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Pulsating Air Pollinator for Greenhouse Cultivation

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Greenhouses have been accepted worldwide for round-the-year cultivation of quality produce. Greenhouse provides a desired climatic condition for crops but, at the same time, has obstacles for natural pollination. A pollinator was designed on the principle of pulsating air jet for pollination. The pollinator was developed with 3D printed three pulsation units with a provision for varied air pulsation frequency and angular movement to cover the complete flower bed. An operator in the greenhouse alleys can easily move this. The developed pollinator was compared with hand pollination and pollination by a blower in tomato crops. The effects of Airflow rates, Pulsation frequencies of air and Exposure times on pollination efficiency and yield were studied. Experiments were performed in tomato plants cultivated in the greenhouse. The highest pollination efficiency (83.66%) was achieved at 1.99 m^3/min airflow rate, 23.50 Hz pulsation frequency and exposure time of 19.40 seconds; Average yield of 19.52 kg was observed at 1.99 m^3/min of airflow rate, 22.25 Hz of pulsation frequency and exposure time of 15.78 seconds in flowers of 5 m length sections. The yield was also higher with developed pollinator compared to pollination by a blower (36.6%) and controlled plot (95.7%).

Keywords: Air Pulsation frequency, Airflow rate, Exposure time, Greenhouse pollinator, Response surface optimization

Introduction

Greenhouses are an efficient solution for round-the-year cultivation. Greenhouse technology has been accepted worldwide for the production of quality products and increased productivity in the off-season. As a result, in the last decade, the area under protected cultivation has expanded to nearly 25,000 hectares in India.[1] Tomato is one of the major crops grown in greenhouse besides capsicum and cucumber. So, for increasing tomato production and productivity in a unit greenhouse factors such as manipulation of the environment, effective pollination, proper pruning of the indeterminate tomato canopy is very significant. Effective pollination of tomatoes in the greenhouse is vital for enhanced fruit formation and production.

The flower of tomato has stigma surrounded by dehiscing anthers due to a short style tube. It eliminates the cross-pollination opportunity and ensures self-pollination in tomatoes.[2] In the tomato plant, pollens are shaded within the flower, need a strong vibrating force to transfer it from anthers to the stigma. In natural conditions, wind or natural pollinators like bees provides this vibrating force to shake the plant and cause pollination. The temperature and humidity of the air also affect the pollination of tomato crops. Portable blowers are used as supplementary pollination methods for wind pollination. These methods increase the fruit formation and yield of tomatoes. Another way of multiple hives of laboratory-reared colonies of bumblebees (*Bombus impatiens*) is also used for pollination.[3,4] However, in small greenhouses (<1000 plants under one cover), bumblebee pollination causes excessive pollination leading to flower injury and abortion. Opened flowers in small greenhouses are few at any given time; bees visit these opened flowers repeatedly, and destroy the protective anther tube and damage the female organs. In a small greenhouse, manually pollinating plants is cost-effective. Gently shaking plants or tapping flowers release pollen from male flower parts to female structures. Hand-held pollinator wands with vibrating heads are used to touch the base of flowers. Also, there are battery-operated or electric tooth brushes used to pollinate flowers. A study[5] reported that pollination with an electric vibrator could increase yield. In another study[6], it was indicated that electric vibrators could be

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used to pollinate greenhouse tomato with equal effectiveness as bumblebees. However, all these pollinating techniques used in small greenhouses are labor-intensive and time-consuming.

Based on the above facts, a mechanical device for pollination was developed with pulsating air jet, which gently shakes the flower for pollination and moves in alleys of a greenhouse. The pulsating air jet with optimized frequency and number of blowers arranged on the frame of the pollinator with angular movement was developed for efficient pollination. It was moved by an operator in the greenhouse's alleys, which facilitated the operation and reduced the human drudgery of manually operated portable blowers.

Materials and Methods

An experimental setup was developed to determine the required air velocity range for effective pollination. The design parameters for the pollinator were determined by conducting experiments on the experimental setup and considering available literature. Based on these design parameters pollination unit was fabricated.

