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Development of Electrostatic Spray Coating Machine for Edible Coating of Fruits

K. N. HANUMANTHARAJU*, K. THANGAVEL[1], D. S. POORNIMA[2], S. GANAPATHY[1] AND D. MANOHAR JESUDAS[1]

Department of Food Technology, Ramaiah University of Applied Sciences, Bangalore-560 054 (Karnataka), India
**(e-mail : rajuknhgowda@gmail.com; Mobile : 97406 03639)*

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ABSTRACT

Edible coating is in a form of thin layer on the fruit surface, which delays the senescence of fruit materials by forming semi-permeable barrier for permeation of gases and moisture. The thickness and uniformity of coating on fruits play crucial role on permeability of the coating solution. Based on these backgrounds electrostatic spray coating machine was developed and it consisted of high voltage generator and electrostatic spray coating section. Developed electrostatic sprayer section involved electrostatic spray (twin fluid) nozzle with high voltage power supplying unit (1 kV to 5 kV), liquid discharge (10 to 30 ml/min) and pressurized air (2.5 and 4 kg/cm^2) from the air compressor. The maximum value of charge to mass ratio (CMR) obtained at 4 kg/cm^2 pressurized air flow rate was 1.70 mC/kg at 5.0 kV applied voltage under10 ml/min of spray liquid discharge rate.

Key words : Electrostatic spray coating, spray nozzle, high voltage

INTRODUCTION

Edible coating is a thin layer of protective layer over the fruit which protects the fruits against the surrounding environment by acting as a semi-barrier. Generally, fruit quality depends on the organoleptic, nutritional and microbiological properties which are adversely affected by the surrounding environment, especially on oxygen, water vapor and light (Vieira *et al.*, 2016). These environmental factors trigger certain physico-chemical reaction such as transpiration, respiration, microbial and biochemical activities. These triggered physico-chemical activities have a negative effect on the shelf life of fruits and vegetables. These physico-chemical activities can be reduced through covering the fruit with a semi-barrier material (Hanumantharaju *et al.*, 2019).

The effectiveness of coating depends on the method of application. The edible coating is applied either by dipping the fruit in the solution or mixing both fruits and edible coating solution in a pan or spraying the coating solution on the fruits (Hanumantharaju *et al.*, 2020a). Coating solution contamination in dipping and turbulent mixing in panning are the major drawbacks (Hanumantharaju *et al.*, 2020b). These drawbacks make them less important and not convenient for large scale operations (Jemima *et al.*, 2021). Spray coating involves atomization of coating solution for distributing over the food product which eliminates above mentioned drawbacks. Conventional spray method uses gravitational and inertial forces to deposit the hydraulically atomized droplets (300-600 μm diameters) which results in poor surface coverage, inefficient droplet deposition, and excessive rebound and runoff of spray liquid. In the normal spray coating, underlying or unexposed food material surface to the spray nozzle will not be coated, which in turn makes the non-uniform coating of the fruit (Kashif *et al.*, 2014). Hence, there is a need for improved methods of spray application.

Electro spray systems have several advantages over mechanical spray atomizers. In electrostatic sprayers, atomized spray liquid particles receive the charge at the end of the nozzle and follow the trajectory path towards

[1]Department of Food Processing, Tamil Nadu Agricultural University, Coimbatore-641 003 (Tamil Nadu), India.
[2]Post Harvest Technology Center, University of Agricultural Sciences, GKVK, Bengaluru-560 065 (Karnataka), India.

the nearby grounded object thereby forming the uniformity of coating due to wraparound effect of charged particles (Lefebvre and McDonell, 2017). Difference in normal and electrostatic spray coating is shown in Fig. 1.

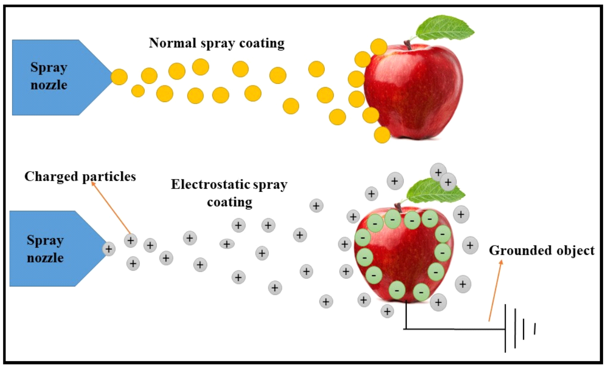

Fig. 1. Difference in uniformity of normal and electrostatic spray coating.

