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RF and Microwave Low Power Dielectric Heating Using Parallel Plate Applicator to Control Insect Pests on Tomato Plant

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Abstract—This paper focuses on electromagnetic exposure to control insect pests in agriculture using parallel plate applicator. A tomato plant and "*Helicoverpa armigera*" eggs and larvae are exposed to 915 MHz and 2450 MHz. A parallel plate applicator is fabricated and matched with Radio Frequency and Microwave source at 50 Ω. The power up to 250 W was applied to parallel plate applicator in an anechoic chamber to observe the behavior and heating effect on commodities inside the applicator. The rise in temperature of the tomato plant and tomato with insect pest stages were different for different dielectric properties. The reduction in the hatching was observed after the exposure. The first instar to fifth instar larvae erratic movement was observed during exposure. The faster response of heating was observed at the higher side of exposed power. The effect on the heating rate considering the variations in the space between two parallel plates of the applicator is analyzed in this research. The parallel plate capacitor is referred to as an applicator in this paper.

1. INTRODUCTION

The innovations and developments in the field of agriculture play a vital role in the economical growth of many countries. The Integrated Pest Management (IPM) is required due to lots of variety in the food products and their pests. One of the new ways of doing the insect control is Radio Frequency (RF) and Microwave frequency (MW) irradiations [1]. The non-ionized radiation of RF and MW is used for post-harvest product and grains at very high power [2]. The dielectric heating to control insect pests in agriculture with IPM technology will help to minimize the use of chemical fumigations and residues in food products. This research aims to present a novel approach that exploits the RF and MW technology to control insect pests during the growth of a plant.

Electromagnetic energy is a very powerful tool in the agricultural field provided that it is used correctly. RF and MW exposure can be used for disinfestations of insect pests such as "Helicoverpa armigera" in agriculture. Biological materials absorb the electromagnetic energy, and its interaction depends on the dielectric properties of the material. The alteration in signal strength was observed with a body shadow effect in motion conditions and indoor enclosures at the Wi-Fi frequency of 2.45 GHz [3]. The human body was exposed to RF electromagnetic field, and an electric field was measured using personal exposimeter. Different exposure models reveal that human body has a significant influence on the results of measurements in various locations near the body. Discrepancies in the results of measurements of exposimeter can be compensated by applying a correction factor to the measurement results or to the exposure limit values. The location of a single exposimeter on the waist to the back side of the human body or on the front of the chest reduces the range of exposure assessments uncertainty [4]. The electromagnetic radiation exposure limits defined by International Commission on Non-Ionized Radiation Protection (ICNIRP) for the occupational and general public exposure of time varying E-fields

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at the frequency range of 2 to 300 GHz are 137 V/m and 61 V/m, respectively. The basic restrictions on power density for frequencies between 2 and 300 GHz is 50 W/m^2 for occupational exposure and 10 W/m^2 for general public [5]. The dielectric properties of any material consist of two parts; Dielectric constant (ϵ') which is the ability of any biological tissue to store electromagnetic energy and dielectric loss factor (ϵ'') which shows the ability of any biological tissue for the conversion of electromagnetic energy into thermal energy when subjected to electromagnetic radiation. It is represented as:

$$\epsilon = \epsilon' - j\epsilon'' \tag{1}$$

where,

$$\epsilon'' = \epsilon''_d + \epsilon''_\sigma \tag{2}$$

where, ϵ''_d represents the contribution of dipole dispersion to a biological body's dielectric loss factor, and ϵ''_σ contributes ionic conduction to dielectric loss factor. The ϵ''_σ is determined as:

$$\epsilon''_\sigma = \frac{\sigma}{2\pi f \epsilon_0} \tag{3}$$

where σ is ionic conductivity of biological tissue (S/m), f the frequency of electromagnetic radiation in Hz and ϵ_0 the permittivity of free space. Permittivity, electrical conductivity, material density and specific heat are the required parameters to understand the effects of RF and MW energy on biological tissues [6–9]. The equations used to determine the change in temperature are as follows:

$$W = \frac{1}{2}\int \epsilon \mid E \mid^2 dv \tag{4}$$

where, W is in Joules (J), and E is the electric field intensity in V/m. The Specific Absorption Rate (SAR) is the rate at which electromagnetic radiation is absorbed by biological tissue and can be determined using Equation (5).