Air Velocity for Efficient Pollination

Tomato plants were grown in pots. The plants were used to determine the range of air velocity for effective pollination when they had flowering on them. The experimental setup was equipped with a blower having a wide range of air velocity. The air velocities of (15 m/s [0.0105 m³/s], 30 m/s [0.021 m³/sec], 45 m/s [0.0315 m³/s], 60 m/s [0.042 m³/s] respectively.) were blown on the tomato plants for 60 seconds thrice in a week until fruiting. The number of flowers before and after the fruiting was recorded for determining pollination efficiency.

Design Values of Pollinator Components

Design parameters required for pollinators were effective air velocity range, air pulsation frequency, pollination height, angular movement of blowers, and the number of pollination units to cover the flower band of tomato plants and width of the pollinator frame. The effective velocity range was determined by conducting experiments. It was in the range of 30–45 m/s. The air pulsation frequency needed was 15–25 Hz.[7] Based on the dimension of the flower band, the number of pollinator units, angular movement of the pollinator unit, and height of the pollinator frame were determined. The width of the pollinator mainframe was based on row to row distance between tomato plants (alleys) in greenhouses to move without damaging plant/root.

Development of Pollinator for Greenhouse

The pollinator's main components were the mainframe on which all components, namely wheels (four), a vertically adjustable frame, pulsating blowers, and a control box with electrical/electronic circuitry, were mounted.

Mainframe

The mainframe (500 × 750 mm) was fabricated with a width to facilitate movement between rows of crops and to cover the width of the flowering band. The material used to fabricate the whole frame was mild steel angle iron, square pipe and flats. The frame consisted of a base frame with wheels, an adjustable frame to cover vertical height, a handle, a Coupler for pulsating blowers, and a system for angular movement of pollination units. The assembled structure with various components is shown in Fig. 1(a).

Angular Movement for Pollination Unit

Three pulsating blowers were arranged vertically on the frame of the pollinator for complete flower band coverage. The wiper motor was connected mechanically with the blower to give the angular movement to the blowers (30°, 15° up and 15° down), as shown in Fig. 1b. This angular movement was provided by worm geared motor powered with 12 V DC. This motor was mechanically connected to all three blowers with a connecting rod.

Coupler for Pulsating Blowers of Pollinator

A box was designed to attach the pollinator`s pulsating blowers unit with the mainframe (180 mm × 180 mm × 100 mm), made of a mild-steel sheet of 2 mm thickness. At one end, it was joined by welding on two male sections of the adjustable frame and the other to the attachment of the pulsating blower. Three boxes were used to attach three pollinator`s pulsating blowers units (Fig. 1c).

Blower

The blower was selected based on an effective velocity range for efficient pollination (30–45 m/s). A blower, as shown in Fig. 1b, was chosen with an airflow rate of 2.6 m³/min (Table 1). It was commercially available at a reasonable price (INR.700). The electric power available in the greenhouse is used for the blower.

Speed Controller for Blower

A blower motor speed controller was used to control the airflow rate of the blower. This controller consisted of a bi-directional high-power Silicon Control Rectifier (SCR). The output voltage was adjusted between 50–220 V for use to control blower speed.