The size of electro spray droplets can range from hundreds of micrometers down to several tens of nanometers. The size distribution of the droplets can be nearly mono-disperse (Peretto *et al.*, 2017). Droplet generation and droplet size can be controlled to some extent via liquid-flow rate and voltage at the capillary nozzle. It has been reported that the application efficiency can be increased up to 80% with 50% less spray dosage by using electrostatic spraying (Lefebvre and McDonell, 2017). Considering the advantages of electrostatic spray coating machine over other methods of coating for edible coating of fruits, this study was undertaken to develop the prototype electrostatic spray coating machine.

MATERIALS AND METHODS

The developed electrostatic spray coating machine consists of high voltage power supply unit and electrostatic spray nozzle unit. The high voltage power supply unit consists of controller unit, buck convertor and fly-back transformer.

The important function of controller circuit was controlling the output (1-13kV) of high voltage. It consisted of three main circuits.

Microcontroller : To provide 0-5 V DC current to the controller (DSIC 30F4011).

MOFSET driver circuit : To operate MOFSET in the buck convertor by supplying +10V to -5V high frequency (2.5 kHz) square waves of 100 to 200 µAmps.

Buck convertor : The main purpose of buck convertor was to provide pure pulsating (2.5 kHZ) DC to the fly back transformer. In this circuit MOFSET was connected to the MOFSET driving circuit through V GATE and V SOURCE point with 10 k ohm resistor. Power supply for the circuit was provided by bridge rectifier which converts 230 V AC to 12 V DC. MOFSET was connected with 6 V diode, 1 µF/6A induction coil and 200 µF capacitor for supplying high frequency DC to the fly back transformer.

The duty cycle and frequency from the MOSSET driver circuit actuated the MOFSET (IR Z44N) and accordingly charging and discharging of current took place through the MOFSET.

The buck convertor supplied 0-18 V pure pulsating DC current to the fly back transformer. Voltage range in the buck convertor was regulated in the (VIN REF and VIN ACTUAL) controller circuit by varying duty cycle and frequency of the pulse width.

Fly back transformer for high voltage DC : Fly back transformer consisted of two primary winding (1 auxiliary winding with 4 turns and 1 main winding with 6 turns). One end of the auxiliary and main winding was connected to two anti parallel transistors. In that, collector and collector, emitter and emitter of the transistor were connected to each other. Again, source of the transistor was connected to another end winding through 4700 µF/35V capacitor. Another end of the auxiliary winding was connected to the 220 ohm/5W resistor. As soon as auxiliary winding conducted electric current, it activated the anti-parallel transistor in order to activate main winding and created a frequency which was sufficient to operate fly back transformer. In this circuit, the main winding did not operate till the voltage reached to 5 V.

The output of the fly back transformer was connected to the 0.1 µF/22kV capacitor to get pure DC. This pure high voltage DC was measured using high voltage probe at a spark gap of 8 mm between positive to negative terminals. Circuit diagram for high voltage power supply is given in Fig. 2.

Design and development of an electrostatic spray nozzle : The electrostatic spray nozzle was developed by considering volume of spray and the charge to mass ratio required for edible