$$\text{SAR} = \frac{\sigma \mid E \mid^2}{\rho} \tag{5}$$

where σ is electric conductivity (S/m), ρ the material density (Kg/m^3) and SAR in W/Kg [8]. The change in temperature ΔT for the agro product is determined using Equation (6).

$$\frac{\Delta T}{\Delta t} = \frac{\text{SAR}}{C} \tag{6}$$

where, C is the specific heat of the material (J/Kg°C) and Δt the time duration in seconds. The increase in temperature of a material due to absorption of electromagnetic energy can be expressed as:

$$Q = \rho C \frac{\Delta T}{\Delta t} = 55.63 \times 10^{-12} f E^2 \epsilon'' \tag{7}$$

where, Q is the power density in W/m^3. The increase in temperature depends on the power, frequency, exposure time and dielectric loss factor. This equation considers heat conduction only in biological tissue and not in the surrounding environment. The simulation of the applicator and dielectric heating of material was carried out in COMSOL Multiphysics software [10–12]. The dielectric properties of a tomato plant, tomato and insect pests were measured using an open-ended coaxial probe with Agilent N5221A at SAMEER, Mumbai [13].

2. MATERIAL AND METHODS

The "*Helicoverpa armegra*" egg samples were collected from developed plant and Entomology Laboratory, Mahatma Phule Agriculture College, Pune, India [14]. The first instar to fifth instar larvae was collected from the field and kept in separate bottles as shown in Fig. 3. Rohini and Abhinav tomato plants were developed, and different stages of tomatoes were collected from the same plant for chemical analysis as shown in Fig. 1 & Fig. 2. The same developed tomato plant was used for electromagnetic exposure in an anechoic chamber. Four different stages of tomatoes and tomato plant leaves and stem were sent for chemical analysis before and after the electromagnetic exposure. The beta carotene and pH of tomato samples, as well as Chlorophyll and pH of the tomato plant leaves were

Figure 1. The developed Rohini tomato plant.

Figure 2. Different stages of Tomato samples for testing.

Figure 3. Helicoverpa 1st instar to 5th instar in separate bottles.

Figure 4. Thermocol container with tomatoes, plant leaves and ice bags.

considered as chemical analysis parameters [15, 16]. A thick thermocol container with ice bags is used to carry commodities to the test laboratory after electromagnetic exposure to maintain the temperature below 20°C as shown in Fig. 4. Ten egg samples, a tomato plant, four tomato samples and one sample of each larvae stage were placed inside the applicator during exposure. With the help of a thermal camera, the temperature of tomatoes and eggs were monitored. The movement of the first instar to the fifth instar was observed using closed circuit camera in the control room during exposure.

2.1. Applicator Design and Testing

The applicator is a copper parallel plate capacitor designed for 915 MHz and 2450 MHz at 50 Ω impedance with the design details as shown in Table 1. Equation (8) is used to calculate applicator parameters. The applicator with and without dielectric between two plates at various frequencies was simulated [17].

$$C = \frac{\epsilon A}{d} \tag{8}$$

where,

C = value of the capacitor

d = distance between the parallel plate capacitors
A = area (size) of the parallel plate capacitors
ϵ = permittivity

Table 1. Applicator parameters and dimensions.

Operating Frequency (F)	Distance between the plates (D)	Area of plate (A)	Capacitor at $X_c = 50\,\Omega$
915 MHz	16 cm	25 cm × 25 cm	3.54 pf
2450 MHz	10.21 cm	10 cm × 15 cm	1.3 pf

Figure 5. Testing setup of the applicator with VNA in the laboratory.

Figure 6. Applicators with different distance between plates at 915 MHz & 2450 MHz.

The applicator cold test was conducted with the help of Vector Network Analyzer (VNA) having specification 9 KHz to 13.5 GHz of R&S-ZVL model to measure Voltage Standing Wave Ratio (VSWR) and Return Loss (S_{11}) as shown in Fig. 5. The variation in applicator impedance due to plant and air dielectric inside the applicator was observed as 51 Ω and 42 Ω respectively. Before applying high power to the applicator, once again VSWR was verified with the power system of an anechoic chamber. The applicator was tested for 50 W to 250 W power in the anechoic chamber. To observe the effect of electromagnetic exposure on a tomato plant, tomato and insect pests with different stages were carried into an anechoic chamber. The temperature of an anechoic chamber and tomato sample were maintained at 25°C before electromagnetic exposure.

