ग्रीनहाऊस के लिए परागण के यंत्र का प्रारुप और विकास

DESIGN AND DEVELOPMENT OF POLLINATOR FOR GREENHOUSE

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DESIGN AND DEVELOPMENT OF POLLINATOR FOR GREENHOUSE

A Thesis

By

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CERTIFICATE

This is to certify that the thesis entitled '**Design and development of pollinator for greenhouse**' submitted to the Post-Graduate School, ICAR–Indian Agricultural Research Institute, New Delhi, in partial fulfillment of the requirements for the award of the degree of **Master of Technology in Agricultural Engineering**, embodies the results of *bonafide* research work carried out by **Mr. Akshay Sanjay Mahadik (Roll No. 20923)**under my guidance and supervision, and that no part of this thesis has been submitted for any other degree or diploma.

The assistance and help availed during the course of investigation as well as source of information have been duly acknowledged by him.

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LIST OF ABBREVIATIONS

AC	Alternating Current
AC Adapter	Alternate Current to Direct Current converter
AFR	Air Flow Rate
ANP	Annual Net Profit
AU	Annual Utility
BBD	Box Behnken Design
BEP	Break Even Point
BPDS	Body Part Discomfort Score
CF	Custom hiring charges
DC	Direct Current
Eq.	Equation
ET	Exposure Time
FC	Annual Fixed Cost
g/s	Gram per Second
HR	Heart Rate
HTR	High Temperature Regime
Hz	Hertz
IC	Initial Cost of Machine
ICSP	In-Circuit Serial Programming
IDE	Integrated Development Environment
ITR	Intermediate Temperature Regime
kCal	Kilo Calorie

LTR	Low Temperature Regime
m/s	Meter per second
m^3/min	Meter cube per minute
MS	Mild Steel
ODS	Overall Discomfort Score
PBP	Payback Period
PE	Pollination Efficiency
PFA	Pulsation Frequency of Air
PGB	Plant Growth Bioregulator
R^2	Coefficient of Determination
RCBD	Randomised Complete Block Design
rpm	Revolution per minute
rps	Revolution per second
RSM	Response Surface Methodology
SCR	Silicon Control Rectifier
SPSS	Statistical Package for the Social Sciences
U. S.	United States
USB	Universal Serial Bus
VO_2	Volume of Oxygen consumption

Chapter 1

INTRODUCTION

The world population is increasing day by day. So, there is need to increase the production rate of food to fulfill the demand of food material. Also, there are various reasons for reduction of food production such as drought, salinity, crop diseases, floods which lead to non-availability of food to people resulting in malnutrition. To avoid such type of problems of food shortage Greenhouse technology has been accepted worldwide to produce quality products and increase productivity even in off-season. As a result, in last one decade the area under protected cultivation has expanded to nearly 25,000 hectares in India (Sabir and Singh, 2013).

Greenhouse is a structure which is covered with glass, acrylic, polythene etc. where the favorable condition for plant growth is maintained. Also, this protected structure provides protection to the plants from various factors such as diseases and external climatic condition. It offers a feasible solution for round the year cultivation. Tomato is one of the important ingredients in Indian food recipes. Also, tomato is one of the major crops grown in greenhouse besides peppers (capsicum) and cucumber. Hence, for increasing the tomato production in greenhouse consideration should be given to factors such as manipulation of the environment, effective pollination, properly prune the indeterminate tomato canopy etc.

Effective pollination of tomato in greenhouse is more important to increase the fruit formation, and simultaneously the production. Pollination is the process where pollen from a male part of a plant are transferred to a female part of a plant for enabling fertilization and production of seeds. Fruit and seed formation are the results of successful pollination. Birds, bees, butterflies and wind are some of natural modes of pollination.

Referring the classical botanical literature, theory of pollination can be explained. Flower structure, flower development and environmental factors influences mechanism of pollen transfer from anther to stigma. Environment is very important factor for proper fruit setting (Moore,1964). The anther sacs dehisce at maturity. Dehiscence is described as mechanical rupture of the epidermal cells of a fibrous layer of cells in the anther wall due to hygroscopic action. If it is not fully mature, hot sun, dry air, or wind will not bring about dehiscence. Dehiscence occurs after 24 to 48 hours of patella opening. Each anther sac contains number of pollens which splits in antrorse manner after dehiscence and fall on pistil to complete pollination (Hayward, 1948). Burk *et.al*. (1930) found that variety and length of the pistil were important factors affecting pollination. Hafen (1961) stated that on dark, cloudy days pollen does not shed, and on such days, therefore, it is practically useless to agitate blooms.

The flower of tomato has stigma within the anther tube due to short style (Plate 1.1). This eliminates the cross-pollination opportunity and gives assurance of self-pollination in the tomato (Rick, l978). In tomato plant, pollens are shaded within the flower, needs a strong vibrating force to transfer it from anther to stigma. In natural conditions wind provides this vibrating force to shake the plant. The temp and humidity of air also affects the pollination of tomato crop. Blower can also be used as supplementary pollination method for wind pollination. This increases the fruit formation and yield of grown tomatoes.

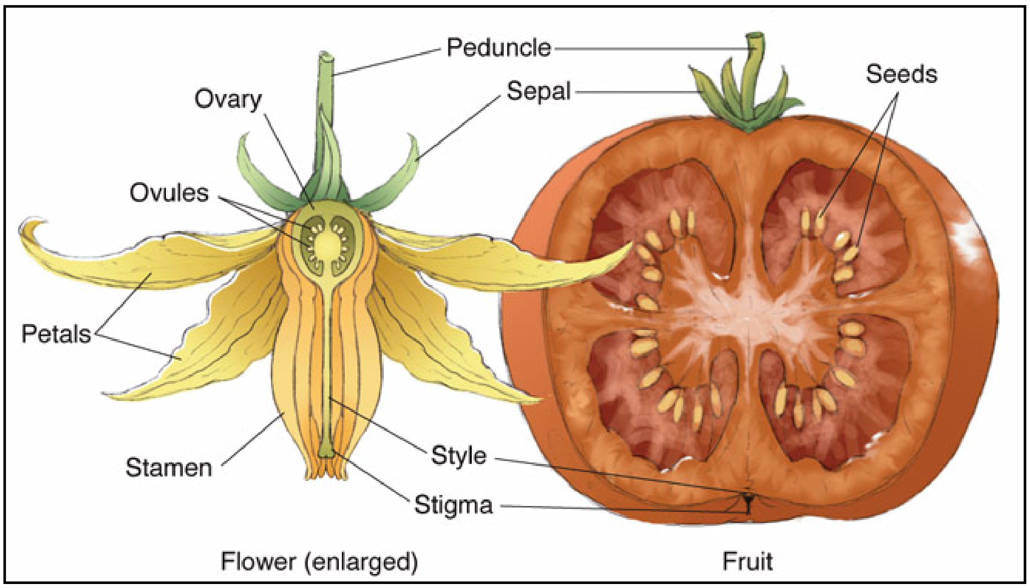


Plate 1.1: Flower and fruit of tomato

Generally, greenhouse provides micro environment for plants, but at the same time it presents structural obstacle for natural pollinators like bees and wind flow which affects the natural pollination of tomato in greenhouses. In absence of the wind, human intervention is needed for effective pollination.

Multiple hives of laboratory-reared colonies of bumblebees (*Bombus impatiens*) are used effectively to pollinate tomato crop in lager greenhouses (Morgan, 2000).

However, in case of small greenhouses (< 1000 plants under one cover), bumblebee pollination caused excessive pollination leading to flower injury and abortion. The opened flowers in small greenhouses were few at any given time which were not sufficient to supply enough pollen for the foraging bees from the smallest commercially available hive. So, bees visited the opened flowers repeatedly, and destroyed the protective anther tube, and damaged the female organs.

In a small greenhouse, manually pollinating plants is cost-effective. Gently shaking plants or tapping flowers releases pollen from male flower parts to female structures. Hand-held pollinator wands have vibrating heads used to touch the base of flowers. Also, there is battery-operated or electric tooth brush used to pollinate flowers. Most of the investigations on electric vibrators for pollination of tomato flowers were conducted in greenhouses in Europe. Kerr and Kribs (1955) used electric vibrator in tomato crop. Wollard and Carlisi (l986) reported that if tomatoes were pollinated with an electric vibrator, plant yield could be increased. Snyder (l995) indicated that electric vibrators can be used to pollinate greenhouse tomato cultivars with equal effectiveness as bumble bees. But all these pollinating techniques used in small greenhouses are tedious and time consuming. So, there is need to provide a device for efficient pollination.

Based on above facts, a mechanical device for pollination was proposed with pulsating air jet which gently shake the flower for pollination. The pulsating air jet with optimized frequency and number of blowers arranged on the frame of pollinator was developed for effective pollination. It was movable in the alleys of greenhouse which facilitate the operation and reduced the human drudgery of manually operated portable pollinators. Keeping in view the need for pollinator, a study entitled “Design and development of pollinator for green house” was done with the following objectives:

1. To determine design parameters of pollinator
2. To develop and evaluate pollinator for greenhouse

Chapter 2

REVIEW OF LITERATURE

Pollination is the important process where pollens are transferred from anther to stigma for enabling fertilization and production of fruits and seeds. Some of natural modes of pollination are birds, bees, butterflies and wind. However, in greenhouses these natural pollination by wind is absent and pollination is carried out by using various colonies of bees. The density of bee colony and their intensity affects the pollination level. Hence these factors need to be considered. Environmental parameter like temperature, humidity etc. also has effect on pollination. In case of small greenhouses manual pollination is preferred over bee pollination because frequent arrival of bee on same flower damages anther. But this manual pollination is tedious and time consuming. So, new mechanical pollinator is developed to overcome these problems in greenhouse tomatoes.

Design and development of pollinator for greenhouse tomatoes requires certain parameters to be studied along with various methods of pollination of tomatoes. Review of previous research work done related to natural pollination of tomatoes, bee pollination in greenhouses, effects of environmental parameter on tomato pollination and mechanical pollination in tomatoes was done. The review of literature done for this study is presented under the following sub headings:

i. Pollination of tomatoes in open fields

ii. Pollination of greenhouse tomatoes

   a. Bee pollination in greenhouses

   b. Mechanical pollination in tomatoes

   c. Comparative study of various pollination methods

iii. Effects of environmental parameter on tomato pollination

iv. Mechanical pollinators for other crops

2.1 Pollination of tomato in open field

Hanna, (1999) conducted studies to determine the effect of using an air blower for assisting natural wind pollination on fruit and yield characteristics of three tomato cultivars in the year 1994, 1995, and 1997. Tomato flowers and plant was vigorously shaken by air blower assisted treatment. The shaking was done on every other day for four weeks at midday. Flowers and plants in the control treatment were exposed to wind only. In the treated plants, the yield was significantly higher in two years. Marketable and total yields in all years were significantly higher for all tested cultivars, and yields of culls in two years were significantly lower. Number of seeds per fruit, fruit diameter and weight increased in all years.

Al-Abbadi, (2010) conducted an experiment to study and evaluate effects of natural pollination on tomato cultivated in open field at Agriculture Faculty Research Station at Mutah University (Karak, Jordan) and these were compared with those isolated with muslin cloth in similar field condition without any pollinator agents. Five rows were for natural open-pollination and five caged tomato rows were evaluated. Data of 15 plants were randomly selected in each row were recorded and analyzed statistically. The percentage of fruit size, fruit weight, fruit set, the number of seeds per fruit and fruit firmness were the measures of pollination effectiveness. Results showed that open cultivated plants had highest fruit sets as compared to isolated plants with muslin cloth due to exposure of pollination agents. The fruit weight and number were 2.5 times higher in case of open pollinated compared to isolated plants. Also, number of seeds per fruits and fruit size indicated a significant increase for the open field-grown tomato compared with the isolated plant.

Franceschinelli *et al.* (2013) reported that the tomato plant has a specific relationship with native pollinators, because the form of tomato flowers is adapted to buzz pollination. Hence, they have specific relationship with the native pollinators (native bees). Pollination deficiency in crop is due to absence or low densities of bees in tomato fields. This study indicated that open field tomato with bee visiting flower had higher pollen load on stigma than unvisited flowers. Also, it showed that fruit production increased due to pollen load on stigma. Thirty-seven plants of three crops were selected where each had one inflorescence bagged in the field. Stigmas were collected from bagged and non-bagged flowers and the amount of pollen on their surfaces was quantified. Comparison of fruit production was done after 40 days where fruits were weighed, measured, counted and had their seeds counted. Stigma of non-bagged flowers had more pollen grains for pollination than stigma of bagged flowers. Fruit production was higher in non-bagged inflorescences than in bagged inflorescences. Also, heavier fruits were produced by non-bagged flowers than bagged flowers. There were more seeds in the non-bagged fruit. The results showed that native bees buzz-pollinate tomato flowers increased the pollen load on their stigma and consequently increased fruit production and quality of fruits.

In open field condition pollination is done by natural pollinators such as bees, birds, butterflies and wind. Air blower can be used as supplement for pollination

2.2 Pollination in greenhouse

2.2.1 Bee pollination in greenhouse

ASADA *et al.* (1996) examined pollination of tomato (Lycopersicon esculentum MILL) by four native species of Japanese bumblebees (*B. ignitus SMITH, Bombus hypocrite hypocrita PEREZ, B. diversus diversus SMITH and B. ardens ardens SMITH*). The pollination by Japanese bumblebees gave higher fruit rate (84-100%) and very less amount of puffy fruits (0-7%). The pollination efficiency of Japanese bumblebees and an imported non-native bumblebee (*B. terrestris*) had no significant difference between them. Native bumblebees were recommended for pollination of tomato because there were no ecological risks.