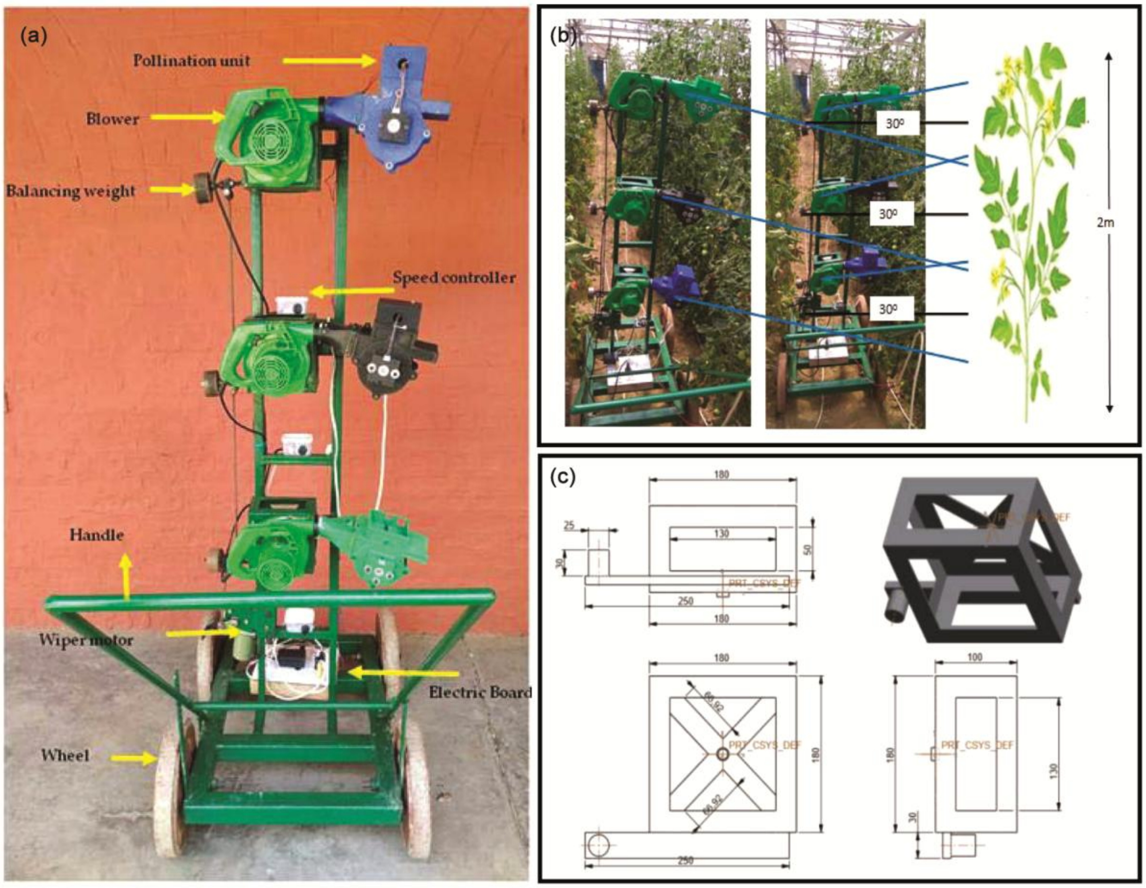

Fig. 1 — Developed pollinator (a) Pollinator, (b) angular movement of pollinator, & (c) Pollinator’s pulsating blower’s coupler

Table 1 — Specification of blower

Parameters	Values
Flow type	Radial flow blower
Air Flow Capacity	2.6 m^3/min
Power	Single-phase AC
Weight	2 kg
No Load Speed	14000 rpm (max)
Dimensions	23.5 × 19 × 17 cm
Cross sectional area of blower outlet	706 mm^2
Material	Plastic body
Power Cord Length	1 m
Voltage	220 V
Amperage	1.5 A
Height	100 mm
Power Consumption	300 W (max)

Design and Development of Pollination Unit for the Pulsation of Air

The pollination unit was developed with a pulsation frequency of 15–25 Hz. To achieve this, different components, namely blower attachment, revolving valve, main housing, upper casing, upper plate, stepper motor Nema17, back plate, were 3D printed in the laboratory (Fig. 2h). These were integrated with stepper motor, driver and operated with a microcontroller embedded with the program.

Blower Attachment

Blower attachment (Fig. 2a), an extension to the blower with a circular part (diameter = 48 mm) at one end and rectangular shape to accommodate the revolving valve at another end (76 mm × 56 mm), was designed and fabricated. Dimensions of the revolving valve determined the size of the blower attachment. The thickness of 3 mm was selected for 3 D printing to sustain air pressure.

Revolving Valve

A stepper motor has a maximum speed of 360 rpm (6 revolutions per second) under load conditions. A revolving valve with four blades was designed to achieve pulse frequency to 24 Hz (6 revolutions per second × 4). The size of the blade was rectangular, with a length to width ratio of 1.5:1. The width of the blade was considered as 48 mm and length as 72 mm (Fig. 2b).