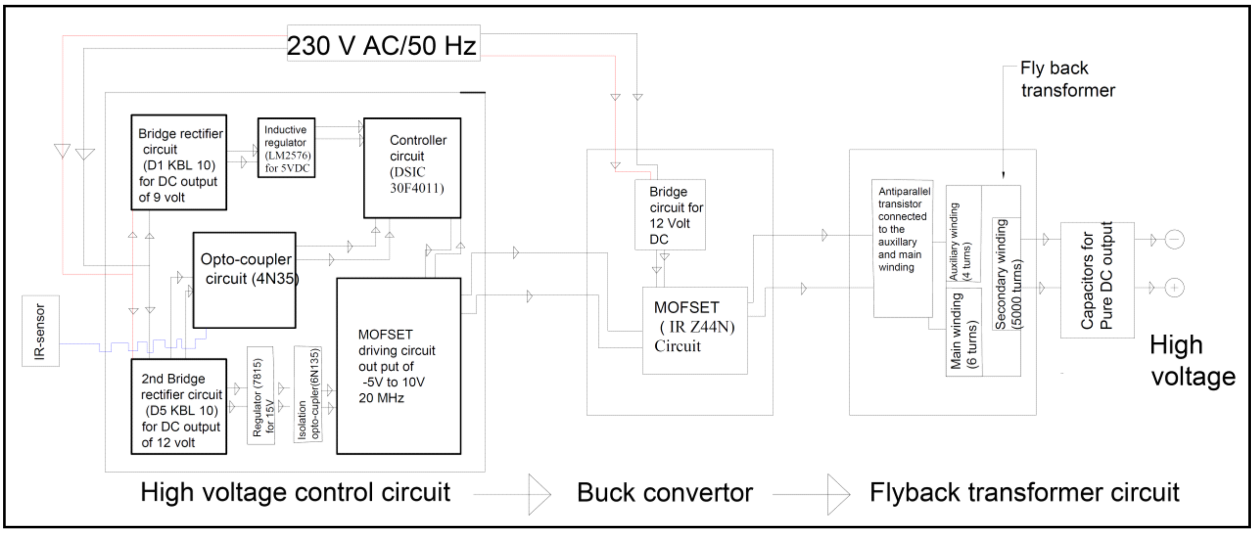

Fig. 2. High voltage power circuit diagram.

coating. Electrode ring diameter and spray nozzle outlet diameter were calculated using the procedure described by Patel *et al.* (2016).

Volume of spray required : Considering the surface area of fruits and maximum thickness of coating, the volume of coating liquid required for coating was calculated as follows.

Volume of spray equired = Surface area of fruits × Maximum thickness of coating ...(1)

Design consideration of charging electrode ring diameter : The charging was mainly due to induction charging of spray particles. Droplet radius was lesser than the jet radius due to disruption of liquid particles by high velocity air stream concurrently or coaxially coming in contact with the liquid air stream. Patel *et al.* (2016) concluded that the thin layer of liquid was ruptured in air assisted spray nozzle due to aerodynamic forces of high pressure of air. If atomization of the particles occurred near to the crest and through the annular space between the electrode and jet, gave greater surface charge density than the calculated value.

Charge to mass ratio of air assisted fluid sprayer was calculated by the equation given below :

$$\left(\frac{Q}{m}\right) = \frac{\text{€}_0 V}{r_j \text{þ}_p t_p \, Ln\frac{r_c}{r_j}} \quad ...(2)$$

Where,

Q/m – charge to mass ratio (C/kg)
€_0 – permittivity of the liquid (C^2/Nm^2)
V – applied voltage (volt)
r_j – needle radius
þ_p – mass density of liquid atomized
t_p – thickness of liquid
r_c – radius of cone.

Length of the cylindrical electrode was decided based on reverse ionization.

$$Lc \le \frac{3\pi\eta r_p V_a (r_c^2 - r_j^2)(r_c - r_j)}{QV} \quad ...(3)$$

Where,

r_p – the radius of droplet,
V_a – viscosity of the liquid
L_c – length of cylindrical electrode

Design consideration of spray nozzle : Polypropylene material was selected for air assisted electrostatic spray nozzle because of its high electrical resistance. Atomization of the edible coating solution in the nozzle was due to the aerodynamic forces of pressurized air which break the liquid to micron size particles.

The nozzle outlet diameter was calculated using the formula.

$$\frac{SMD}{Dh} = 0.33 * \left[\frac{\sigma}{\sigma_a u_a^2 D_p}\right]^{0.6} * \left[\frac{\rho_l}{\rho_a}\right]^{0.1} + 0.68\left[\frac{\eta_l}{\rho_l D_p \sigma}\right]\left[1 + \frac{1}{ALR}\right] \quad ...(4)$$

$$Dh = \frac{SMD}{0.33 * \left[\frac{\sigma}{\sigma_a u_a^2 D_p}\right]^{0.6} * \left[\frac{\rho_l}{\rho_a}\right]^{0.1} + 0.68\left[\frac{\eta_l}{\rho_l D_p \sigma}\right]\left[1 + \frac{1}{ALR}\right]} \quad ...(5)$$

Where,

SMD – auter mean diameter of the liquid (μm)

ALR – air/liquid ratio by mass
Dp – drop diameter (mm)
Dh – nozzle outlet diameter (m)
u – velocity (m/s)
η – dynamic viscosity (kg/ms)
ρ – density (kg/m^3)
σ – surface tension (kg/s^2)