Hogendoorn *et al*. (2000) investigated whether the native green carpenter bees (*Xylocopa Lestis*) could be used as an alternative to bumble bees for tomato pollination. *Lestis* females visited and buzz pollinated tomato flowers in greenhouse. Pollination of tomato flowers by *Lestis* had more seeds and average fruit size than non-pollinated tomatoes by *Lestis.*

Morandin *et al*. (2001) conducted study to assess level of pollination of tomato (Lycopersicon esculentum Mill.) in commercial greenhouse in relation to bumble bee's colony densities and activity. Five categories were selected on the basis of bruising effect caused by bumble bees for the assessment. Photodiode monitors inserted into hive entrance were used to measure colony activity. Up to mean of 400 pollens per stigma, level of pollination was correlated positively with activity of bees. After this, there was no increase in pollination level by increasing activity. In the commercial greenhouse studies, densities of colonies ranged from 7.6 to 19.8 colonies per hectare with mean of 11.660. For sufficient pollination, an average activity of 2,000 bee trips per hectare per day was more than adequate and that this level of activity could be achieved with 7Ð15 colonies per hectare, depending on greenhouse conditions. To achieve this level of pollination, greenhouses requires 15 colonies per hectare. These colonies may be able to increase bee activity through alteration of greenhouse conditions. Levels of pollination decreased as increasing distance from bee colonies, across 50-m rows of tomato plants. This suggests that colonies should be evenly distributed throughout a greenhouse.

In another study by Morandin *et al*. (2001) to assess the tomato quality with level of buzz-pollination by bumble bees in laboratory. Bruising of tomato anther cones by bumble bees was studied in the greenhouses in the Leamington, Ontario area. Bruising was categorised into five levels. For each bruising level the number of pollen grains were determined, and it was found to be a good predictor of stigmatic pollen load. Experimental flowers were pollinated by bumble bees and on the degree of anther cone discoloration bruising levels were assigned. Fruit set, number of days until ripe, tomato weight, roundness, minimum diameter, number of seeds, weight, and percentage sugars were assessed and compared among bruising level. In no pollination, fruit set was 30.2% whereas 83.3, 84.4, 81.2, and 100% of the flowers set fruit in bruising levels 1, 2, 3, and 4, respectively. From no bruising to different levels of bruising number of seeds, minimum diameter, and tomato weight increased. There was no significant increase in weight or diameter above bruising level 1. Also, there was no increase in the number of seeds per fruit after a bruising level 2. The study concluded that there was no significant enhancement of quality after bruising level 2 or above.

Greenleaf *et al.* (2006) investigated how tomato production was affected by wild bees in northern California. Bees enhanced the production of crop by pollination. Wild Bee pollination increased the production of field-grown tomato, and crop generally considered as self-pollinating plant. Bees (*Anthophoraurbana Cresson and Bombus Voznesenski Radoszkowski*) were affected differently by land management practices. Species-specific differences in dependency on natural habitats underscore the importance of considering the natural histories of individual bee species when projecting population trends of pollinators and designing management plans for pollination services. Thus, to maintain entire bee community, multiple approaches should be implemented along with maintaining natural habitat.

Bell *et al.* (2006) conducted a study to evaluate pollination effectiveness of bluebanded bees in greenhouse tomatoes. Pollination by bluebanded bee was compared with mechanical and control. In both mechanical pollination and pollination by bluebanded bee treatments, fruit set, diameter and individual fruit weight was significantly increased compared with control treatment. It was concluded that use of *A. Holmesi* may be an effective alternative for pollination of tomatoes in greenhouse (in Australia) to use of mechanical pollination methods.

Santos *et al*. (2009) conducted experiment to study the effectiveness of stingless bee (*Melipona quadrifasciata*) and honey bee (*Apis mellifera*) in pollination of greenhouse tomatoes. Number of fruits (1414 tomatoes), tomato fruit weight, and number of seeds in fruit were more in greenhouse tomatoes pollinated with stingless bees. Greenhouse tomatoes pollinated with honey bees had the same size and weight as those produced in control greenhouse. Pollination of greenhouse tomatoes with stingless bee was effective than pollination by honey bee.

Ahmad *et al.* (2015) stated that proper pollination practices were needed in greenhouse tomato crops for commercial production of tomatoes. Bumblebees (Bombus terrestris) increases the tomato production for better economic outcome. Effect of different parameters were studied on manual, self and bumblebee pollination methods. There was significant increase in roundness, fruit size and number per truss in bumblebee pollination method. Bumble bees increased quality and yield of tomato in green house and reduced the need of manual pollination.

Amala *et al.* (2017) investigated the effect of buzz pollination of native bee species (Amegilla zonata and blue banded bee) and sweat bee (Hoplonomia westwoodi) on number of seeds and fruit setting in open field tomatoes. A zonata pollinated flowers recorded significant high number of seeds, number of fruit set and fruit weight in flowers compared to the sweat bee pollinated flowers and wind pollination.

Plate 2.1: buzz-pollination by bumble bees

Pollination by various bees were studied in greenhouses but among all these bees bumble bee was found most effective for pollination of tomato. But in small greenhouses these bees pass over the flowers repeatedly and hence, damages the stigma of flower. This reduces the production of tomato. Hence human intervention is needed in small greenhouses for effective pollination.

2.2.2 Mechanical pollination in tomatoes

Nahir (1984) developed a device to induce pollination in tomatoes grown in off season. Two prototypes versions were developed: one tractor-mounted for field grown tomatoes and one back-pack model for greenhouse-grown tomatoes. Both models employed a pulsating air jet as a vibration energy carrier. In the frequency range of 5 to 60 Hz the flower has a single natural (resonant) frequency in the vicinity of 22 Hz. As the air velocity was increased up to 60 m/s, greater flower acceleration was resulted, and pollen deposition was increased. In field tests the use of these prototypes resulted in an increased pollination rate and greater yield of tomatoes. Vibrating wand and electric toothbrush are generally used for pollination of tomato in greenhouses, but these are time consuming and tedious methods. Blowers were also used in one of the studies for pollination but they were not cost effective.

The poor set of fruit formation in tomato in greenhouses is due to inefficient pollination. The effect of truss vibration on pollination was studied by Ilbi *et al*. (1993). Different durations of truss vibrations were selected under various treatments such as truss vibration for one second, three seconds, five seconds and un-vibrated control treatment. The results indicated that truss vibrated plants gave 75% higher yield than control treatment. Yields for 5, 3 and 1seconds treatments were 87.4%, 67.7% and 70.6%, respectively. Difference between treatment duration were not statistically significant

Cuellar *et al*. (2001) defined that actual yields of greenhouse tomato crops were limited due to lack of pollination practices in Colombia. For evaluation effect of pollination on yield and productivity of tomato, two methods of pollination were practiced; use of electric vibrator or mechanical bee and other inducing vibration by striking the guiding wires. Its importance on quality and fruit development rate was also studied. The results showed that the production increased by 34 % per plant by use of the electric vibrator. Also, fruit diameter, fresh weight and number of seeds per fruit

(70 mm, 163.3 g and 128 seeds per fruit respectively) increased with this practice. The fruit growth period of electrical vibrated fruits was shorter (63.9 days) than the control treatment. The wire striking treatment did not indicate any significant increase in all measured variables. An analysis of cost and benefits indicated that the electrical vibrator was profitable, with increase in fruit production. It also had higher proportion of big fruits and greater market value.

Hanna (2004) conducted study to determine effectiveness of air blowers compared to hand held electric vibrator. He reported that blowers were less time consuming and incur less cost of operation or more economical for pollination in two different varieties of tomato. Marketable yield from tomato cultivars with electric vibrator was greater than blower pollinated tomato cultivars. Also, in case of electric vibrator pollinated tomato had lower yield of culls as compared to blower pollinated tomato. Interactions between cultivar and pollinating tools were not significant except for fruit weight. Air blower pollination needed 7.13 man-hours to pollinate 640 plants for 13 weeks whereas electric vibrator required 11.75 man-hours. The time needed to pollination was lower in air blower pollination. Labour cost was $82.25 for the vibrator pollination and $49.92 for the air blower pollination. The overall labour cost in case of blower pollination was lower but marketable yield was also less than electric vibrator pollination. Yield loss using the air blower for pollination could not be compensated by savings in operating costs.

2.2.3 Comparative study of various pollination methods

Monteiro (1985) conducted experiment to study the effect of auxin, gibberellin and vibrator on greenhouse tomatoes fruit-setting and yield in mild winter climatic conditions. Yields was higher in cool greenhouses because of bigger fruit size and more numbers of flowers and fruits. But the harvest was rather delayed in the cool greenhouse. Auxin and vibrator increased fruit size and yield, but decreased the amount of fruits. Gibberellin induced the highest fruit - setting but with very small fruits

Banda and Paxton (1991) carried out an experiment to compare the effectiveness of bees in pollination of tomatoes grown in greenhouse during summer of 1989. Bumble bees and Honey bees were compared with traditional vibration pollination. The effectiveness was measured in case of fruit size, fruit weight, fruit set and see content. Results showed that the bumble bees are effective pollinators in greenhouse tomatoes.

Cribb *et al*. (1993) used four pollination methods namely natural pollination, pollination by honeybee, vibrating wand for pollination and pollination by honeybee and vibrating wand together for pollination of greenhouse tomato. Factorial experiment was used to compare these four methods of pollination. Two late season cultivars of tomatoes were used for study (Criterium and Gold Star). The honeybees and/or vibrating wand for pollination improved the quality and yield of harvestable fruits. Pollination treatments had increased the yield during the first half of cropping period from late May until early October. The highest yield was obtained in case of pollination by honeybees in these two cultivars of tomatoes.

Snyder (l995) used two 7.3 × 29.3 double plastic-covered greenhouses to compare the conventionally used electric pollinator to bumblebees for effective pollination in spring 1993. RCBD was used for analysis. Trust performed better than Caruso in quality and yield, although fruit size was smaller than Caruso in greenhouse (12 replications, RCBD). In another greenhouse (four replications, RCBD), Switch and Match were better than all others (Capello, Belmondo, Rakata and Laura) for quality variables and most yield. Two pollination techniques had similar means across varieties, with marketable weights identical. For greenhouse ranges of 0.1 ha or larger (gutter-connected), bumblebees for pollinating hydroponically grown tomatoes was an economically viable option.

Pressman *et al*. (1999) compared the pollinating efficiency of electric bee with the bumble bee in tomatoes grown in a greenhouse. The experimental data showed that these two methods had similar effect in yield, fruit set, fruit size and seed number under the moderate climatic condition. But in case of severe winter conditions bumble bees were more efficient than electric bees which was practiced 2-3 times a week. Also, high percentage of fruit set was obtained in case of low pollen grains per flower by the bees. Under some of the adverse conditions the flower set by two bees were equal when electric bee was operated every day. This experiment concluded that bumble bees were effective pollinator under the favourable as well as adverse conditions. To achieve the efficiency by the electric bee the frequency of use was to be adjusted according to the circumstances and operated daily in adverse conditions.

Nazer *et al*. (2003) used four pollination techniques; Bumblebees *(Bombusterrerstris L.)*, plant growth bioregulator (PGB) (Parachlorophenoxy acetic acid), hand vibration, and control (natural pollination) in an experiment to study the effect on tomato (Lycopersicon esculentum Mill) production in the greenhouses. At a temperature range of 17-42°C during the day and 2-14°C at night bumble bees visited flowers without any problem. Yield per plant was significantly higher in bumblebee pollinated plants than in the plants treated with PGB, vibration and the control, respectively. In 10 clusters, fruit set of tomato flowers for bumblebee treatment, PGB application, the control and vibration were 99.1, 96.7, 76.7, and 65.7% respectively. The quality of fruits was superior in the bumblebee pollinated flowers. The fruits were hard, with more seeds, and had better appearance and a high specific gravity. The average fruit weight for the bumblebee, PGB, the control and vibration were 100.3, 80.5, 70.6 and 84.1 g, respectively. Bigger sized but puffy fruits (108.4 ml) was produced in the PGB treatment. While vibration treatment had the highest fruit size (126.8 ml), followed by the bumblebee and the control with 99.3 and 98.5 ml, respectively. Bumblebee treatment had significantly higher fruit specific gravity than other treatments, with no significant differences between the vibration and the PGB treatments. The hardest fruits were found in bumblebee treatment, while the PGB and the vibration treatments had fruits with intermediate hardness and the control treatment had the least hard fruits. Average seeds per fruit were 177.0, 61.8, 89.8 and 86.5 for bumblebee, PGB, the control and vibration respectively.

Vidyadhar *et al*. (2015) conducted experiment to study effect of pollination methods and time of pollination on seed yield and quality parameters in cherry tomato grown under different protected conditions. Among the structures, semi-controlled environmental polyhouse recorded significantly higher fruit set of mature berries (40.99%) followed by naturally ventilated polyhouse (40.51%) and insect-proof nethouse (39.25%). More fruit set (41.76%), berry width (23.6mm), berry length (22.2mm), berry weight (6.070 g), number of seeds (68.05), seed yield per berry (0.0872 g), 100-seed weight (0.1291 g) and germination (80.71%) were recorded in pollination by air blower.

Comparative studies on various pollination methods of greenhouses were carried out, which inferred that pollination by bumble bees was most effective method in large greenhouses.

2.3 Effects of environmental parameter on tomato pollination

Sawhney *et al*. (1984) used low (LTR), intermediate (ITR), and high (HTR) temperature regimes to grow tomato plants (*Lycopersicon esculenturn Mill*.). The produced fruits were significantly different in certain characteristics. Fruits were larger both in size and fruit number under LTR, and also contained a higher number of locules than the fruits produced under ITR. Under ITR fruits were larger than those developed under HTR. Fruits from plants maintained in temperature-controlled growth chambers before and after pollination were generally larger than those transferred to a greenhouse after pollination. Fruits grown under LTR had some abnormalities but not in those produced under HTR and ITR.