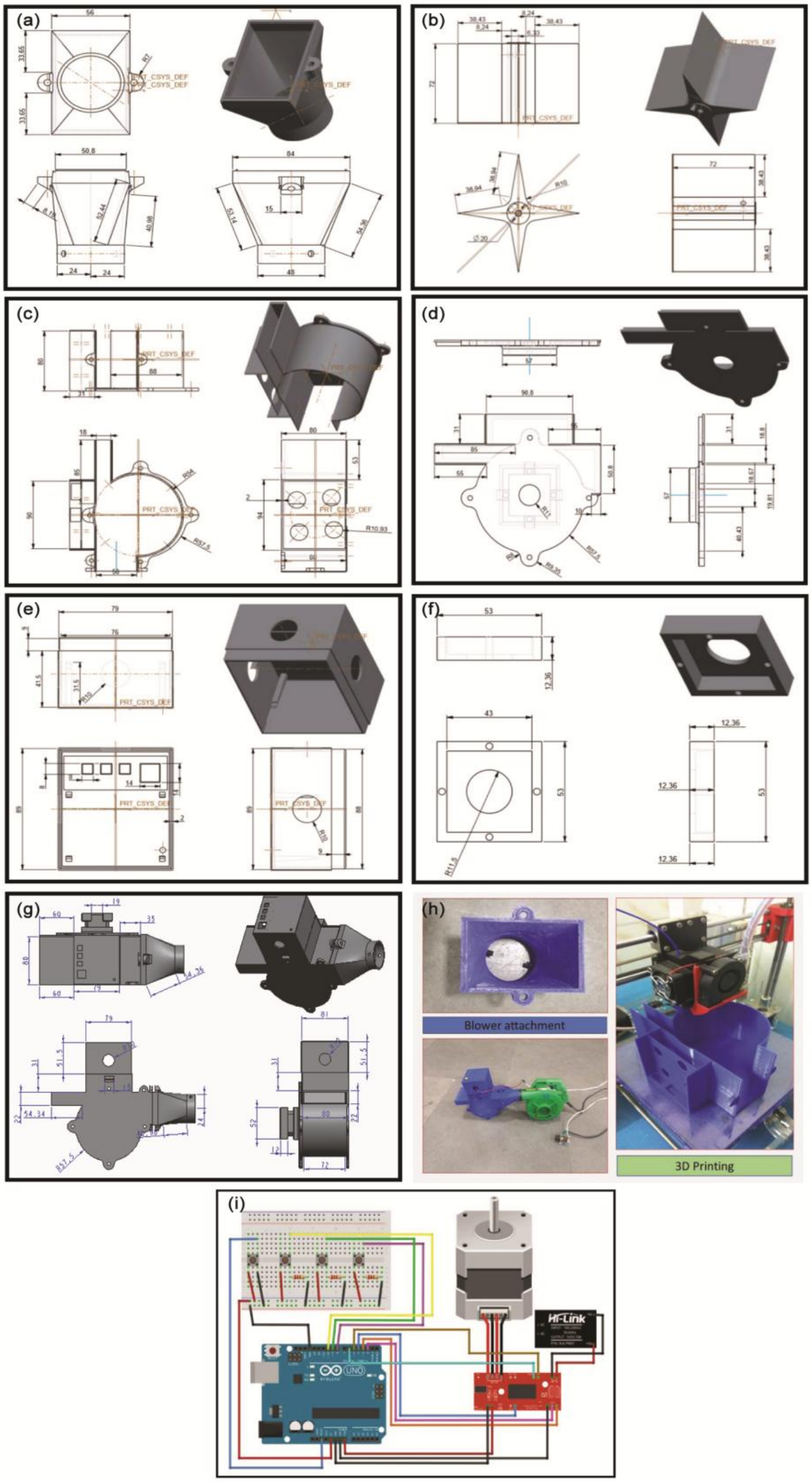

Fig. 2 — Designed Pollination unit: (a) Blower attachments, (b) Revolving valve, (c)Main housing, (d) Upper casing, (e) Upper plate of Nema17, (f) Motor back plate, (g) Assembled pollination unit, (h) 3 D printed –pollination unit to be attached to blower, & (i) Circuitry of stepper motor

Main Housing

It is the main enclosure in which the revolving valve rotates coupled with a stepper motor. It had a cylindrical shape to accommodate the revolving valve without losing air pressure. The diameter selected was 100 mm, as the revolving valve had a 96 mm diameter with 2 mm of clearance on both sides (Fig. 2c) to ensure free rotation with minimum air pressure losses. It had two outlets; one was attached to the outer end of the blower attachment and the other outlet for pulsating air for pollination. Accordingly, components needed for the stepper motor were enclosed in 90 mm × 80 mm × 31 mm cuboids shape housing (Fig. 2c).

