check the response of different stages of mushroom to nearly uniform electric fields such as that due to charged cloud overhead. If corona generation has any positive impact on the growth rate enhancement or increase in yield of mushroom, a uniform electric field would provide successful results. Such nearly uniform fields could be produced by a Van der Graaf generator with large dome. In contrast to other high voltage generators Van der Graaf generators provide less lethal static electricity. As the generator and plant bed does not need resistive coupling, a single generator could provide required electric field environment for many plant beds. In such environment, passive corona generators could be implemented by placing spikes or multi spike metal components close to the plant beds while the Van der Graaf generator is in operation. This concept is pictorially represented in Fig. 7.

It will not be that profitable to apply sophisticated electrical stimulation techniques to enhance the growth rate or yield of common type mushroom which has low cost per unit mass in the market. Thus, it is advisable to concentrate the research copes in this regard to more expensive mushroom varieties with decent demand at the high end of the potential customer base. In this respect, a survey that has been done in the Malaysian market recently revealed that instead of focusing on for-food mushroom, investigating on varieties which have medicinal value, such as tiger's milk mushroom, could bring much higher returns on investment (Jamil *et al.*, 2015; Lai *et al.*, 2013). In the case of edible mushrooms too, it would be more advantageous to research on the growth enhancement of varieties that have high demand as exotic cuisine; matsutake, blue foot, golden chanterelle, nameko, maitake etc.

Another important aspect of artificial electric stimulation of mushroom that has been overlooked so far is the impacts of environmental adaptation of the species on its response to the proposed method. Mushroom may positively respond to the electric stimulation under well controlled environmental conditions inside a laboratory, however, once the method is applied to the same species grown under exposed atmospheric conditions, the response may be different. Recent research has revealed that many plants adapt themselves to the varying climate conditions either in short term or in long term, thus their reactions to even soil nutrients may be changed (Hall *et al.*, 2016; Lange *et al.*, 2016; Rossi 2015). This is an important factor to be investigated before investing on the proposed methods for production enhancement of mushroom.

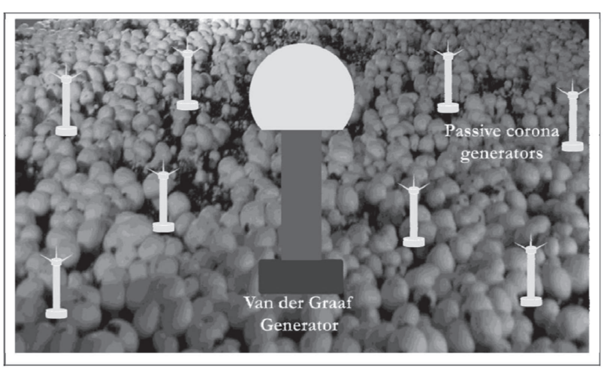

Fig. 7. The concept of applying nearly uniform static electric field to a mushroom bed with passive corona generators placed around.

CONCLUSION

Short exposure time with low amplitude current injection, electric field and pulsed electric field have successfully enhanced the growth rate and yield of many plants such as tomato, strawberry, lettuce and flowers. For mushroom however, the improvements so far were only due to high voltage electric pulses that have been applied to the growing medium at different stages of mushroom development. This high voltage technique has been adopted following the observations done by farmers on the growth enhancement of mushrooms during thunderstorms. However, further investigations are required to determine the quantitative response of mushrooms on several available electrical stimulation techniques, especially at lower voltage levels, where commercial scale application is feasible.

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