Abdul-Baki *et al.* (1995) used optimum- (27/23^{0}C, day/night) and high-temperature (35/23^{0}C) stress regimes to grow heat-sensitive and heat-tolerant *(L. pimpinellifolium Mill. and Lycopersicon esculentum Mill.)* genotypes in greenhouses. Determination of percent fruit set at optimum and high temperatures gave various levels of heat tolerance in genotype. Fruit set ranged from 41% to 84% was under optimum temperature and from 45% to 91% in the heat-sensitive and heat-tolerant genotypes respectively. There was no fruit set in the most heat-sensitive genotypes under high temperature. Fruit set ranged from 45% to 65% in the heat-tolerant genotypes. The response of pollen to heat treatments was genotype dependent and not a general predictor of fruit set under high-temperature stress.

Peet *et al*. (1996) studied the effect of night temperature on pollen characteristics, early fruit growth, growth and fruit set in 'Laura' plants (Lycopersicon esculentum Mill.) at 18, 22, 24, and 26 ^{0}C night temperatures and 26^{0}C day temperature in phytotron facility of North Carolina State Univ. At night temperatures of 18 and 22^{0}C, total and percentage normal pollen grains were higher than at 24 and 26^{0}C. But germination was highest at 26^{0}C. At 18^{0}C night temperatures, seed content was higher compared to other treatments. Fruit on the first cluster and numbers of flowers were lower 26^{0}C night treatment than in the other night temperature treatments. Plant height was greatest at 22^{0}C night temperature treatments but total shoot dry mass was lowest. More rapid development was observed with increasing night temperature due to increase in fruit mass. Night temperatures of 26^{0}C reduced fruit set percentage and fruit number slightly at a 26^{0}C day temperature, even though these temperatures were above optimal for seed formation and pollen production. No effects of night temperature treatment on male sterile plant in the greenhouses was observed.

The environmental parameters have significant effect on pollination of tomato. The temperature and humidity affect tomato pollination. At higher temperature, lower production was observed.

2.4 Mechanical pollinators for other crops

Ibrahim *et al.* (1987) developed a new ground level pollinator (AlNahreen pollinator) for date palm trees as a standard mechanical pollination method in which pollens were collected and blown for deposition on female flower (Plate 2.2). AlNahreen pollinator consists of an engine-driven air compressor. It was mounted on two-wheel cart which was small and hand driven. Aluminum pipes were used to convey the pollen mixture to the bloom area. Its superior performance was proved by field evaluation. Experimental results indicated a considerable increase in number of trees, field capacity and field efficiency that can be pollinated per season. In addition, considerable reduction of pollination cost and labor requirements were indicated. The new pollinator had control over pollen application rate and reduced pollination cost, thus reducing pollen wastage to minimum. Hence, overcoming shortcomings associated with other pollinators.

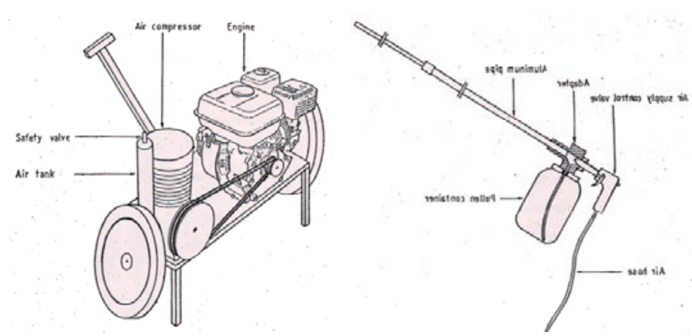
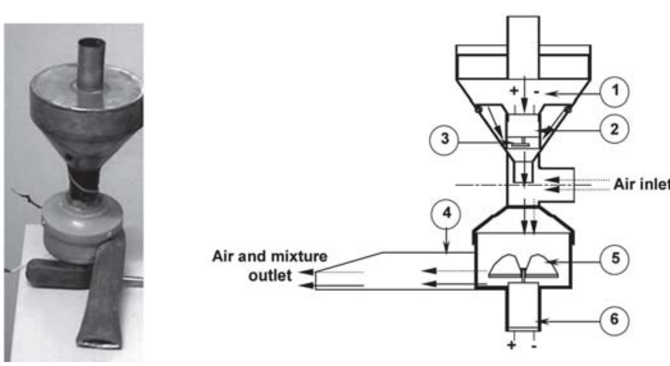


Plate 2.2: Schematic diagram of AlNahreen pollinator

Razeto *et al.* (2005) carried out two artificial pollination field trials in kiwi fruit plants (Hayward) in Central Chile during the 1999-2000 seasons. Both the trial used collected pollens from matua. Various treatments used for the study were hand pollination; hand pollination using a velvet pad attached to a handle; and mechanical pollination using a portable pollen dusting machine; and a control treatment without artificial pollination. A random split plot design with 5 replications for each trial was used. In both the trials, hand pollination and hand pollination with pads increased fruit size, fruit set, fertilized locules per fruit and seeds. Mechanical pollination also increased these attributes but to a lesser extent. The supplementary bee pollination tended to increase seeds, fruit size and fertilized locules per fruit.

Jojoba is a perennial evergreen shrub. It is found in the Sonoran Desert of the southwestern U.S. and northwestern Mexico. It is dioecious plant. Hence, female and male flowers are present in separate plants. It is pollinated by wind. The yield variation was detected due to pollination problems in commercial fields. In a study by Coates *et al.* (2006), pollens were applied mechanically as an alternative which improved fruit set, and increased yield. Both untreated and treated plants, flower set was good and supplemental pollens did not provide significant increase in the number of flowers. These results were due to sufficient pollen was coming from pollinator rows of male plants in the test fields. Weather condition had strong influence on pollen quality. Low pollen viability was observed when pollen was harvested following a two-day period with hot, dry winds. This showed that pollen collection must be a timely operation which ensured availability of pollens for supplementary use.

Yehia *et al*. (2009) carried out a study to design and developed pollination-device (Plate 2.3) for date palm trees. The designed pollinator consisted of a fan fixed on 12-volt electrical motor. The motor was powered by a dry cell battery. Other components were pollination conical-hopper and a vibrating plastic roller (feeder) that was rotated by another 12-volt motor. Flour of pollens plus fine bran having a ratio of 1:1 and air speed of 1.8 m/s gave adequate performance with quantity of mixture inside the hopper as 50 - 100 g (all sizes). This gave a lateral spread of 40 cm, maximum advance of 100 cm, and a mixture discharge of 0.3-0.33 g/s.



1) Pollination-grain hopper,
2) Vibrated plastic-roller,
3) Nonaxial mass,
4) Conical tubes,
5) Fan,
6) 12 V electrical motor

Plate 2.3: Pollination device for date palm

Mostaana *et al*. (2010) developed pollination device to overcome the climbing on palms, a traditional method of artificial pollination which was tedious and costly. New developed mechanical pollinators eliminated the need to climb the palms and reduced the time and work intensity. But the controllability and reliability due to design was low. Also, it needed two workers to perform the operation. So, a new electrical pollinator for date palms was designed and developed. This system used peripheral dispersion method, improved controllability, pollination feasibility reduced operation time, cost, tool size and weight. Mean fruit set attained by the electrical pollinator, traditional method and mechanical pollinator was 68.12, 64.94 and 62.04 % respectively. About 120 palms (For one ha) could be pollinated with the tool which handled 200 cubic centimeters of pollen mixture. The operation was carried out by single worker.

There is global decline in natural pollinators with advancing times so there is need to achieve advancement in artificial pollination. Robotic pollination is an important step forward in agricultural sectors. Robotic pollination does the operation with precision and allows for potentially autonomous operation. However, background research shows that there is sparse development in this area. Barnett *et al*. (2017) evaluated novel robotic pollination system which was mounted on platform. Over 70% of flowers were successfully detected while driving at a slow-speed through kiwi fruit orchard rows Robotic pollinator pollinated over 80% of the flowers by featured wet-application robotic pollination system.

Previous studies in open field condition showed that pollination of tomato in open field condition was carried by natural pollinators such as wind, bees, butterflies and birds. So, there was no need of intervention for pollination of tomato. But in greenhouses, obstacle to natural pollinators is imposed so interventions are needed for pollination. Bumble bees were used for pollination in greenhouses, where bumble bees were effective pollinators in large greenhouses. In small greenhouses bumble bees created problem by damaging stigma of flower and reduces fruit formation. So, mechanical pollinators are used for pollination such as manual hand pollination, pollination with vibrating wand and pollination using blower. Vibrating wand showed good pollination efficiency, but were time consuming and tedious. Hence, blower was used for pollination, but they were less cost effective. So, there is a need for a device which pollinates tomato plants effectively in greenhouses.

MATERIALS AND METHODS

This chapter deals with the description of materials used and method followed in the research work. An experimental set up was developed to determine the required air velocity range for effective pollination. The design parameters for pollinator were determined based upon developed experimental set up, previous knowledge and plant parameters in greenhouse. Based on design parameters, a pollinator was developed. This was evaluated in laboratory and field. The programme of research work is as follows:

i. Development of experimental set up for determining design values of pollinator
ii. Determination of design values of pollinator components
iii. Fabrication of a pollinator for green house
iv. Laboratory evaluation of pollinator
v. Field experiment in greenhouse for performance evaluation of pollinator
vi. Ergonomic evaluation
vii. Statistical analysis
viii. Cost economic analysis

3.1 Development of experimental set up for determining design values of pollinator

Experimental set-up to determine design parameters was developed. Tomato plants were grown in pots. The plants were ready for experiment when they had sufficient flowering on them. These plants were used to determine the range of air velocity for effective pollination. This design parameters were determined by using the experimental set up. The experiment set up was equipped with a blower with wide range of air velocity. This blower was used to blow air on the tomato plants with flowers. Following steps were followed

a) Air was blown on each potted plant with specific velocity (15m/s, 30m/s, 45m/s, 60m/s) for 1 min duration thrice in a week until fruiting sets in

b) Number of flowers before the fruiting and after the fruit formation were recorded

c) Calculation of pollination efficiencies with following formulae,

$$\text{Pollination efficiency} = \frac{Number\ of\ fruit\ sets}{Total\ number\ of\ flowers}$$

d) The velocity and pollination efficiency thus determined the effective velocity range for pollination

In this way the design parameter of pollinator was determined using the experimental set up as shown in Plate 3.1

Plate 3.1: Experimentation for determining velocity range for pollination

3.2 Determination of design values of pollinator components

Various design parameters required for pollinators were effective velocity range, pulsation frequency, pollination height required for covering flowering band of plants, width of pollinator frame, angular movement of blowers and number of blowers to cover flowering band of plants for pollination. The design parameter, effective velocity range was determined by experimental set up. It was in the range of 30-45 m/s. The pulsation frequency needed was determined by referring previous research work. The pulse frequency range for effective pollination was 15-25 Hz. Based on flowering band, number of blowers, angular movement of blower and height of pollinator frame was determined. Width of pollinator frame was determined by measuring row to row distance between tomato plants or alleys of greenhouses.

3.3 Fabrication of a pollinator for green house

Fabrication of pollinator for greenhouse tomato was done as given below:

i. Selection of blower
ii. Design and development of pollination unit to achieve pulsation
iii. Development of frame for pollinator depending upon plant parameters

3.3.1 Selection of blower

The blower was selected on the basis of velocity range for effective pollination, which was 30-45 m/s. A Cheston CHB30 blower as shown in Plate 3.2was selected with air flow rate 2.3 m^3/min. It was a commercial blower selected due to its easy availability in the market and reasonable price along with sufficient velocity range as required.

The dimensions and specification of blower are given in Table 3.1

Table 3.1: Specification of blower used in pollinator

Parameter	Value
Air flow capacity (m^3/min)	2.3
Number of phases	1
Weight (kg)	2
No Load speed(rpm)	14000
Dimensions (mm)	235x190x170
Material	Plastic
Power source	AC Motor
Power cord length (m)	1
Voltage (V)	220
Amperage (A)	1.5
Power source	Corded
Height (mm)	100
Power Consumption (W)	550

Plate 3.2: Blower used in pollinator

3.3.1.1 Speed controller for blower

A speed controller was used to control the air flow rate of the blower (Plate 3.3). This controller uses novel bi-directional high-power Silicon Control Rectifier (SCR). The output voltage was adjusted anywhere between 50V-220V for use with electrical appliances. It can be used for electric stove, water heater tunes thermal, lighting dimmer, small motor speed, electric iron thermostat, and achieve dimming, thermostats, pressure regulator effect.

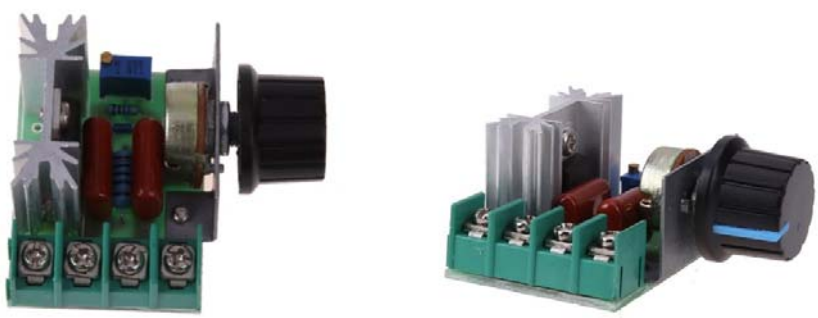


Plate 3.3: Speed controller for blower

3.3.2 Design and development of pollination unit for pulsation of air

The pollination unit was developed with pulsation frequency needed for pollinator by referring literature (Nahir,1984). The required range of pulsation frequency was 15-25 Hz. To achieve this pulsation frequency of air, the pollination unit was developed with various components fabricated using 3D printer.