Upper Casing

The upper casing has the same dimension as the main housing and was used to make the whole enclosure airtight (Fig. 2d). It was attached to the main housing and properly fitted with nut bolts. It had a thickness of 3 mm. It had an arrangement for attachment of stepper motor (Nema17) along with a revolving valve mounted on a motor shaft.

Upper Plate

The upper plate was designed to accommodate all the parts such as the microcontroller driver, AC adapter with the circuit's connections in cuboids shape on the main housing (Fig. 2e). Slots were provided for push buttons to control the stepper motor speed and the frequency of pulsating air.

Nema17 Motor Back Plate

It was designed to give support to the stepper motor when attached to the mainframe through the upper casing. It had dimensions based on the size of the Nema17 motor. It had dimensions of 43 mm (length) × 43 mm (width) × 10 mm (height) with 5 mm thickness (Fig. 2f). The complete assembled pollination unit is shown in Fig. 2g.

The desired air pulsation was achieved by developing the microcontroller program and integrating with stepper motor, driver to control the speed of stepper motor, AC adaptor to supply 12V DC power to the easy driver, push-button to select the speed of stepper motor. The program in the microcontroller used three push buttons and a driver controller along with 10 kohm resistors for three different speeds of the stepper motor (Fig. 2i). These three speeds were 360, 300 and 240 rpm. A stepper motor controlled the revolving valve's revolution mounted on the axis of the stepper motor. The revolutions selected were 4, 5 and 6 revolutions per second. The revolving valve with four blades (4 × 4, 4 × 5, 4 × 6), pulsation frequencies of 16, 20 and 24 Hz, could be achieved.

Laboratory Evaluation of the Prototype

The evaluation in terms of the amplitude of flowers for different combinations of airflow rates, pulse frequencies, and distances of the application was performed by motion image clipping. The measurements were recorded on the grid frame. It was fabricated with a 25 mm flat of mild steel having a thickness of 5 mm. The grid frame had dimensions of 400 mm × 400 mm. It was provided with a variable height stand made of MS square section of 20 mm × 20 mm × 900 mm (male) and a female section of 25 mm × 25 mm × 900 mm (Fig. 3). Any air pulsation strike plant or flower, deviation from the grid was measured. Mean amplitude of flowers for different combination were determined by clipping the motion images and measuring the displacement from the mean position in the grid. Pulsation was measured by observing the movement of flowers and paper by videography. A pressure sensor was also used by observing the number of peaks of the airflow per second of the pollination unit. The pressure sensor was connected with Arduino Uno for data recording using Arduino IDE software output. A total of seventeen combinations were used to assess the effect of airflow rate (AFR), pulsation frequency of air (PFA) and distance (with three levels each) for "Box Behnken Design"[9] with three replications (51 combinations) in the laboratory (Table 2). The airflow meter (anemometer) was used to measure the air velocity of the blower using a standard method. The airflow rate was calculated using the formula given below

$$\text{Air discharge rate } (\text{m}^3/\text{s}) = \text{Air velocity } (\text{m/s}) \times \text{Area of outlet of the blower } (\text{m}^2)$$

Field Evaluation of Pollinator in Greenhouse

Field evaluation of developed pollinator was carried out in the crop season (February-May 2018)

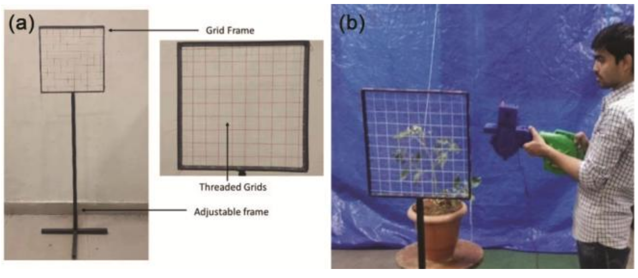

Fig. 3 — Height-adjustable grid frame for lab evaluation

Table 2 — Combinations of variables using Box Behnken Design for lab and field experiments