Subscripts indicate

a – air
l – liquid

The mean diameter of the coating solution for fine coating should be less than 300 µm. Available data used for finding out the diameter of the nozzle are presented below :

Air density : 1.226 kg/m^3
Droplet diameter inside the nozzle is assumed to be : 4 mm
Density of the coating liquid : 106 kg/m^3
Viscosity of the edible coating solution : 4.058 pa/s
Air velocity from the compressor through 8 mm pipe at 2 kg/cm^2 pressure : 15 m/s

Surface tension of the edible coating solution varies from : 30-40 kg/sec^2
Mass flow of liquid : 0.5×10^{-7} kg/m^3/s
Mass flow of air : 7.34×10^{-5} kg/m^3/s

$$Dh = \frac{300}{5.680 \times 10^{-3}}$$

For 300-micron size particle size of edible coating solution

$$D_h = 0.00356 \text{ meter} = 4 \text{ mm}$$

Cross section of developed electrostatic spray nozzle is shown in Fig. 3. The nozzle had 5 mm hole at the top for pressurized air to enter into the nozzle. The hole was converged to 2 mm diameter for 2 mm distance. The converged path of 2 mm diameter hole was diverged to 4 mm diameter to avoid non-uniform distribution of air, which occurred when liquid was supplied to the nozzle through a needle of 1 mm diameter. Coating liquid was supplied through the needle which was inserted at the end of diverging path of central hole (2 to 4 mm dia.) in the nozzle. The output end of the needle was exactly at the center of the 4 mm hole.

High voltage induction electrode : Induction method of charging was chosen due to its ease and safe implementation as compared to corona and conduction charging. In induction charging, electrode ring played a major role for charging the liquid. Hence, it was necessary to get high conductivity and low resistance material for the electrode ring. Copper was selected for electrode ring by referring prior research works on electrostatic sprayer. The diameter and length of the copper ring electrode were decided based on the theoretical formula 3. Copper ring electrode of 3 mm thickness and 5 mm diameter was mounted at the end of nozzle coaxially to the needle tip. Electrode ring was placed near to the spray liquid without any contact of spray liquid. Due to induction, spray liquid attained the charge. If electrode was positively charged then the spray liquid attained negative charge and vice versa.

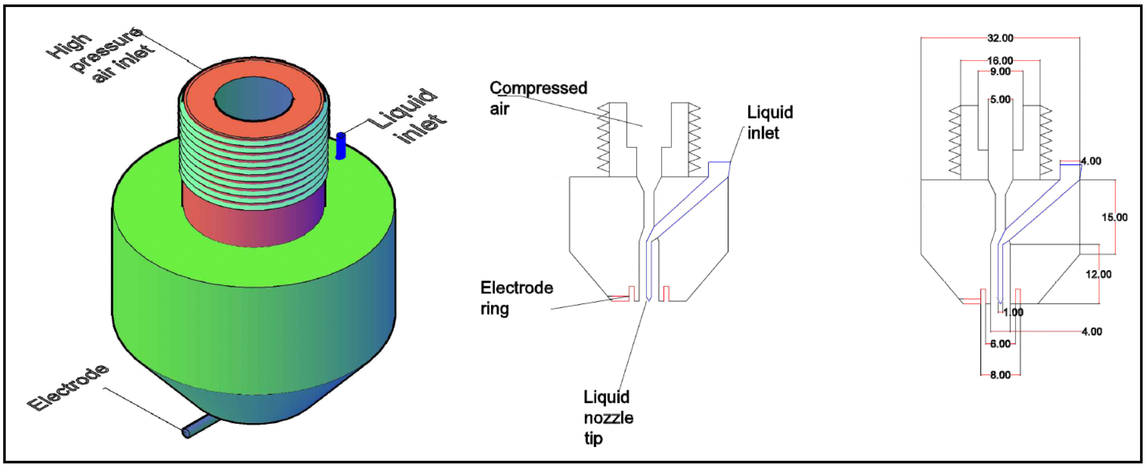

Fig. 3. Schematic diagram of developed electrostatic spray nozzle.