The pollination unit had the following parts;

i. Blower attachment
ii. Revolving valve
iii. Main casing
iv. Upper casing
v. Upper plate
vi. Nema17 back plate
vii. Arduino programming

3.3.2.1 Blower attachment

Blower attachment was designed on the basis of blower dimensions. The blower had outlet with 410 mm outer diameter (with ovule shape). So, to attach the extension to the blower this part (blower attachment) with circle (Ø = 430 mm) at one end and rectangular shape at another end (76mm x 50mm) was fabricated. It was based on dimensions of revolving valve. Thickness of3mm was selected for the attachment to sustain air pressure. Dimensions of blower attachment are shown in Plate 3.4.

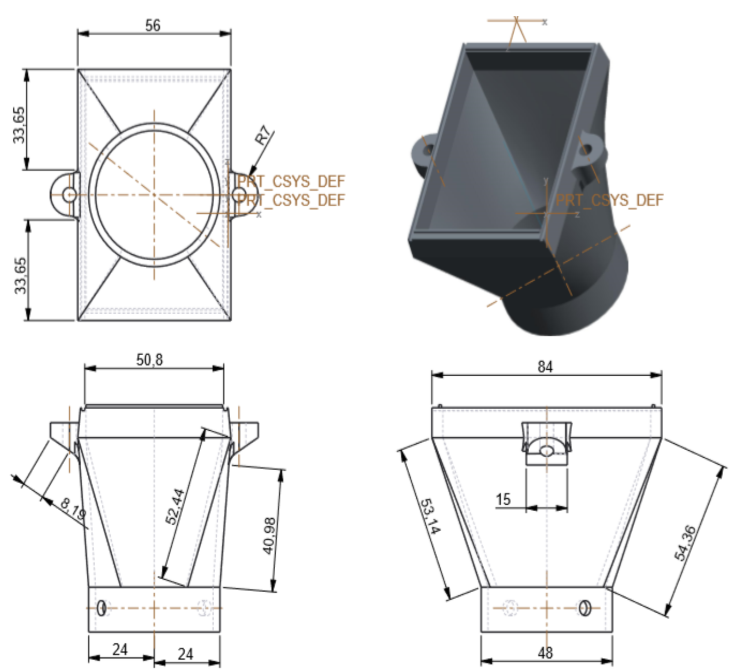


Plate 3.4: Dimensions of blower attachments

3.3.2.2 Revolving valve

The size of revolving valve was based on blower outlet dimensions. Also, the number of blades were decided considering the maximum speed of stepper motor. Practically observing, it was found that stepper motor runs at maximum rpm of 360 under load condition. So, this accounts for 6 revolutions per seconds. Previous studies indicated that the effective range of pulsation frequency was 15-25 Hz (Nahir,1984). In this way, selecting 4 blades, maximum achievable pulse frequency was 24 Hz (4×6 rev per second = 24 cycles per second). The size of blade was considered rectangular with length to width ratio of 1.5:1. The width of blade was considered as 48mm and length as 72mm.Dimensions of revolving valve are shown in Plate 3.5.

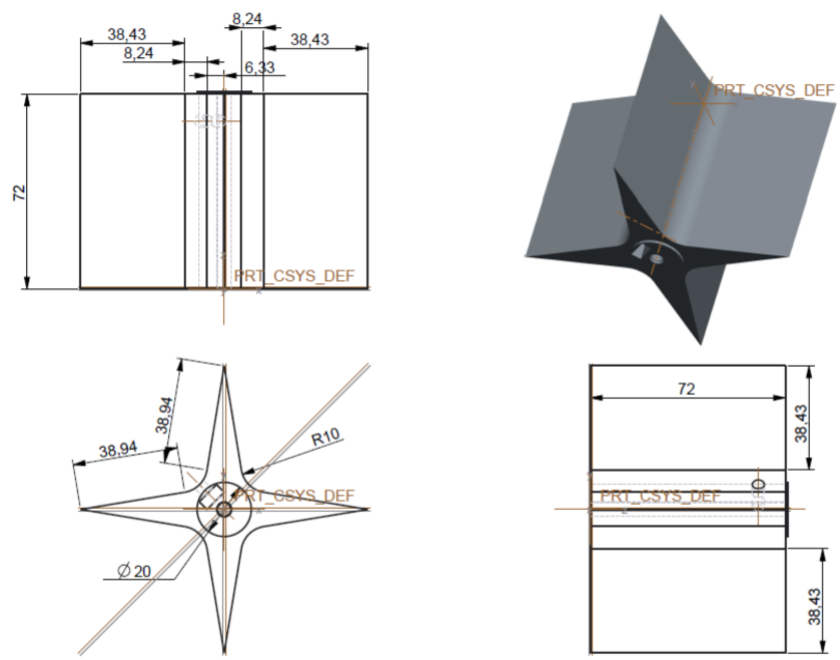


Plate 3.5: Dimensions of revolving valve

3.3.2.3 Main casing

It is the main enclosure in which the revolving valve rotates due to rotation of stepper motor. It had middle part like a cylinder to accommodate the revolving valve. The diameter of cylinder was selected on the basis of diameter of revolving valve. Diameter was selected as 100mm as revolving valve had 96mm diameter with 2mm of clearance on both sides. It had two outlets, one was attached to outer end of blower attachment and the other outlet for pulsating air for pollination. Both the outlets had rectangular cross-sectional area, the blower attachment end outlet with dimension of 50 × 76 mm whereas the other end had same length but width depending on maximum open area with valve rotating in it. It was calculated as

$$Width = Radius\ of\ cylinder - width\ of\ blade \times \cos 45 + clearance$$

$$Width = 50 - 48 \times \cos 45 + 2 = 18\ mm$$

Also, thickness of 2 mm was provided for desired strength. Accordingly, Arduino and other components needed for stepper motor were enclosed in 90mm × 80mm × 31mm cuboid shaped over main casing. Dimensions of main casing is shown in Plate 3.6.

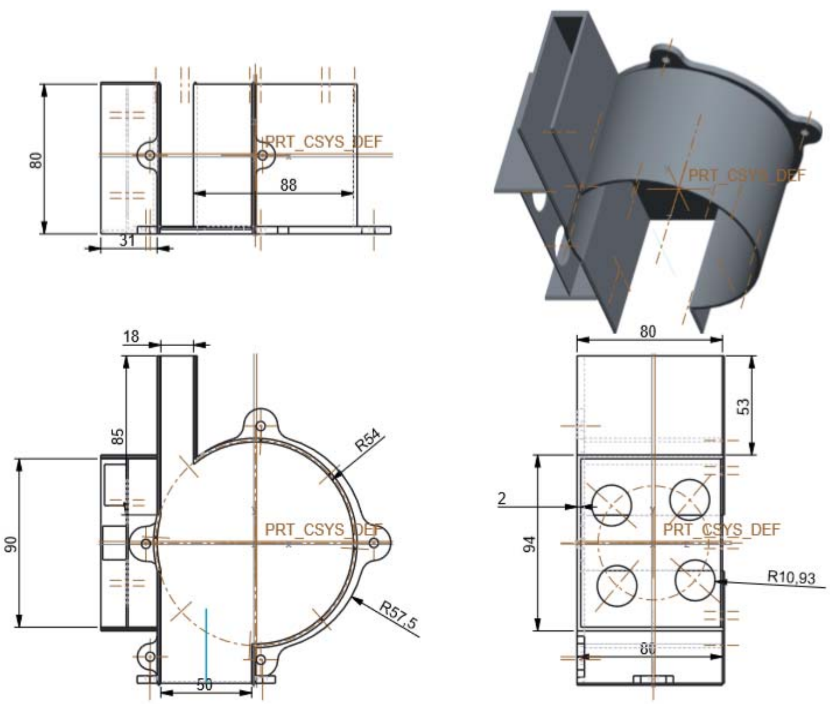


Plate 3.6: Dimensions of main casing

3.3.2.4 Upper casing

Upper casing has the same dimension as main frame and was used to make the whole enclosure air tight. It was attached to the main casing by using LN bolts. It had thickness of 3 mm. Also, it had arrangement for attachment for Nema17 motor along with revolving valve mounted on motor shaft. Dimensions of upper casing are shown in Plate 3.7

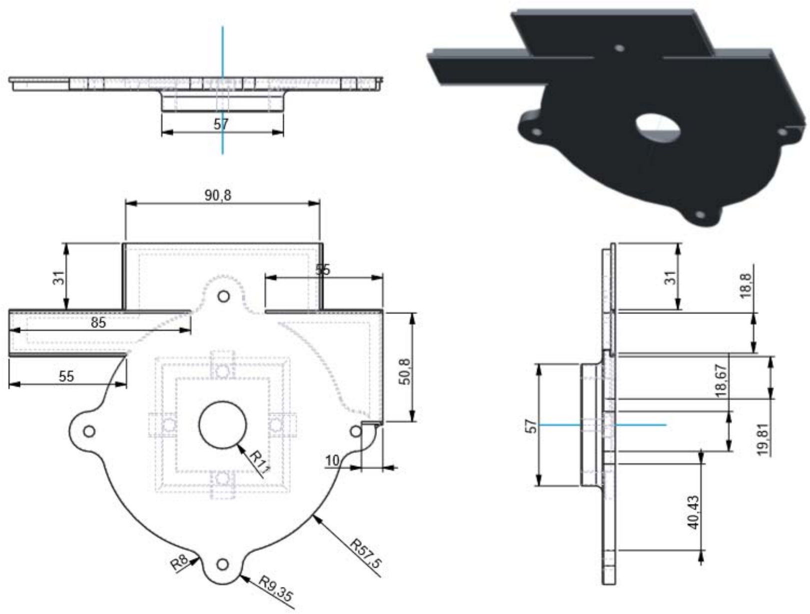


Plate 3.7: Design of upper casing

3.3.2.5 Upper plate

It was designed to accommodate all the parts such as Arduino Uno, easy driver, AC adapter with proper connections in cuboid designed on main frame. Slots were provided for push buttons to control speed of stepper motor. Dimensions of upper plate are shown in Plate 3.8

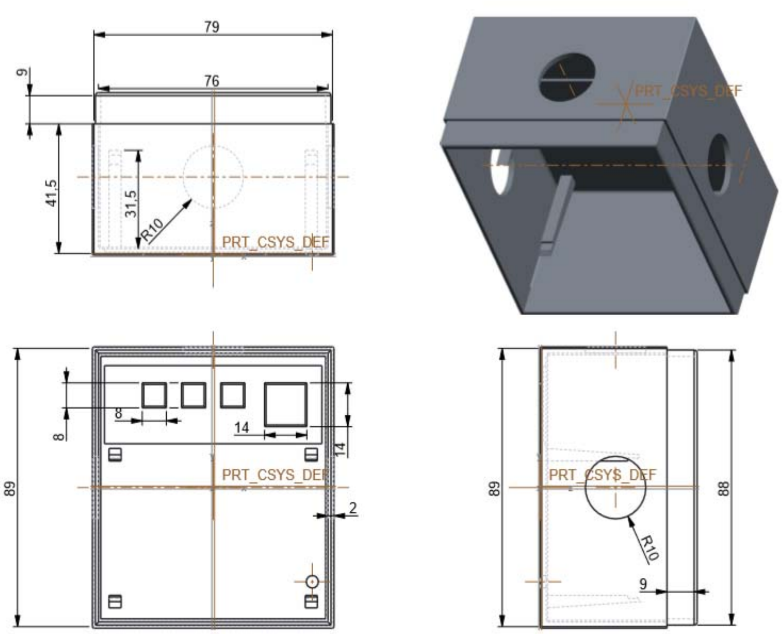


Plate 3.8: Dimensions of upper plate

3.3.2.6 Nema17 motor back plate

It was designed to give support to stepper motor when attached to main frame through upper casing. It had dimensions based on dimensions of nema17 motor. It had dimensions of 43mm (length) × 43 mm (width) × 10mm(height) with 5 mm thickness as shown in Plate 3.9.