Combinations number	Laboratory evaluation			
	Field evaluation			
	Distance (mm)	AFR (m^3/min)	PFA (Hz)	Exposure time (s)
1	200	2.0	24	15
2	300	1.5	16	20
3	300	1.5	24	20
4	100	1.0	20	10
5	200	2.0	16	15
6	200	1.5	20	15
7	200	1.0	24	15
8	200	1.5	20	15
9	200	1.5	20	15
10	300	2.0	20	20
11	100	1.5	24	10
12	100	2.0	20	10
13	300	1.0	20	20
14	200	1.5	20	15
15	200	1.0	16	15
16	200	1.5	20	15
17	100	1.5	16	10

for tomato (*Lycopersicon esculentum Mill.*) crop in the greenhouse of ICAR-Indian Agriculture Research Institute, New Delhi. Experiments were performed in ten rows of tomato plants with 50 m length with a row to row spacing of one meter. Each row was divided into 5 m length sub-plots (Fig. 4). Before the field experiment, a bunch of flowers on each plant was tied with yellow ribbon and red ribbon for pollination by developed pollinator and manual pollination, as shown in Fig. 5. Manual pollination was done as normal practice by shaking the threads used for tying the climbers or plants whenever someone moves in the greenhouse and it comes out to be ten times on an average daily and by a portable blower with manual movement. Manual pollination by hand refers to simply tapping the flower to release pollen from anther and transferring it to stigma. Pollination by pollinator for combinations of three airflow rates (AFR), three pulsation frequency of air (PFA), and three exposure time (ET) were used. Seventeen combinations with three replications (51 combinations) in field condition were used (Table 2) for performance evaluation for "Box Behnken Design". The developed pollinator was evaluated for pollination efficiency and yields compared to manual pollination (by shaking the plants with hands ten times), use of blowers manually and control (Fig. 6). The pollination by pollinator was carried three days a week after flowering and continued till fruit formation. Flowers with yellow and red ribbon were counted for each 5 m length subplots. The number of fruits to the number of flowers indicated pollination efficiency. Also, the yield and size of the fruit were recorded.

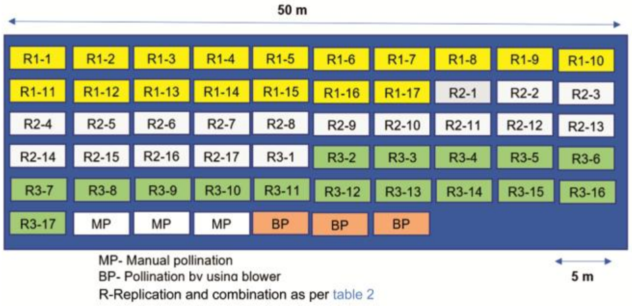

Fig. 4 — Experiment layout in the greenhouse

Fig. 5 — Tying of plants: (a) Yellow ribbon tied to refer pollination by developed pollinator, (b) Red ribbon tied to refer pollination by manual pollination; Pollination by (c), Hand (d) Blower, & (e) Designed pollinator

Results and Discussions

Laboratory Evaluation

Effect of Air Velocity on Pollination

The effect of air velocity on pollination efficiency was investigated at four levels (15, 30, 45, and 60 m/s). The combination of distance and airflow rate was able to vibrate the flowers for pollen detachment. It was observed that the pollination efficiency increased with an increase in air velocity up to a certain limit and then decreased with a further increase in air velocity.

An increase in air velocity increases the amplitude of flowers (deviation from the mean position), which will release the pollens effectively up to a certain threshold velocity. However, beyond this limit, higher dispersion of pollens may occur and results in pollen movement out of flower, causing wastage of pollens and a decrease in pollination efficiency. The pollination efficiency was highest at 45 m/s air velocity, followed by 30 m/s, 60 m/s, and 15 m/s. The pollination efficiency was 66.67%, 64.28%, 58.33% and 53.85% for air velocities 45, 30, 60 and 15 m/s respectively. So, the effective range of air velocity was 30–45 m/s; based on this observation, the blower was selected.