The complete setup was exposed to frequencies 915 MHz and 2450 MHz at power of 50 W to 250 W for 10 minutes in anechoic chamber. The gap of 20 minutes was maintained between two observations to avoid thermal runaway. The field intensity around the applicator was measured to understand the radiation pattern around the applicator using a field probe. The radiation patterns of an applicator at 915 MHz and 2450 MHz frequencies are shown in Fig. 9. The electric field around the applicator can be controlled with the help of proper shielding to the applicator so as to avoid the effect of radiation on a personnel handling the applicator. The simulation of the applicator with and without shielding is done in COMSOL Multiphysics and shown in Fig. 10. The internal field strength was measured to determine the heating rate of different dielectric material inside the applicator. The distance between two plates ($d = 30$ cm) of an applicator is designed to measure the large size plant as shown in Fig. 6.

3. RESULTS AND DISCUSSION

The results of VSWR measurement on VNA of an applicator are shown in Table 2. The complete test setup inside an anechoic chamber is shown in Fig. 7.

Table 2. Applicator response in terms of VSWR at different power levels and frequencies, when coupled with VNA and power source instruments.

<table>
<tr><th rowspan="2">Sr. No.</th><th rowspan="2">Power (Watts)</th><th colspan="2">High power source @ anechoic chamber</th><th colspan="2">On VNA @ 0 dBm power</th></tr>
<tr><th>VSWR at frequency 915 MHz</th><th>VSWR at frequency 2450 MHz</th><th>VSWR at frequency 915 MHz</th><th>VSWR at frequency 2450 MHz</th></tr>
<tr><td>01</td><td>50</td><td>1.87</td><td>1.37</td><td rowspan="5">1.67</td><td rowspan="5">1.22</td></tr>
<tr><td>02</td><td>100</td><td>1.87</td><td>1.37</td></tr>
<tr><td>03</td><td>150</td><td>1.87</td><td>1.37</td></tr>
<tr><td>04</td><td>200</td><td>1.87</td><td>1.57</td></tr>
<tr><td>05</td><td>250</td><td>1.87</td><td>1.54</td></tr>
</table>

Table 3. The electric field intensity with different power levels at 915 MHz & 2450 MHz frequencies inside and outside the applicator with $D = 16$ cm and 10.21 cm respectively.

Power (Watts)	Electric field intensity inside applicator V/m @ 915 MHz	Electric field intensity inside applicator V/m @ 2450 MHz	20 cm around applicator Electric field intensity (V/m) @ 915 MHz	20 cm around applicator Electric field intensity (V/m) @ 2450 MHz
50	185	135.88	18.30	10.10
100	233.20	182.91	65.59	55.40
150	272.12	230.00	100.00	88.00
200	310.00	283.41	140.23	126.07
250	349.40	314.00	159.00	138.60

Figure 7. Complete set up of dielectric heating in an anechoic chamber.

During exposure, it was observed that the heating rate of 915 MHz was faster than that of 2450 MHz. The heating of commodities inside the applicator was different due to different dielectric constants. Fig. 8 shows a variation in temperature of different commodities during electromagnetic exposure at 915 MHz and 2450 MHz. The differential heating was observed between the host plant and insect pests. The exposed power above 200 W was found effective for dielectric heating to control insect pests.

The erratic movement of the second instar to fifth instar larvae was observed during exposure above 200 W initially, and it behaved normally after 30 to 40 seconds. It was observed that the applied power was not sufficient for larvae mortality. In general, 90% eggs were hatched at 25°C within 3 days after

Table 4. The electric field intensity with different power levels at 915 MHz & 2450 MHz frequencies in and outside the applicator with $D = 30$ cm.

Power (Watts)	Electric field intensity inside applicator V/m @ 915 MHz	Electric field intensity inside applicator V/m @ 2450 MHz	20 cm around applicator Electric field intensity (V/m) @ 915 MHz	20 cm around applicator Electric field intensity (V/m) @ 2450 MHz
200	203.20	169.45	95.00	91.00
250	239.00	190.12	127.56	118.87

Table 5. The chemical analysis of tomato and leaves before and after the electromagnetic exposure.