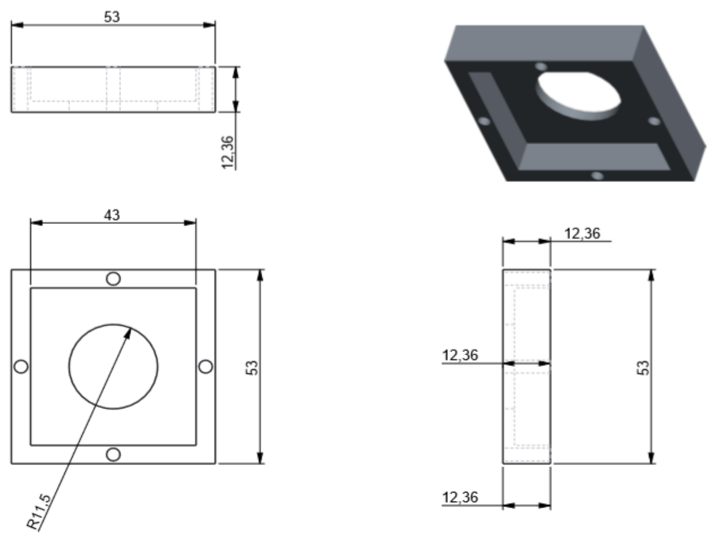


Plate 3.9: Dimensions of Nema17 motor back plate

The whole arrangement of pollination unit is shown in Plate 3.10 and all the components of pollination unit are shown in Plate 3.11

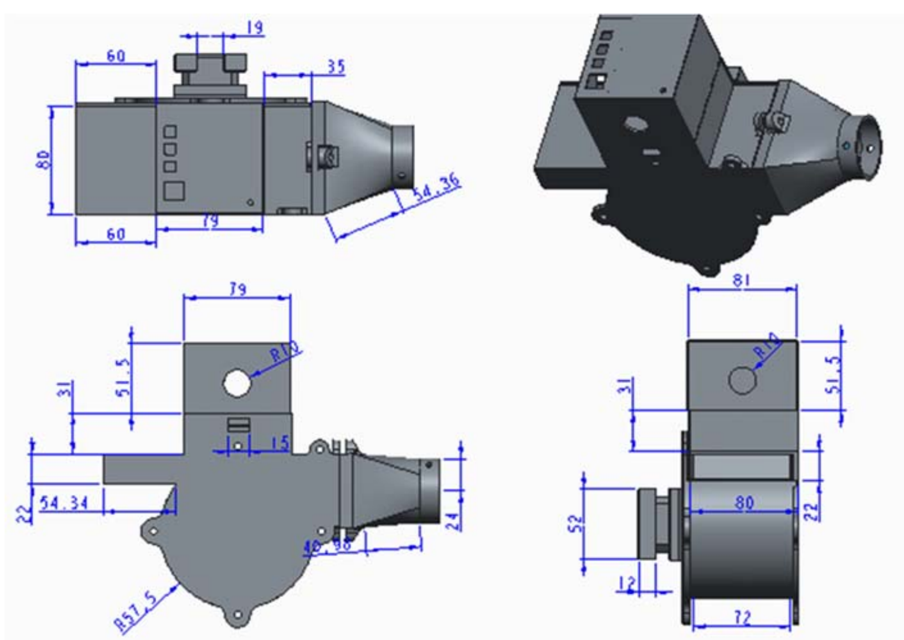


Plate 3.10: Assembled pollination unit

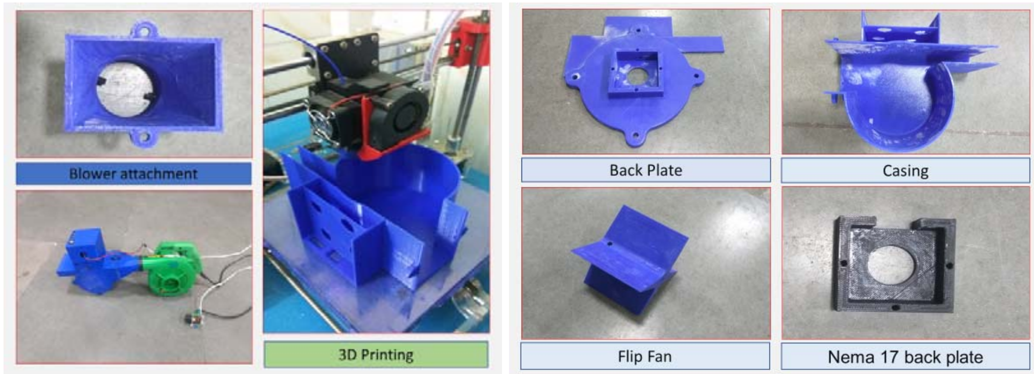


Plate 3.11: Various components of pollination unit

3.3.2.7 Arduino programming

A stepper motor was used to create required pulsation frequency by rotating revolving valve. To drive stepper motor at different speeds, an easy driver (stepper motor controller) controller was used along with program given in Appendix I. The program in Arduino Uno used 3 push buttons and easy driver controller along with 10K ohm resistors to control 3 different speed of stepper motor (Plate 3.12). These three speeds were 360, 300 and 240rpm which gave 3 different pulse frequencies as 24, 20,16 Hz with blade rotor.

The desired air pulsation was achieved by developing Arduino programme by integrating following components

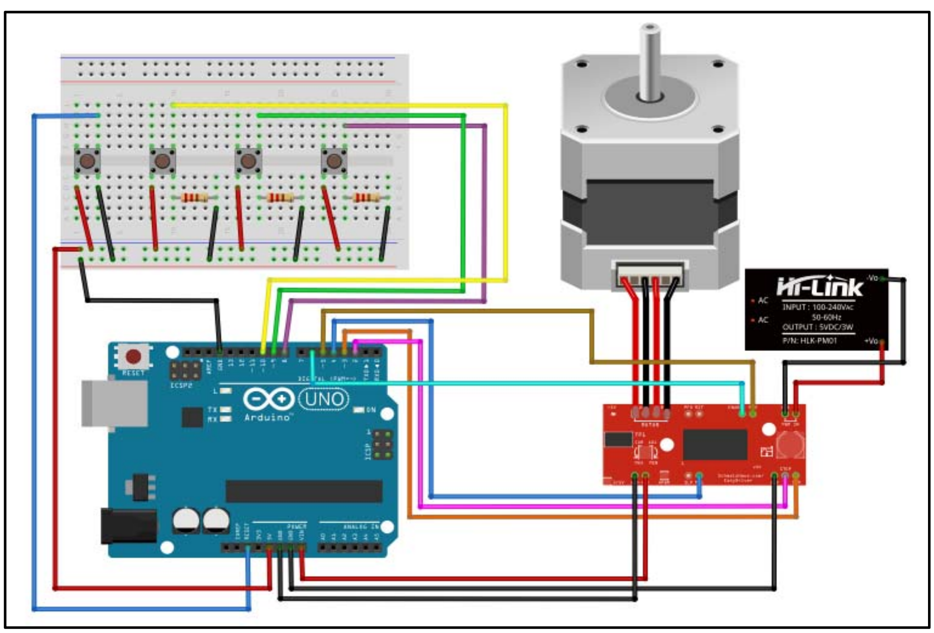


Plate 3.12: Circuit diagram for Arduino programming

3.3.2.7.1 Stepper motor for rotating the revolving valve

A stepper motor is one of the types of brushless DC electric motor (Plate 3.13). It is also known as step motor or stepping motor. It divides a full rotation into a number of equal steps. The motor's position can be commanded to move and hold at one of these steps without any feedback sensor (an open-loop controller), as long as the motor is carefully sized to the desired application in respect of torque and speed.

Bipolar motors have a single winding per phase. The current in a winding needs to be reversed in order to reverse magnetic pole. So, the driving circuit was complex, typically with an H-bridge arrangement. The step angle is a crucial parameter for a stepper motor to guarantee its working accuracy. Smaller values of step angle indicate higher accuracy than bigger ones. Hence, in the present system a small step angle of 1.8° was chosen for the motor. Based on the parameters mentioned above, a two-phase hybrid stepper motor was used in this study. Specifications of stepper motor are given in Table 3.2

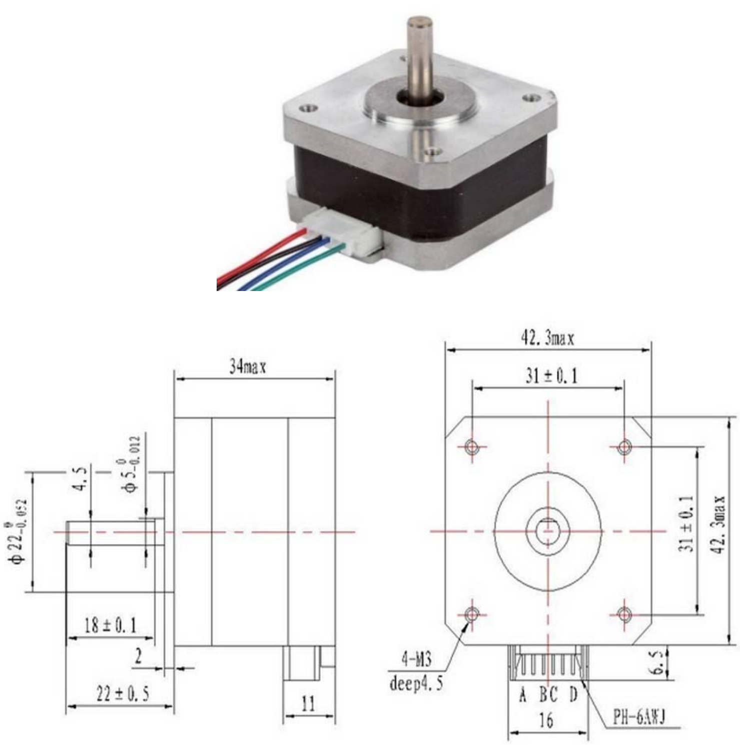


Plate 3.13: Stepper motor and its dimensions

Table 3.2: Specifications of Stepper motor (NEMA 17)

Parameter	Value
Model Series	17HS4417B15-X3
Steps	200
Step angle (degree)	1.8
Motor size (mm)	40 × 42
Rated current (A)	1.7
Phase resistance (Ω)	1.5
Phase inductance (mH)	2.8
Holding torque-Minimum (N.cm)	40
Detent torque-Maximum (N.cm)	2.2
Rotor torque (g.cm)	54
Lead wire (Number)	4
Shaft size (Diameter × Length) in mm	5×24
Motor weight (g)	280

3.3.2.7.2 Arduino Uno for uploading programme

Arduino is an open source microcontroller kits for building digital devices shown in plate 3.14. These are interactive objects which can sense and control objects. The Arduino Uno is a microcontroller board. It is based on the ATmega328P. It had 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analogue inputs, a 16 MHz crystal oscillator, a USB connection, a power jack, a reset button and an ICSP header. It is programmable with the Arduino IDE. It is powered through USB cable or by external 9V battery. It supports microcontroller and connected to a computer with a USB cable. The specifications of Arduino Uno are given in Plate 3.14

Plate 3.14: Arduino Uno

Table 3.3: Specifications of Arduino Uno

Parameter	**Value**
Microcontroller	ATmega328P
Operating voltage (V)	5
Input voltage recommended (V)	7-12
Input voltage limits (V)	6-20
Digital I/O Pin (Number)	14 (6 PWM output)
Analog input pins (Number)	6
DC current per I/O Pin (mA)	20
DC current for 3.3V Pin (mA)	50
Flash memory (Kb)	30
Static Random-Access Memory (Kb)	2
Electrically erasable programmable read only memory (Kb)	1
Clock speed (MHz)	16
Length of board (mm)	68.6
Width of board (mm) Weight (g)	53.4 25

3.3.2.7.3 Easy Driver to control speed of stepper motor

The Easy Driver is a Stepper Motor Controller (A3967) shown in Plate 3.15. Easy diver is a simple stepper motor driver to use, compatible with anything that can output a digital 0 to 5V pulse. The Easy Driver requires a 6V to 30V supply to power the motor, and it can power any voltage of stepper motor. The Easy Driver has an on-board voltage regulator for the digital interface that can be set to 5V or 3.3V. By connecting a 4-wire stepper motor and a microcontroller, precise motor control can be achieved. Easy Driver are used to drive bi-polar motors, and the motors wired as bi-polar (4, 6, or 8 wire stepper motors).

Specifications of Easy Driver are

i. Compatible with 4, 6, and 8 wire stepper motors of any voltage
ii. Adjustable current control from 150mA/phase to 700mA/phase
iii. Power supply range from 6V to 30V

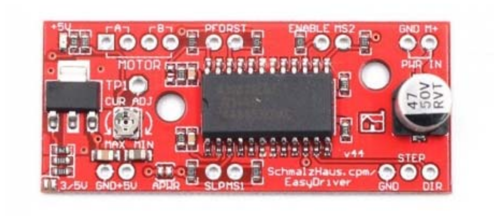


Plate 3.15: Easy Driver

3.3.2.7.4 Resistors

Resistor are the electronic components which oppose the flow of electrons or electric current in an electric circuit. They are made up of ceramic coating with nickel alloy or metal oxides (tin oxide). Resistors when connected in series, same current will flow through them and sum of each resistors will give the total resistance. Likewise, parallelly connected resistors will have same voltage across them and total current is the sum of current in individual resistors. In this study 10 k ohm resistors were used for control switch as shown in Plate 3.16.

Plate 3.16: 10K Resistors

3.3.2.7.5 Push-button to control the speed of Nema17 stepper motor

A push-button is a simple switch mechanism. It generally controls process or a machine. Usually, it is made up of metal or plastic. To accommodate the human hand or finger, it has flat or shaped surface. So, it is easily pressed or pushed. Buttons are mostly biased switches, although there are many un-biased buttons which still requires a spring to return to their un-pushed state. Push buttons used for speed regulation of Nema17 stepper motor are shown in Plate 3.17

Plate 3.17: Push buttons

3.3.2.7.6 AC adapter to supply 12V DC power to Arduino Uno and easy driver

An AC adapter (also known as AC/DC adapter or AC/DC converter) is a type of external power supply, often enclosed in a case similar to an AC plug as shown in Plate 3.18. Adapters for battery-powered equipment may be described as chargers or rechargers. AC adapters are used with electrical devices that require power but do not contain internal components to drive the required voltage and power from main power. The internal circuitry of an external power supply is very similar to the design that would be used for a built-in or internal supply.

External power supplies are used both for equipment with no other source of power or with battery-powered equipment, where the supply when plugged in can sometimes charge the battery in addition to powering the equipment.

Use of an external power supply allows portability of equipment powered either by mains or battery without added bulk of internal power components. Another advantage of these designs is increased safety; since the hazardous 120 or 240 volt mains power is transformed to a lower, safer voltage at the outlet and the appliance that is handled by the user is powered with lower voltage.

Plate 3.18: AC adapter

3.3.3 Development of main frame for pollinator

Main frame was developed for pollinator by considering crop parameters such as row-to-row distance of crops and width of flowering band. The frame was fabricated with parts mentioned below

i. Base frame with wheels
ii. Adjustable frame to cover vertical height zone
iii. Handle
iv. Pollination attachment unit
v. Angular movement for pollination unit

The whole assembled frame with various components is shown in Plate 3.26.