Effect of Air Flow Rate, Pulsation Frequency of Air and Distance on the Amplitude of Flowers

Effect of airflow rate (AFR), pulse frequency of air (PFA), and distance on the amplitude of flowers was investigated under laboratory conditions. It was observed that with an increase in AFR from 1 to 2 m^3/min, the amplitude of flowers increased. In the case of pulse frequency, the results showed that increase in pulse frequency of air up to 21.26 Hz, the amplitude of flowers increased. However, it decreased with a further increase in the pulse frequency of air. The higher amplitude of flowers observed at 21.26 Hz may be due to the coincidence of resonance frequency of flowers. The distance of the pollination unit from the flower was inversely proportional to the amplitude of flowers. Maximum amplitude was observed at a lower distance of 100 mm. The data was analyzed using Box Behnken Design. The overall model was significant at a 1% level of significance. The R^2 = 0.9799 for the model indicated that the model explained 97.99% variability. The graphical representation for an optimal solution for the maximization of amplitude, pollination efficiency and yield is shown in Fig. 6a.

Field Evaluation

Effect of Air Flow Rate (AFR), Pulse Frequency of Air (PFA) and Exposure Time (ET) on Pollination Efficiency

Effect of airflow rate (AFR), pulse frequency of air (PFA), and exposure time (ET) on pollination efficiency was investigated in the greenhouse. The maximum pollination efficiency (83.66%) with the highest desirability value of 1 was found at an airflow rate of 1.99 m^3/min at a pulsation frequency of 23.50 Hz and exposure time 19.4 seconds (Fig. 6b). A previous study[8] also showed that pollination efficiency was higher at 22 Hz for a cultivar of tomato in the greenhouse field condition. The data were collected based on Box Behnken Design and a second order Respose Surface model was fitted to the data. It was observed that the model was significant at 5% level. The R^2 for the model was 0.9628, which was very high. Increasing AFR increases pollination efficiency. The maximum pollination efficiency of developed pollinator was 83.66%, whereas manual hand pollination, pollination by blower, and untreated were 79.48%, 64.82% and 50.93%, respectively.

Effect of Airflow Rate (AFR), Pulse Frequency (PF) and Exposure Time (ET) on Yield

The effect of airflow rate (AFR), pulse frequency of air (PFA) and exposure time (ET) on yield was investigated in the greenhouse. The maximum yield for the number of flowers selected in 5 m length plots was 19.52 kg. The highest yield was observed at 1.99 m^3/min. It might be due to the higher pollination efficiency at this AFR. With an increase in PFA, the increased yield was observed up to 22.25 Hz, but it decreased with a further increase

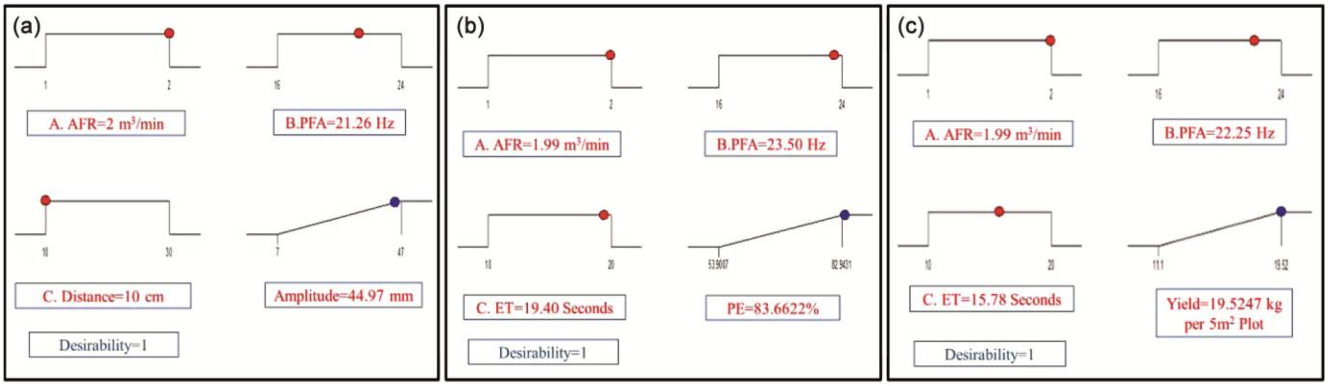

Fig. 6 — Optimal solution for (a) Maximization of Amplitude of flowers, (b) Maximization of Pollination Efficiency, & (c) Maximization of Yield