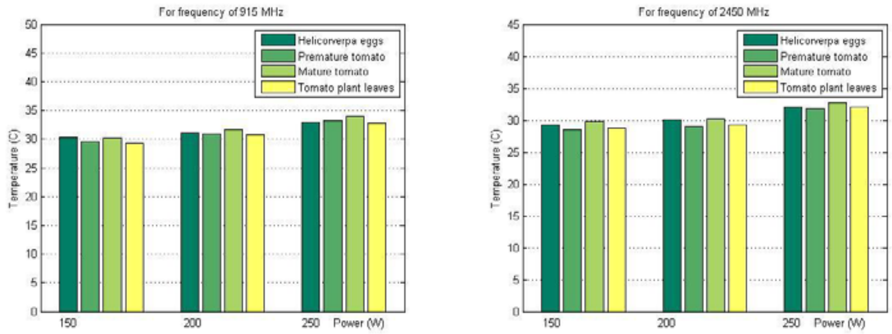
Item	Before electromagnetic exposure			After electromagnetic exposure		
	Beta-carotene (μg/100 g)	pH	Chlorophyll (μg/100 g)	Beta-carotene (μg/100 g)	pH	Chlorophyll (μg/100 g)
Tomato stage I (premature)	142.24	4.72	–	139.70	4.70	–
Tomato stage II (premature)	156.40	4.74	–	153.21	4.73	–
Tomato stage III (Mature)	135.47	4.92	–	133.96	4.86	–
Tomato stage IV (Mature)	145.21	5.15	–	141.30	4.95	–
Tomato leaves	–	5.76	4.70	–	5.6	5.76

Table 6. The final temperature of eggs and tomatoes at different power levels.

Power (Watts)	Initial temperature 25°C, Exposure duration 10 min.							
	Helicoverpa-eggs Temp. °C		Premature tomato Temp. °C		Mature tomato Temp. °C		Tomato plant Leaf Temp. °C	
	915 MHz	2450 MHz	915 MHz	2450 MHz	915 MHz	2450 MHz	915 MHz	2450 MHz
150	30.3	29.3	29.6	28.5	30.2	29.8	29.3	28.8
200	31.1	30.0	30.9	29.0	31.6	30.2	30.8	29.3
250	33.0	32.1	33.2	31.8	34.0	32.7	32.8	32.0

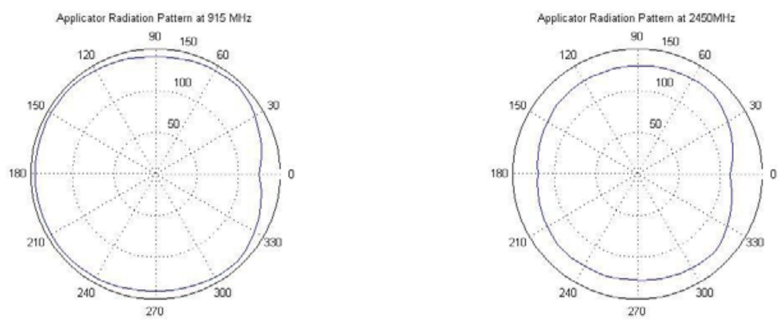
the eggs were laid on a leaf [18–23]. 90% of eggs were hatched at 200 W and 76% eggs hatched at 250 W after the exposure. The early hatching was also observed for 30% of eggs exposed to the power of 250 W. The further life cycle analysis of hatched larvae did not experimented. It was observed that the open sides of the applicator are responsible for undesired dissipation of the heat in the surrounding. Relatively longer time was therefore taken to increase the temperature of the commodities placed in the applicator. To stop the heat transfer into the surrounding, 5 mm acrylic sheet was placed in the open portion of an applicator during exposure. Table 3 shows the field intensities inside and outside of the applicator. The simulation of the applicator with shield shows that very little power is present beyond the shielding, and it is possible to keep the power density below the range defined by ICNIRP. A larger gap between the applicator plates was not very effective for dielectric heating as it produced low field intensity as shown in Table 4. A compact and high power source up to 1000 W is required to interface with the parallel plate applicator for further testing and actual use.