3.3.3.1 Base frame

Row-to-row distance of tomato crop in greenhouse was one meter in the CPCT, IARI. So, width of frame was selected as 500 mm with length to width ratio of 1.5:1. Hence, length was 750mm. The square section pipe of 50mm × 50mm with 4mm thickness was used. Square section was selected because of heavy weight of section provided stability at base with higher height operation. Four rubber wheels of 300 mm diameter × 25mm width were provided for movement. Base frame is shown in Plate 3.19.

Plate 3.19: Fabricated base frame with wheel

3.3.3.2 Adjustable frame to cover vertical distance of flower zone

Depending upon the flowering band which is up to 2m from ground, to cover that height, male square sections with 20mm × 20mm × 1300mm with 2mm thickness and female sections with 25mm × 25mm × 1300mm with thickness 2mm were used to make adjustable frame. Male section was welded to base frame at mid-length of frame and 180mm apart. To vary the height, holes were drilled on both male and female section which could be used for fixing desired height of pollination. Adjustable frame is shown in plate 3.20

Plate 3.20: Height adjustable frame

3.3.3.3 Handle

The design of handle depends upon anthropometric data of workers in India namely bideltoid breadth, inside grip diameter, middle finger palm grip diameter and olecranon height as shown in Plate 3.21. Bideltoid breadth is the horizontal distance across the maximum lateral protrusion of the right and left deltoid muscles. Grip diameter (inside) is the diameter of the widest level of cone which the subject can grasp with his thumb and middle finger touching each other. Middle finger palm grip diameter is the diameter of the widest level of the cylinder which subject can grasp with his palm and middle finger touching each other. Olecranon height is the vertical distance from standing surface to the height of the undersurface of the elbow, measured with the arm flexed 90^0 and upper arm vertical used for deciding handle height. Table 3.4 gives data of s anthropometric parameters needed for handle design of main workers.

Table 3.4: Anthropometric dimensions for handle design

Anthropometric dimensions	Mean (mm)	Range (mm)	5^{th} Percentile (mm)	95^{th} Percentile (mm)
Bideltoid breadth	416	252-260	361	471
Olecranon height	999	780-1234	913	1085
Inside grip diameter	48	30-79	39	57
Middle finger palm grip diameter	28	14-64	18	38

Source: Majumdar *et al*. 2009

Width and height of handle should not be less than 95th percentile bideltoid breadth (471 mm) and 5th Percentile Olecranon height, respectively. So, 500mm handle width was made with height of 1000mm. Handle was made of MS pipe of 20 mm diameter. According to Parekh (1980), for the proper grip the longest finger should not touch the palm while holding the handle and at the same time it should not exceed the inside grip diameter. So, the handle diameter should lie between inside grip diameter of 5th Percentile and 95th percentile of middle finger palm grip diameter. Hence, handle diameter should be between 38 to 39 mm. For this handle diameter, rubber grip was used upon 20 mm MS pipe which made the diameter 38 mm.

Bideltoid breadth

Inside grip diameter

Middle finger palm grip diameter

Olecranon height

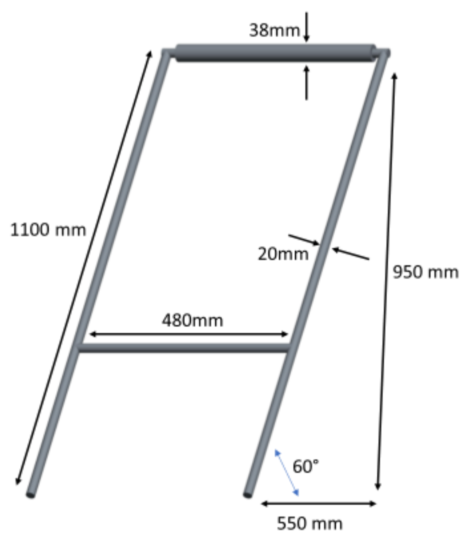


Plate 3.21: Critical Anthropometric dimensions and handle design

3.3.3.4 Pollination attachment unit

Box was designed to attach the pollination unit with the frame using plain bearing as shown in Plate 3.22. Box with dimensions of 180mm × 180mm ×100 mm with 2mm thickness, was made of MS sheet of 2 mm thickness. At one end it was attached to the plate by welding on two male sections of adjustable frame using a plain bearing and another attached to the blower.

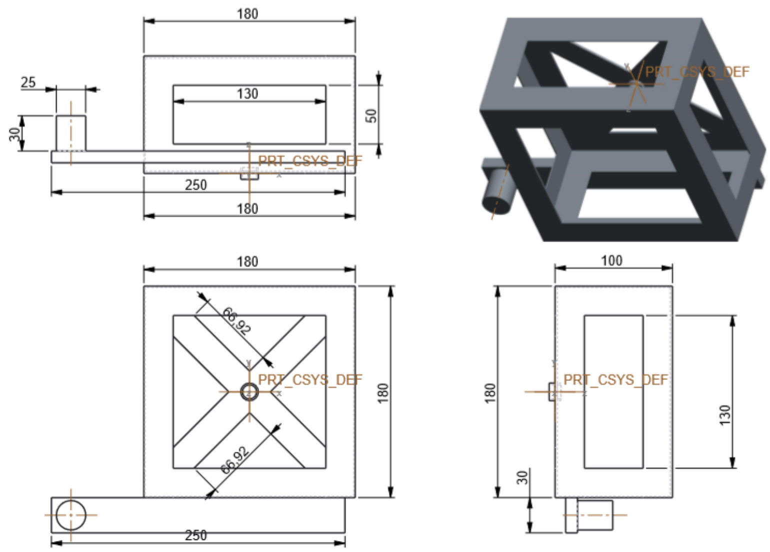


Plate 3.22: Pollination attachment unit

3.3.3.4.1 Plain bearing for free movement of pollination unit with frame

A plain bearing, or more commonly sliding bearing and slide bearing, is the simplest type of bearing, comprising of a bearing surface and no rolling elements (Plate 3.23). Therefore, the journal (the part of the shaft in contact with the bearing) slides over the bearing surface. The simplest example of a plain bearing is a shaft rotating in a hole. Plain bearings, in general, are the least expensive type of bearing. They are also compact and lightweight, and they have a high load-carrying capacity. Plain bearing 6202-2z was used for movement of pollination unit.

Plate 3.23: Plain bearing

3.3.3.5 Angular movement for pollination unit

Three blowers were arranged on the frame of the pollinator to cover the flowering band. Another provision was provided for covering the whole band was angular movement of blower up to 30^0 (15^0up and 15^0 down) as shown in Plate 3.24. This angular movement was provided using 12V DC motor. This motor was mechanically connected to all the three blowers.

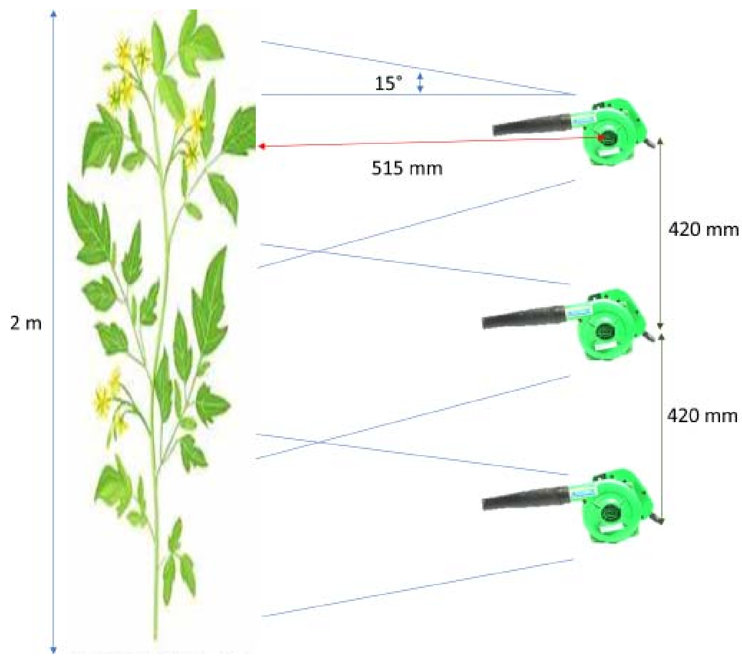


Plate 3.24 Angular movement of blowers

3.3.3.5.1 12 V DC motor for providing angular movement to the pollination unit

12V DC motor as shown in plate 3.25, generally consists of a metal arm. Metal arm has one end pivoted, whereas the other end has rubber blade attachment to it. Often electric motor is used to power the arm. The speed adjusted with several continuous or more intermittent settings. This motor is used for providing movement to pollinator ± 15^0 to cover the desired flowering zone in greenhouses.

Plate 3.25: 12V DC motor

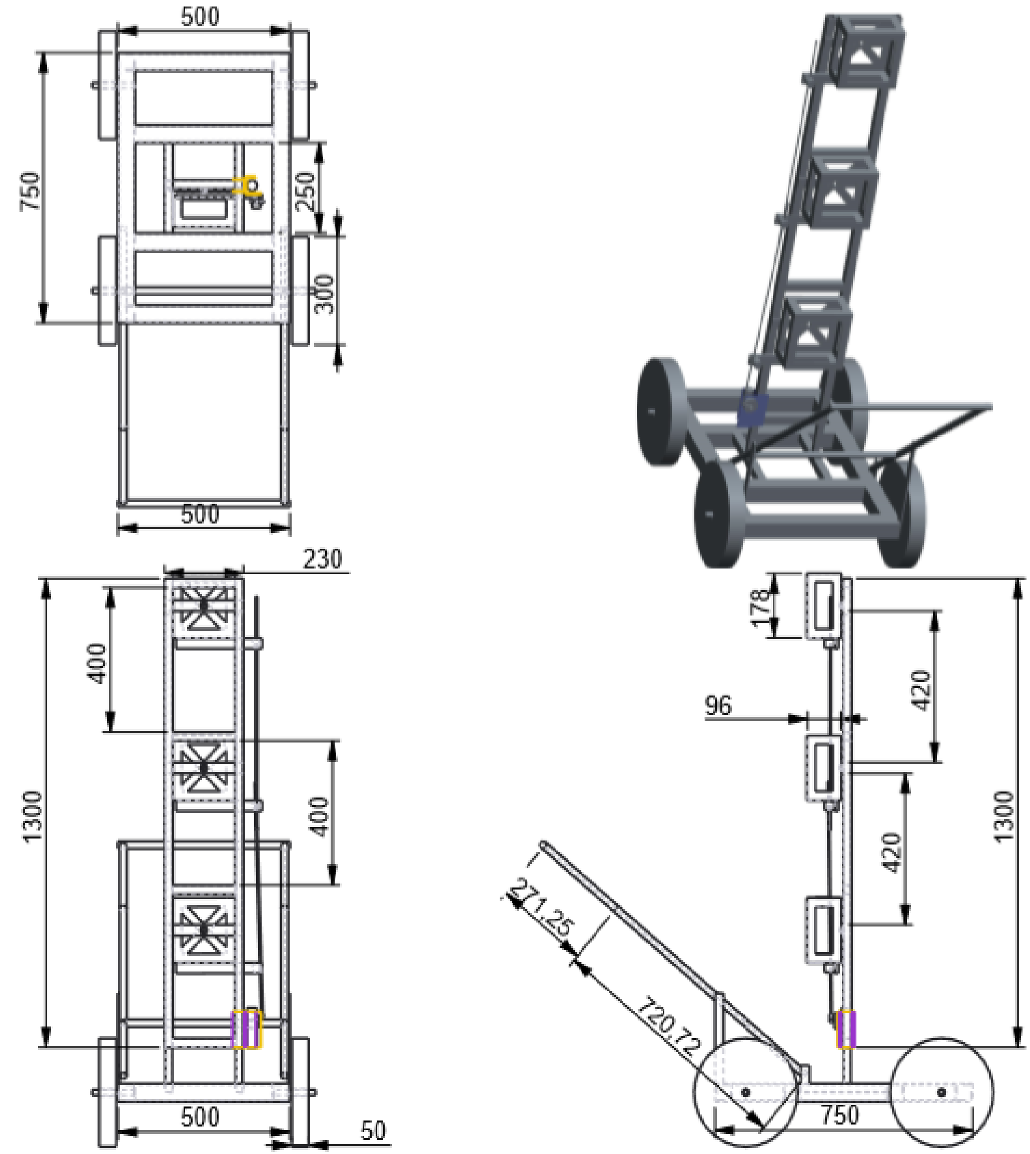


Plate 3.26: Assembled components of pollinator

3.4 Laboratory evaluation of prototype

In the Farm Machinery laboratory in the Division, evaluation of fabricated prototype in terms of amplitude of flowers with combination of air flow rate, pulse frequency and distance of application was performed with the help of video clipping. The measurements were recorded on grid frame

3.4.1 Design of grid frame

The grid frame was fabricated with 25mm strip of MS having thickness of 5mm. The grid frame had dimensions of 400mm × 400mm. It was made by welding 4 strips together as shown in Plate 3.27 All 4 strips were drilled at distance of 20mm to create the grid. White and red thread was used for grid formation. It was provided with variable height stand made of square section of 20mm × 20mm × 900mm (male) and female section of 25mm × 25mm × 900mm (plate 3.27). Any movement of plant or flower with respect to grid was measured.