Developed electrostatic coating machine : The developed high voltage electrostatic spray coating machine is shown in Fig. 4. The machine was evaluated to analyze the charge to mass ratio in order to confirm the electric charge of the spray droplets. The charge to mass ratio of the spray droplets was one of main parameters for deciding the electric discharge through a spray droplet. Hence, charge to mass ratio of the developed electrostatic spray coating machine was tested using the following procedure :

Charge to mass ratio (CMR) of spray liquid : It is referred as quantity/amount of charge present in a given mass of liquid and it helps in knowing the charging effect of the liquid. Experiments were conducted at varying air pressure, flow rate and voltage at the electrode. The liquid was sprayed on the Faraday's cage. Faraday's cage was a mesh type cylindrical cage and used to measure the spray cloud charge (Patel *et al.*, 2017). Sometimes, it could be fabricated in different shapes and sizes with different sensing elements according to the requirement of experimental setup, without violating the basic concept. Following general thumb rule, Faraday's cage was designed and fabricated with aluminum mesh and covered with three side polypropylene material. The experimental setup for measuring the charge to mass ratio of atomized coating liquid is shown in Fig. 5.

Faraday's cage was located 60 cm below the nozzle on the isolated surface. Amount of static charge accumulated on the spray liquid droplets was calculated based on the amount of liquid collected in a cage and multi meter reading (spray cloud current in milli amps) connected in between the Faraday's cage and ground. The charge to mass rate was expressed in mC/kg.

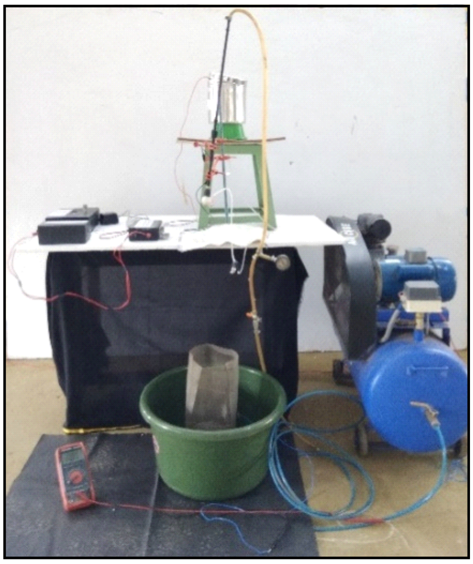

Fig. 5. Determination of charge to mass ratio by a developed electrostatic spray nozzle.

$$\text{Charge to mass ratio (CMR)} \ \frac{Is}{Q_m} \ldots\ldots\ldots(3.15)$$

Where,

I_s – spray cloud current (milli Amps/s)

Q_m – mass flow rate (kg/s)

RESULTS AND DISCUSSION

Electrostatic sprayer section involved

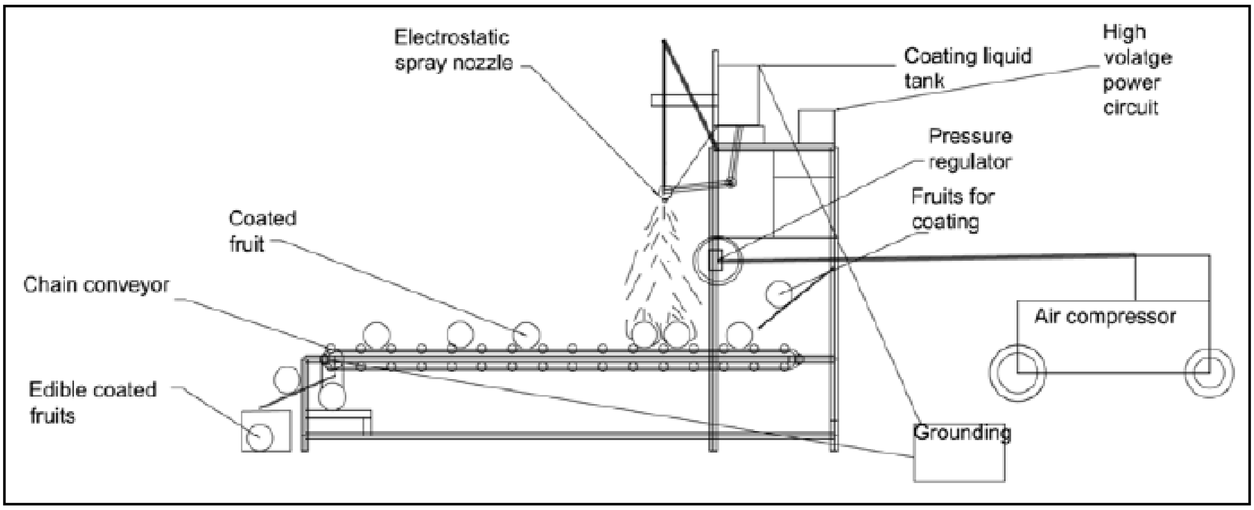

Fig. 4. Line diagram of developed electrostatic spray coating machine.

electrostatic spray nozzle with high voltage power supplying unit, liquid inlet and pressurized air from the air compressor. The developed electrostatic spray coating machine operated under output voltage of 1-13 kV, liquid spray discharge 10-30 ml/min and air pressure 2.5- 4 kg/cm^2.