The beta-carotene analysis is done by spectrophotometer in the test laboratory. It was observed that after dielectric heating, beta-carotene was not reduced much as shown in Table 5. The reduction in beta-carotene and Chlorophyll was observed at high temperature [24, 25], but it was negligible here



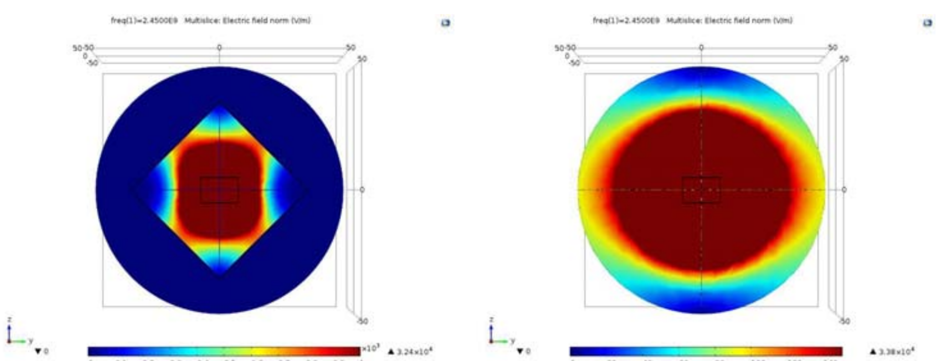
(a) (b)

Figure 8. Change in temperature at different power for different commodities inside applicator at (a) 915 MHz and (b) 2450 MHz.



(a) (b)

Figure 9. The radiation patterns of an applicator at (a) 915 MHz and (b) 2450 MHz.



(a) (b)

Figure 10. E field with (a) and without (b) shield protection simulated in COMSOL multiphysics.

after the heat treatment of 10 minutes. The pH measurement of tomatoes and leaves was done using a pH meter. According to the Center for Food Safety and Applied Nutrition at the U.S. Food and Drug Administration, fresh tomatoes fall into the 4.3–4.9 range when it comes to acidity. A more mature and ripen tomato was on the lower side of the acidic range. The experimentation result in Table 6 shows the temperature rise of 5°C to 14°C in different commodities after electromagnetic exposure at different powers. The temperature rising up to 35°C to 42°C does not affect the nutrients of tomatoes for short time exposure, but it will change yield and nutrients at this temperature for a long duration [24, 26, 27]. Fig. 8 shows the change in temperature above the reference temperature of 25°C at different powers as well as different temperatures of commodities at the frequencies of 915 MHz and 2450 MHz.

4. CONCLUSION

The designed copper parallel plate applicator was successfully tested at the frequencies of 915 MHz & 2450 MHz with power source of 50 Ω impedance up to 250 W. A larger distance between applicator plates is not suitable for fast heating; however, high power may be helpful. The conducted experimentation shows negligible change in chemical parameters of tomato and leaves at this power level after and before the electromagnetic exposure. The effect of electromagnetic exposure on eggs and first instar was noticeable, but no mortality was observed in other larvae stages. 14% reduction in hatching and early hatching was observed after short time exposure, which disturbs the insect pests life cycle. To achieve the faster heating of eggs and larvae mortality, the power of 250 W is not enough. More than 250 W power source is needed in the analysis of controlling the insect pests on a tomato plant. This technique can work effectively in agriculture with IPM to control insect pests.

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REFERENCES

1. Stuart, O. N. and E. L. Stetson, "RF and MW energy for potential agriculture applications," *J. Microwave Power*, 65–70, 1985.
2. Nelson, S. O. M., "Review and assessment of radio-frequency and microwave energy for stored-grain insect control," *Transaction of the ASAE*, Vol. 39, No. 4, 1475–1484, 1996.
3. De Miguel Bilbao, S., J. Garca, V. Ramos, and J. Blas, "Assessment of human body influence on exposure measurements of electric field in indoor enclosures," *Bioelectromagnetics*, Vol. 36, No. 2, 118–132, 2015.
4. Gryz, K., P. ZradziNski, and J. Karpowicz, "The role of the location of personal exposimeters on the human body in their use for assessing exposure to the electromagnetic field in the radiofrequency range 982450 MHz and compliance analysis: Evaluation by virtual measurements," *Bio. Med. Research International*, Vol. 2015, Article ID 272460, 2015.
5. "Guidelines for limiting exposure to time-varying electric, magnetic and electromagnetic fields (up to 300 GHz) ICNIRP guidelines," *Health Physics*, Vol. 74, No. 4, 494–522, April 1998.
6. Wang, T. J., et al., "Dielectric properties of fruits and insect pests as related to radio frequency and microwave treatments," *Biosystems Engineering*, Vol. 85, No. 2, 201–212, 2003.
7. Wang, T. J., "Radio frequency and microwave alternative treatments for insect control in nuts: A review," *J. Agriculture Engg.*, Vol. 34, No. 10, 105–120, 2001.
8. Nelson, S., "Potential insect-control applications for microwaves," *USDA-ARS Paper*, 245, 1973.
9. Nelson, S. O. M., "Dielectric properties of agricultural products and some applications," *Res. Agr. Eng.*, Vol. 54, No. 2, 104–112, 2008.
10. Nelson, S. O. M., "Title of the journal paper," *Journal Title Abbreviation*, Vol. 34, No. 10, 1064–1076, 2013.
11. Pryor, R. W., "Modeling dielectric heating: A first principles approach," *COMSOL Conference 2015*, Vol. 34, No. 10, 1064–1076, 2013.
12. Yang, D., M. Converse, et al., "Expanding the Bioheat equation to include tissue internal water evaporation during heating," *IEEE Transactions on Biomedical Engineering*, Vol. 54, No. 8, 1382–1388, 2007.