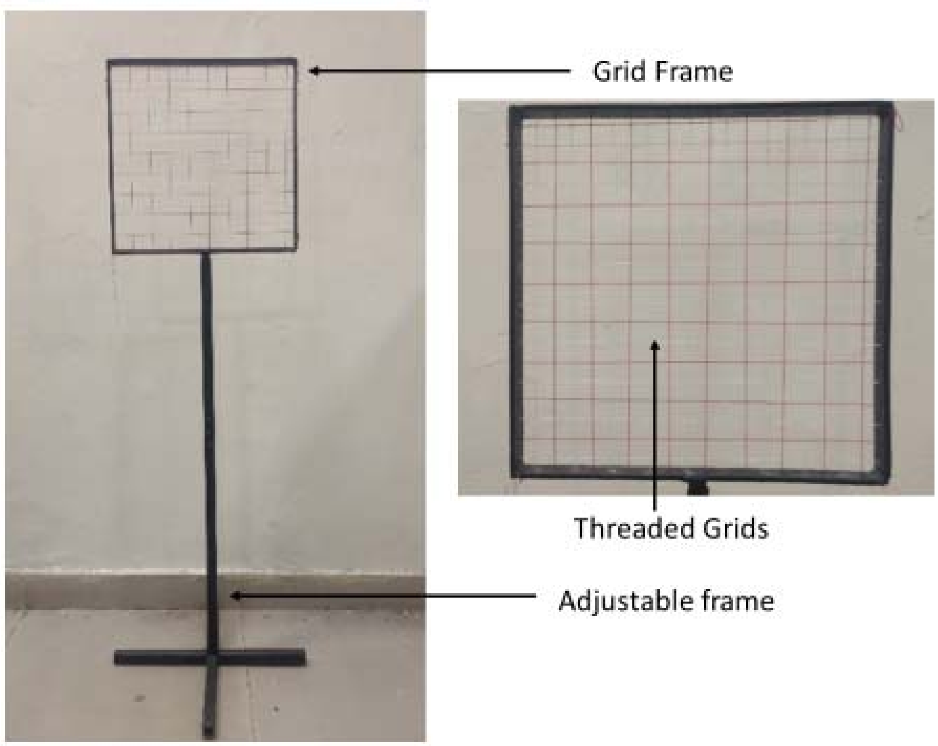


Plate 3.27: Height adjustable grid frame for lab evaluation

3.4.2 Procedure for laboratory evaluation

Laboratory evaluation (Plate 3.28) was carried out as outlined in the plan of experiments (Table 3.5) with the following steps;

i. Three potted tomato plants at flowering stage were subjected to various combination of air flow rate (1, 1.5, 2 m^3/min) and pulse frequency (16, 20, 24 Hz) with least effect of environmental wind on plants at 100, 200 and 300mm distance.

ii. Video graphed for each combination to measure the amplitude of flower.

iii. Experiments replicated for other two potted plant

iv. Mean of amplitude of flowers for different combination were determined by clipping the videos and measuring the displacement from mean position in the grid.

Plate 3.28: Lab evaluation

Table 3.5: Experimental plan for laboratory testing of pollinator

Independent variable	**Level**	**Dependent variable**
Pulse frequency (Hz)	3 (16, 20, 24)	Amplitude of flowers
Air flow rate (m^3/min)	3(1, 1.5, 2)	
Distance of application (mm)	3 (100, 200, 300)	
Replications	3	
Total number of observations	3×3×3×3= 81	

3.5 Field evaluation of pollinator in greenhouse

Performance evaluation was carried out in greenhouse of CPCT, IARI. Field evaluation of pollinator was carried out in February-May season of 2018 for tomato (*Lycopersicon esculentum Mill.*) crop. There were 10 rows of tomato plants with row to row spacing of one meter with 50 m length. Each row was divided into 5 m^2 plots. Each row had 10 plots. Before field experiment, bunch of flowers on each plant were tied with yellow ribbon and red ribbon to distinct pollination by pollinator and manual pollination, respectively, as shown in Plate 3.29 and 3.30.

Plate 3.29: Tying red ribbon for manual pollination

Plate 3.30: Tying yellow ribbon for pollination by developed pollinator

Field experiment was carried in four categories, namely

i. Pollination by pollinator using combinations of 3 air flow rates, 3 pulse frequency and 3 speeds as given in Table 3.6
ii. Manual pollination (Traditional way)
iii. Pollination by blower
iv. Untreated plot

3.5.1 Pollination by pollinator

Pollination was carried out with the developed pollinator where different combinations of 3 air flow rate, 3 pulse frequency and 3 exposure time were used (Plate 3.31). Total seventeen combinations were used for "Box Behnken Design" with 3 replications. So, total of 51 combinations were used for evaluation of pollinator. The pollination by pollinator was carried out in the greenhouse for 3 days in a week after flowering had set in and continued until fruits were formed for yellow ribbon tied portion of plants.

Plate 3.31: Field evaluation with developed pollinator

3.5.2 Manual pollination

Manual pollination (Plate 3.32) was carried out in 3 plots under following steps;

i. Hand was placed gently inside the tomato plant branches.

ii. Hand was moved rapidly back and forth about 10 times to shake the plants. This movement spread the pollens.

iii. Steps 1 and 2 was repeated for each tomato plant.

Plate 3.32: Manual pollination

3.5.3 Pollination by blower

Three plots were pollinated by blower to measure pollination efficiency and yield.

3.5.4 Untreated plot

Three plots were untreated as no pollination method was applied to measure pollination efficiency and yield in this case.

3.5.5 Measurements from field evaluation

The number of flowers of yellow ribbon tied portion of plants were counted for each 5m^2 plot. Then, the formed fruits after pollination by various combination of developed pollinator, manual pollination, pollination by blower and untreated plots were counted (Plate 3.33). Hence, ratio of number of fruits to number of flowers gives the measure of pollination efficiency. Also, quantitative yield in kg was recorded for number of selected flowers in each 5m^2 plot. For measurement of fruit diameter average of 10 fruits from each plot was measured with the help of electric Vernier calliper (Plate 3.34).

Plate 3.33: Fruit counting

Plate 3.34: Measurement of fruit diameter by Vernier calliper

Table 3.6 Experimental plan for Field testing of pollinator

Independent variable	**Level**	**Dependent variable**
Pulse frequency (Hz)	3 (16, 20, 24)	Pollination efficiency Yield
Air flow rate (m^3/min)	3 (1, 1.5, 2)	
Exposure Time (seconds)	3 (10, 15, 20)	
Replications	3	
Total number of observations	3×3×3×3=81	

3.6 Ergonomic evaluation of developed pollinator

Ergonomic evaluation was carried out with 6 subjects for various treatments such as manual pollination, pollination using blower and pollination by designed pollinator (Plate 3.35). The type of measurement carried out in this evaluation were measurement of physiological parameters; in this heart rate monitor and k4b2 were used to measure HR, VO_2, expanded calories. and measurement of subject postural parameters; in terms of BPDS (body part discomfort score) and ODS (overall discomfort score).

Plate 3.35: Ergonomic evaluation using manual pollination, pollination by blower and developed pollinator

3.6.1 Measurement of Physiological parameter

3.6.1.1 Portable pulmonary gas analyzer K4B2

It is an instrument for the measurement of oxygen uptake during sport or real-life activities. It is generally used for medical purpose. The K4 b2 consists of the following parts:

i. *K4 b2 Portable Unit*

The subject during the test wear anatomic harness. It contains the sampling pump, O_2 and CO_2 analysers, barometric sensors, transmitter and electronics. It was powered by the rechargeable battery fixed to the back side of the harness. $K_4b_2$was also provided with a small display, the portable unit shows value of HR, VCO_2, VO_2, temperature, battery charge level and barometric pressure in real time.

ii. *K_4b_2 Receiver Unit*

The receiver Unit consists of a small unit connected to a PC through the RS 232 serial port. The transmission was achieved by a miniaturized transmitter module located inside the Portable Unit.

iii. *The Flow Meter*

The turbine flow meter assembly consists of a bidirectional turbine and an optoelectronic reader. The reader measures infrared light interruptions caused by the spinning blade inside the turbine. The device may be used to measure a wide flow range and is not affected by ambient conditions (pressure, humidity, room temperature, exhaled gas composition). Daily calibration of the turbine is not necessary, but calibrations should be performed regularly to assure accurate measurements.

iv. *The HR Probe*

The HR probe consists of three parts: the elastic belt containing the transmitter and the receiver the two parts should be assembled as close as possible to one another to acquire the most effective communication signal.

v. *The Harness*

It is a holder for the portable unit and other accessories during the test which is worn by patient.

3.6.1.2 Portable heart rate monitor

The heart rate of subjects during the experiments was measured using Polar S160 heart rate monitor. It is compact and portable instrument to monitor the heart rate. This polar S610 heart rate monitor has the following four basic components:

i. *Chest Belt Transmitter*

It has two electrodes fixed in the groove rectangular area on the underside of the belt transmitter, which picks up heart rate from body of the subject and converts to electromagnetic signals. For better sensing, the electrodes are wetted with moist cloth for proper contact with worker’s skin.

ii. *Elastic Strap*

The elastic strap holds the transmitter comfortably on the subject and allows normal breathing.

iii. Receiver Unit

This is like a wrist watch, which receives the signals from transmitter and displays it on the screen and record the data in the memory. The range between receiver and transmitter should not be more than one meter. The receiver unit has button to operate the heart rate monitor. It has provision to set up high target zone and low target zone limits for safe operational conditions. When the subject reaches the limit of heartbeat it will indicate through alarm.

iv. Infrared Interface

This unit connects the receiver unit to the computer. The interface will transmit the recorded heart rate values of the subject during experiment to the computer. This transmitted heart rate value is displayed in graphical form representing time vs. heart rate values, maximum, minimum average heart rate value of the subject during experiment.

3.6.2 Measurement of subject postural parameters

3.6.2.1 Body Part Discomfort Score (BPDS)

To measure localized discomfort Corlett and Bishop (1976) technique was used. In this method, the subject was asked to mention all body parts with discomfort. Hop technique was used in this method. Subject body was divided into 21 regions by using hop technique shown in Fig 3.1. The starting from most painful to next most painful in the descending order till no further areas are referred. The number of different groups of body parts under extreme discomfort to no discomfort represent the number of intensity levels of pain experienced. The total body part discomfort score for a subject will be the sum of individual score of body parts assigned by the subject. The overall BPDS would be the average value of all the subjects.

3.6.2.2 Overall Discomfort Score (ODS)

For the assessment of overall discomfort score. 5-point discomfort scale (1-no discomfort to 5-extreme discomfort) was used which is an adoption of Corlett and Bishop (1976) technique. At the end of each experiment subject was asked to indicate their overall discomfort rating on this scale. The overall discomfort ratings by three subjects were added and averaged for mean rating. The same procedure was repeated for all experiments with all the selected subjects.

The five points scale is given below-

1-No discomfort

2-Little discomfort

3-Mild discomfort

4-Great discomfort

5-Extreme discomfort

The number shows the level of discomfort experienced by the subject during experiment.

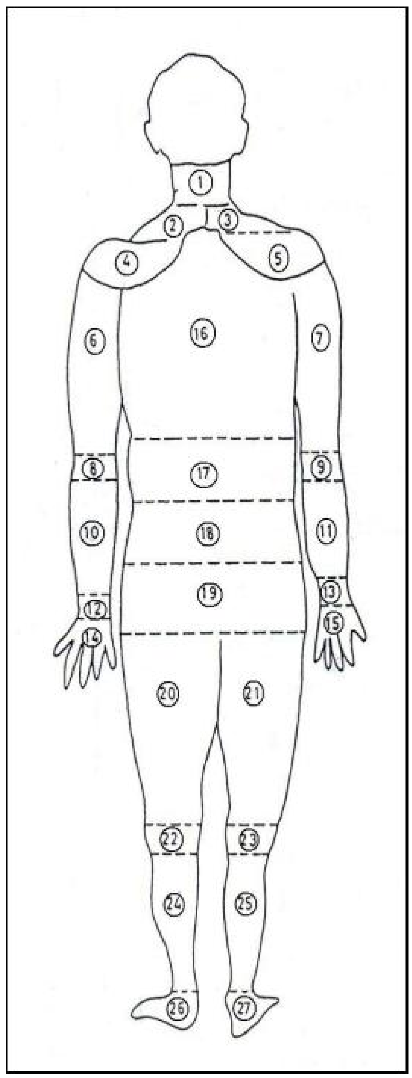


Fig 3.1: Body regions for evaluating discomfort score

3.7 Statistical analysis

The experiments for testing of developed pollinator was analysed using BBD (Box Behnken Design). This was done to obtain the necessary analysis of variance of the mean and interaction of the selected variables (3 levels of pulse frequency, 3 levels of air flow rate and 3 levels of speed) as well as the dependent variables (Yield and Pollination efficiency). BBD is suitable for second order polynomial fitting. The desirable second order model for BBD with three factors are as follows:

$$y = \beta_0 + \beta_1 * A + \beta_2 * B + \beta_3 * C + \beta_{12} * AB + \beta_{13} * AC + \beta_{23} * BC + \beta_{11} * A^2 + \beta_{22} * B^2 + \beta_{33} * C^2$$

The results from the laboratory testing of the developed pollinator device were analysed using BBD at three different air flow rate, three pulsation frequency and distance for study the effect on for effect on amplitude.

The experimental data obtained from field evaluation was analysed using BBD (Box Behnken Design). The analysis of variance of mean and interaction was obtained for selected level variable viz., different air flow rate (1, 1.5 and 2 m^3/min), different pulse frequency (16, 20 and 24 Hz), and different exposure time (10, 15 and 20 seconds) as well as dependent variables viz., pollination efficiency (number of fruits/ number of flowers) and yield (calculated in kg).

Ergonomic data was analyzed using non parametric Friedman's test. The mean of BPDS, HR and Total energy expenditure was analysed at various pollination methods and pollination by developed pollinator for various subjects. Ergonomic data is given in Appendix II

3.8 Cost Economics

The cost economics was carried out to evaluate the feasibility of the pollinator developed in terms of total cost of operation, payback period and break-even point.

3.8.1 Total cost of operation

The total cost of pollinator was determined based on fixed cost and variable cost. The following variables were considered in determining the cost of operation.