above 22.25 Hz. However, higher pollination efficiency was observed at 22.25 Hz. Exposure time also influenced yield. The maximum yield was observed at an exposure time of 15.78 seconds. However, the exposure time of 19.40 seconds gave higher pollination efficiency but with less fruit weight. Whereas at an exposure time of 15.78, lower pollination efficiency was observed but higher yield due to larger fruit size and weight. It was observed that the overall model is significant at 1% level of significance. The $R^2 = 0.9886$ for the model indicated that the model could explain 98.86 variability, which is very high (Fig. 6c). The yield was higher in the case of developed pollinator at AFR, PFA and ET compared to manual hand pollination (0.4%), pollination by a blower (36.6%) and untreated plot (95.7%).

The combination of distance and airflow rate was able to vibrate flowers for pollen detachment and transfer to stigma. The airflow being in pulses/ packets will not give continuous flow, which can damage the plant and keep the flowers deviated in one position. An increase in air velocity increases the amplitude of flowers, which will release the pollens effectively up to threshold velocity. However, beyond this limit, higher dispersion of pollens may occur and results in pollen dispersion out of flower, causing wastage of pollens and a decrease in pollination efficiency. So, the optimum value of air velocity is significant for a particular crop as pollens detachment with desired force and spread at the desired distance is achieved. The distance of the pollination unit from the flower was inversely proportional to the amplitude of flowers. The maximum amplitude was observed at a distance 100 mm, as beyond that, the stream of air may be losing the force to vibrate flower. The lower distance can result in reduced pollen efficiency with high air impact. Exposure time influenced pollination efficiency. Maximum pollination efficiency was observed at an exposure time of 19.40 seconds for a 5-meter span. It ensures the vibration of the flower about eight times (at about 21 Hz pulsation frequencies) for 100 mm blower exposure, which is adequate to detach pollens and fall in the ovary. This exposure time also matches with the forward speed of one km/hr, which is very compatible with the operator movement. The pollination with pollinator had an advantage over blower pollination, which gives a constant flow of air without pulsation. Hand pollination is also random and had lower pollination efficiency requiring considerable time for the operation. The developed device is very low cost and fabricated from commercially available material; this can be used for other crops grown in greenhouses with a minor modification.

Cost Economics

The cost of the developed pollinator was INR 15000 and the cost of operation per hour was INR 80. The cost of manual hand pollination was approximately INR 1500 per ha, whereas pollination by pollinator was INR 400 per ha. The breakeven point was 75 hours/year with a payback period of two years. The cost of operation decreased with a reduction in time for pollination per unit area than manual hand pollination.

Conclusions

The developed pollinator performed well in tomato cultivation in the greenhouse with higher pollination efficiency (83.66%) compared to manual hand pollination, pollination by the blower, and untreated plot (79.48%, 64.82% and 50.93%, respectively). The higher yield was obtained with developed pollinator compared to manual hand pollination, pollination by the blower, and untreated plot; it was found 0.4, 36.6, and 95% higher, respectively.

A maximum yield of 19.52 kg was obtained at the optimum values of AFR. Optimal solution infers maximization of amplitude (44.97 mm) at AFR of 1.99 m^3/min, a distance of 100 mm, and a pulse frequency of 21.62 Hz. Maximum pollination efficiency of 83.66% was obtained at optimum values of AFR, Pulse frequency of air and exposure time of 1.99 m^3/min, 23.50 Hz and 19.40 seconds, respectively; Higher yield was obtained at airflow, pulse frequency of air and exposure time (1.99 m^3/min, 22.25 Hz and 15.78 seconds, respectively) higher than with manual hand pollination, pollination by blower and untreated plot. The cost of the developed pollinator was INR 15,000, which is affordable for farmers. The cost of operation per hour was INR 80/hour (INR 400/ha). The breakeven point and the payback period were 75 hours/year and two years, respectively, for the developed pollinator.

Acknowledgments

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