13. Gaikwad, S. V., A. N. Gaikwad, et al., "Low power microwave heating to control insect pests on tomato plants," *International Microwave Power Institute (IMPI) 48th Symposium*, 1064–1076, 2014.
14. Puneeth, P. and V. A. Vijayan, "Parasitization capacity of trichogramma chilonis ishii (Hymenoptera: Trichogrammatidac) on the eggs of helicoverpa armigera (Lepidoptera: Noctuidae) under laboratory conditions," *International Journal of Science and Nature*, Vol. 5, No. 3, 462–465, 2014.
15. Lincoln, R. E. and J. W. Porter, "Inheritance of Beta-carotene in tomatoes," *Genetics*, Vol. 35, No. 2, 206–211, 1950.
16. Peng, J., J. Tang, et al., "Dielectric properties of tomatoes assisting in the development of microwave pasteurization and sterilization processes," *LWT-Food Science and Technology*, Vol. 54, No. 2, 367–376, 2013.
17. Gaikwad, S. V., A. N. Gaikwad, et al., "Simulation modeling and implementation of RF and MW system to control the insect pests in agriculture," *2015 Annual IEEE India Conference (INDICON)*, 1–4, 2015.
18. Perovic, D. J., M. Johnson, et al., "The mortality of Helicoverpa armigera (Hübner) (Lepidoptera: Noctuidae) neonate larvae in relation to drop-off and soil surface temperature: the dangers of bungy jumping," *Australian Journal of Entomology*, Vol. 47, No. 4, 289–296, 2008.
19. Dhillon, M. K. and H. C. Sharma, "Influence of temperature and Helicoverpa armigera food on survival and development of the parasitoid, Champoletis chlorideae," *Indian Journal of Plant Protection*, Vol. 36, No. 2, 240–244, 2008.
20. Nelson, S. O. M., "The effect of ambient temperature on the development of cotton bollworm (Helicoverpa armigera)," *Plant Protect. Science*, Vol. 42, No. 4, 135–138, 2013.
21. Dhillon, M. K. and H. C. Sharma, "Effect of storage temperature and duration on viability of eggs of Helicoverpa armigera Lepidoptera: Noctuidae," *Bulletin of Entomological Research*, Vol. 97, No. 1, 55–59, 2007.
22. Kumar, S., R. K. Saini, et al., "Natural mortality of Helicoverpa armigera (Hbner) eggs in the cotton ecosystem," *Journal of Agricultural Science and Technology*, Vol. 11, 17–25, 2010.
23. McDonald, R. E. and T. G. McCollum, "Heat treatment of mature-green tomatoes: Differential effect of ethylene and partial ripening," *Journal of the American Society for Horticultural Science*, Vol. 123, No. 3, 457–462, 1998.
24. Abdelmageeda, A. H., N. Grudab, et al., "Effect of high temperature and heat shock on tomato (Lycopersicon esculentum Mill.) genotypes under controlled conditions," *Conference on International Agricultural Research for Development*, Vol. 34, No. 10, 1064–1076, 2003.
25. Mark, R. and S. Church, "Nutrient analysis of fruit and vegetables," *Analytical Report*, Vol. 34, No. 10, 1064–1076, UK, 2013.
26. Ploeg, V. and E. Heuvelink, "Influence of sub-optimal temperature on tomato growth and yield: A review," *Journal of Horticultural Science & Biotechnology*, Vol. 80, No. 6, 652–659, 2005.
27. Adams, S. R., K. E. Cockshull, et al., "Effect of temperature on the growth and development of tomato fruits," *Annals of Botany*, Vol. 88, 869–877, 2001.