The observed spray charge to mass ratio (CMR) of the developed electrostatic spray coating machine considering pressurized air flow rate at 2.5 and 4 kg/cm^2 is presented in Figs. 6 and 7. Charge to mass ratio of the spray liquid is presented as a function of the liquid discharge rate (D) and applied voltage (V). The maximum value of CMR at 2.5 and 4 kg/cm^2 pressurized air flow rate was 0.62 and 1.70 mC/kg, respectively, at 5.0 kV applied voltage under 10 ml/min discharge rate.

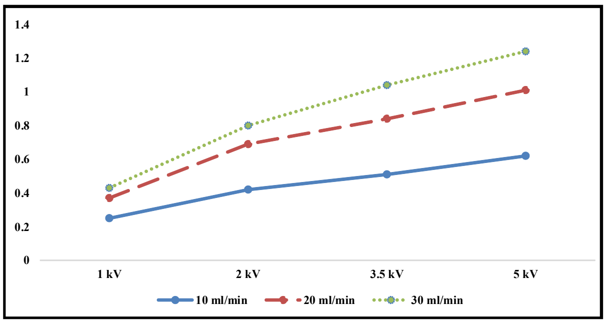

Fig. 6. Charge to mass ratio (mC/kg) of the coating solution under variable discharge rate and applied voltage at 2.5 kg/cm^2 air pressure.

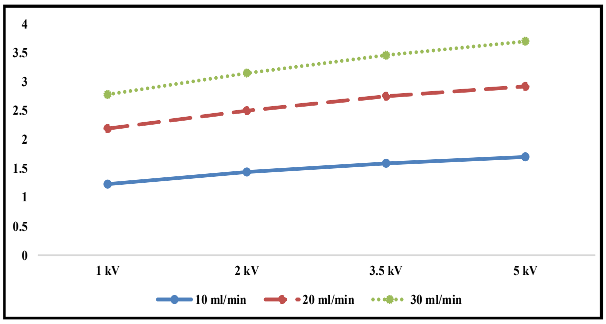

Fig. 7. Charge to mass ratio (mC/kg) of the coating solution under variable discharge rate and applied voltage at 4 kg/cm^2 air pressure.

The minimum value of CMR at 2.5 and 4 kg/cm^2 pressurized air flow rate was 0.06 and 0.59 mC/kg, respectively, at 1.0 kV applied voltage under 30 ml/min discharge. At a given pressurized air flow rate, the CMR was increased linearly with charging voltage. The spray charge was increased significantly ($P<0.05$) under all discharge rates with increased applied voltage up to 5 kV. The spray CMR decreased when liquid discharge increased from 10 to 30 ml/min at all applied voltages. Higher discharge rate might have lowered the atomization of liquid, which in turn increased the droplet size causing low surface area for charging. Patel *et al.* (2016) mentioned that CMR increased with increased applied voltage up to the saturation point and maximum charge to mass ratio of 10.20 mC/kg at 2 kV with 4 bar applied air pressure was observed in the study.

The CMR increased with increased pressurized air flow rate at constant applied voltage and discharge rate. High air pressure increased the hydrodynamic force on spray liquid in the nozzle, which in turn decreased the droplet size and time required for atomization of the liquid. Hence, it increased the surface area available for charging, which might have increased the CMR of the spray liquid. Patel *et al.* (2017) observed an increased charge to mass ratio of a spray liquid with increase in the liquid pressure in the induction type electrode.

CONCLUSION

Developed electrostatic spray coating machine for the application of edible coating can produce a higher transfer efficiency and greater deposition on unexposed surface. These types of coating will guarantee the uniform coating. Electrostatic coating can also reduce the processing time required for coating fruits. The size of the droplets formed by the electrostatic spray nozzle was much smaller and uniform as compared to normal spray coating method. It avoided the excessive utilization of coating solution by using electrostatic spray coating. By considering all these outcomes it proved to be the best option for uniform edible coating of fruits and vegetables.

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