A) <u>Fixed cost</u>

i. Depreciation
ii. Interest
iii. Insurance taxes and housing

B) Variable cost

i. Repair and maintenance

ii. Labour cost

Assumptions-

A. Fixed cost

i. Average annual use = 100 hours per year

ii. Life of machine, years= 7 years

iii. Salvage value @ 10% of initial cost

iv. Rate of interest @ 12% of capital cost

v. Housing, taxes and insurance cost@ 3% of initial investment per year

B. Variable cost

i. Labour cost per day (250 Rs.)

ii. Repair and maintenance cost @ 10% of the initial investment per year

3.8.2 Break-even point

The break-even point is the point at which the gains equal to the losses. A break-even point defines when an investment will generate a positive return. There is no profit made or loss incurred at the break-even point. The break-even point is the lower limit of profit when prices are set and margins are determined.

$$BEP = FC / (CF - C)$$

Where, BEP= Break-even point, h/year

FC = Annual fixed cost, Rs. /year

CF = Custom hiring charges, Rs. /h

C = Operating cost, Rs. /h

$CF = 1.25 \times (C + 0.25C)$

3.8.3 Payback period

The Payback period (PBP) is defined as the length of time required to recover an initial investment through cash flows generated by the investment. It is calculated by the equation given as:

$$PBP = IC/ANP$$

Where, PBP = Payback period, year

IC = Initial cost of machine, Rs.

$ANP = (CF - C) \times AU$

Where, ANP = Annual net profit,

AU = Annual utility, h/year

Chapter 4

RESULTS

Four potted tomato plants were tested in the laboratory for different blower speeds ranging from 15 m/s to 60 m/s for selecting effective air velocity range for pollination. The effect of selected speeds on pollination efficiency were studied. Based on results of experiments blower was selected and pollination unit for accommodation of stepper motor, rotor and control unit to achieve pulsation of air jet was designed and developed. The laboratory testing of selected blower with pollination unit was carried out with three air flow rates, three pulsation frequencies and distance for finding maximum amplitude of flowers. The results of the laboratory testing of the developed blower extension were statistically analyzed and presented. After laboratory testing of the pollination unit, it was installed on the designed frame for field study. The evaluation was done at three air flow rates, three pulsation frequencies and exposure time for studying the effect on yield (kg per number of selected flowers in 5m^2 plot) and Pollination efficiency (%). The results were analyzed for their statistical significance and presented. This chapter deals with the results obtained from this study and results are presented under the following sub headings.

(i) Effect of air velocity on pollination

(ii) Design values of developed pollinator

(iii) Performance of pollination unit under laboratory conditions

(iv) Performance of developed pollinator under field condition

(v) Ergonomic analysis of different pollination methods for operator comfort and physiology

(vi) Cost economic analysis.

4.1 Effect of air velocity on pollination

The results from laboratory experimental set up gives the effect of velocity on pollination efficiency. Under this experimental set up various tomato plants were pollinated in lab conditions using blower at different speeds (15, 30, 45 and 60 m/s). The data collected from experiments are given in Appendix III. The effect of speed on pollination efficiency is shown in Fig 4.1.

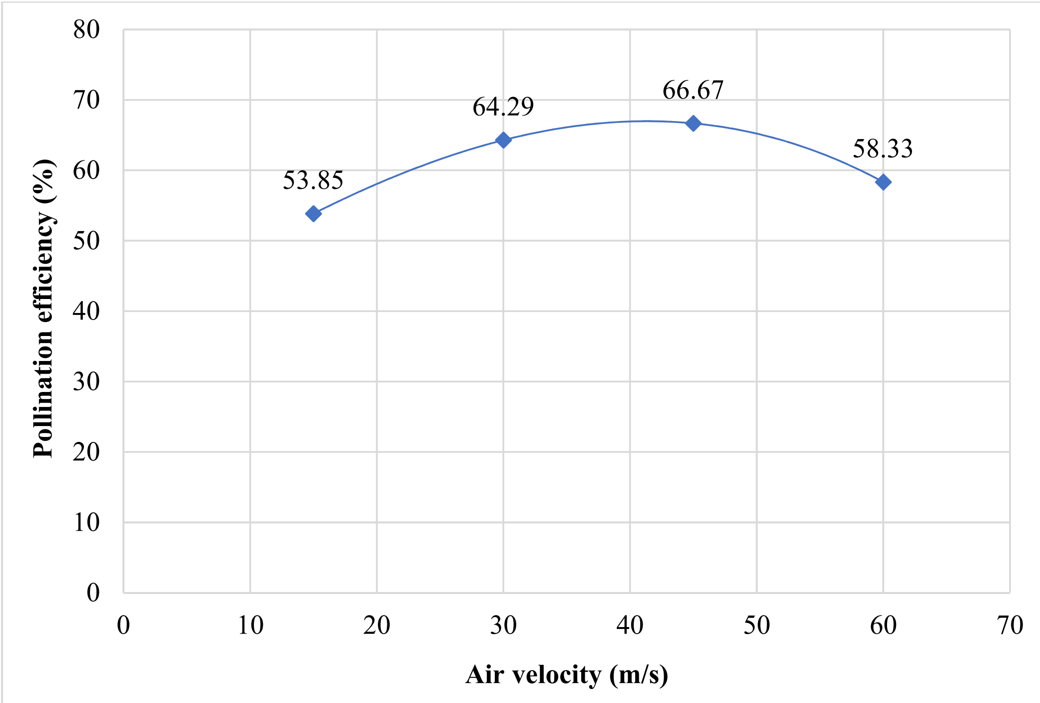


Fig 4.1: Effect of speed on pollination efficiency.

As shown in Fig. 4.1, increase in air velocity of blower up to 45m/s increased pollination efficiency and further increase in air velocity decreased the pollination efficiency. This might be due to higher air velocity up to 45m/s, pollen release was effective. But increasing air velocity beyond 45m/s cause dispersion of pollens out of flower and hence, pollination efficiency was lower.

4.2 Design values of developed pollinator

The pollinator was fabricated as given in Chapter III. It consists of selection of blower, design and development of pollination unit and development of frame for the pollinator and integration of all the developed units. The pollinator was fabricated in the workshop of Division of Agricultural Engineering, IARI, New Delhi. The developed pollinator with components is shown in Plate 4.1. The details of components of pollinator are given in Table 4.1.

Plate 4.1: Developed pollinator with various components

Table 4.1: Materials used for construction of pollinator with their specifications

Sr. no.	Name of component	Material used for construction	Specification/ Dimensions
1.	Base Frame	MS square pipe	3300×40×40×4mm
2.	Male female arrangement	MS square pipe	3100×25×25×2mm 2600×20×20×2mm
3.	Pipe for handle	MS pipe	3400×20mm
4.	Ground wheels	Rubber	-
5.	Cheston Blower	Plastic	550 W
6.	Nema17 motor	-	-
7.	Speed controller	-	50-220 V
8.	Arduino Uno	-	-
9.	Ac adapter	-	240 V to 12 V
10.	Easy driver	-	5 to 12 V
11.	Wiper motor	-	5 to 24 V
12.	Extension board	-	8 plugs
13.	Plain bearings	-	6202
14.	Nut, bolts, and washers	Steel alloy	-
15.	Wanhao printer filament	PLA filament	-
16.	LN bolts and nuts	Steel alloy	5×90cm 3×50cm

4.3 Performance of pollination unit under laboratory conditions

4.3.1 Effect of air flow rate (AFR), pulse frequency of air (PFA) and distance

The experiment was conducted as per the research methodology discussed in Chapter III. The data was analyzed using Box Behnken Design in the design expert software and ANOVA table for Response Surface Quadratic Model were determined (Table 4.2).

From Table 4.2, the overall model is significant at 1% level of significance. Based, on the ANOVA, it is observed that the linear effect of AFR, PFA and distance are highly significant at 1 % level of significance. The quadratic effect of PFA is highly significant at 1 % level of significance and distance is significant at 10% level of significance. Further, the interaction effect of PFA and distance is significant at 5% level of significance.

Table 4.2: ANOVA for amplitude with respect to air flow rate (AFR), pulse frequency of air (PFA) and distance

ANOVA for Response Surface Quadratic model						
Analysis of variance table [Partial sum of squares - Type III]						
Source of variance	**df**	**Sum of square**	**Mean Square**	**F Value**	**p-value (Prob > F)**	**Significance**
Model	9	1448.72	160.97	37.88	< 0.0001	*Significant ****
A-AFR	*1*	*153.13*	*153.13*	*36.03*	*0.0005*	*Significant ****
B-PFA	*1*	*72.00*	*72.00*	*16.94*	*0.0045*	*Significant ****
C-Distance	*1*	*1081.12*	*1081.12*	*254.38*	*< 0.0001*	*Significant ****
AB	*1*	*0.25*	*0.25*	*0.059*	*0.8153*	
AC	*1*	*25.00*	*25.00*	*5.88*	*0.0457*	*Significant ***
BC	*1*	*0.25*	*0.25*	*0.059*	*0.8153*	
A^2	*1*	*0.000*	*0.000*	*0.000*	*1.0000*	
$\boldsymbol{B^2}$	*1*	*95.00*	*95.00*	*22.35*	*0.0021*	*Significant ****
$\boldsymbol{C^2}$	*1*	*16.84*	*16.84*	*3.96*	*0.0868*	*Significant **
Residual	7	29.75	4.25			
Cor Total	16	1478.47				

(*significance at 10%, ** significance at 5%, * significance at 1%)**

A = Air flow rate (m^3/min), B = Pulse frequency of air (HZ) and C = Distance (mm)

The $\mathbf{R^2 = 0.9799}$ for the model indicates the model is able to explain 97.99% variability. The **adjusted** $\mathbf{R^2 = 0.9540}$ indicates the significant portions of variations explained by the model is about95.40% which is desirable. It is to be noted here that, the adjusted R^2 increases if only significant variables are included in the model. Further, the **Adeq Precision value of 24.112** (value > 4 is desirable) is also reasonably high. Thus, all these criteria suggest that the model is appropriate for the given data set. Based on analyzed results, the final fitted second order model is:

Amplitude = -112.37500 + 16.25000 AFR + 12.31250* PFA + 0.26250* Distance + 0.12500* AFR * PFA - 0.50000* AFR * Distance + 6.25000E-003* PFA * Distance + 4.86738E-014 *AFR² - 0.29687* PFA² -0.020000* Distance²* ……… *Eq.1*

$$Amplitude = -112.37500 + 16.25000 \cdot AFR + 12.31250 \cdot PFA + 0.26250 \cdot Distance + 0.12500 \cdot AFR \cdot PFA - 0.50000 \cdot AFR \cdot Distance + 6.25000E{-}003 \cdot PFA \cdot Distance + 4.86738E{-}014 \cdot AFR^2 - 0.29687 \cdot PFA^2 - 0.020000 \cdot Distance^2 \quad \ldots\ldots\ldots \text{Eq.1}$$

Based on the second order model, the optimal solution which results maximization of amplitude is

Table 4.3: Optimal solution for maximization of amplitude

Solutions					
No	**AFR (m^3/min)**	**PFA (Hz)**	**Distance (mm)**	**Amplitude (mm)**	**Desirability**
1	2.00	21.26	100.00	44.97	0.94

The desirability for the optimal solution is 0.94 which is quite high and hence the optimum combination is highly recommended. The graphical representation for optimal solution for maximization of amplitude of flowers is given in Fig 4.2:

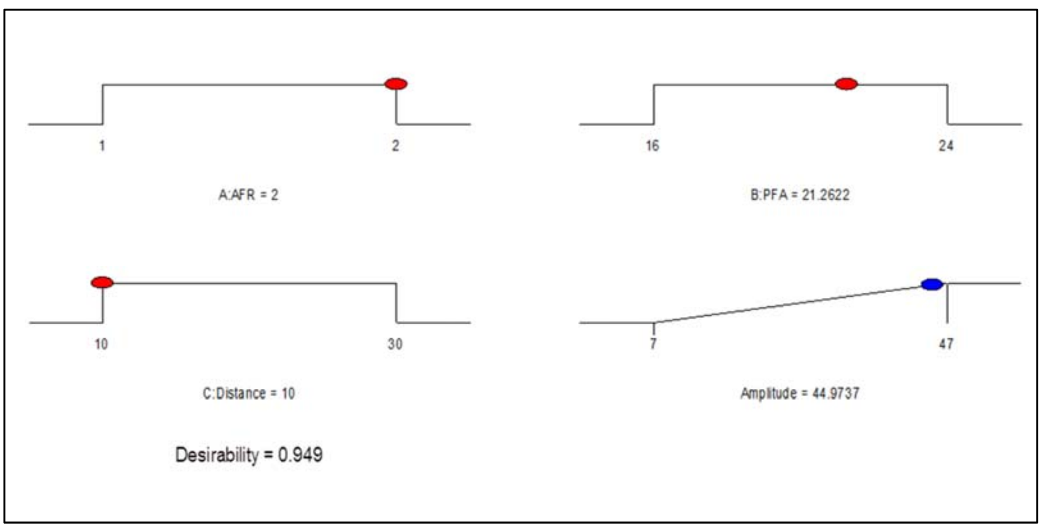


Fig 4.2: Optimal solution for maximization of amplitude of flowers.

The optimal solution of amplitude of flowers based on air flow rate and pulse frequency of air at optimum level of distance is shown in Fig 4.3. The red portion in graph indicates maximization of amplitude. The maximum amplitude of 44.97 mm was found at 2 m^3/min (AFR) and 21.26 Hz (PFA). Maximum amplitude was found at 2 m^3/min (at higher level of AFR) due to higher air velocity and 21.62 Hz of PFA due to coincidence of resonance at this frequency.

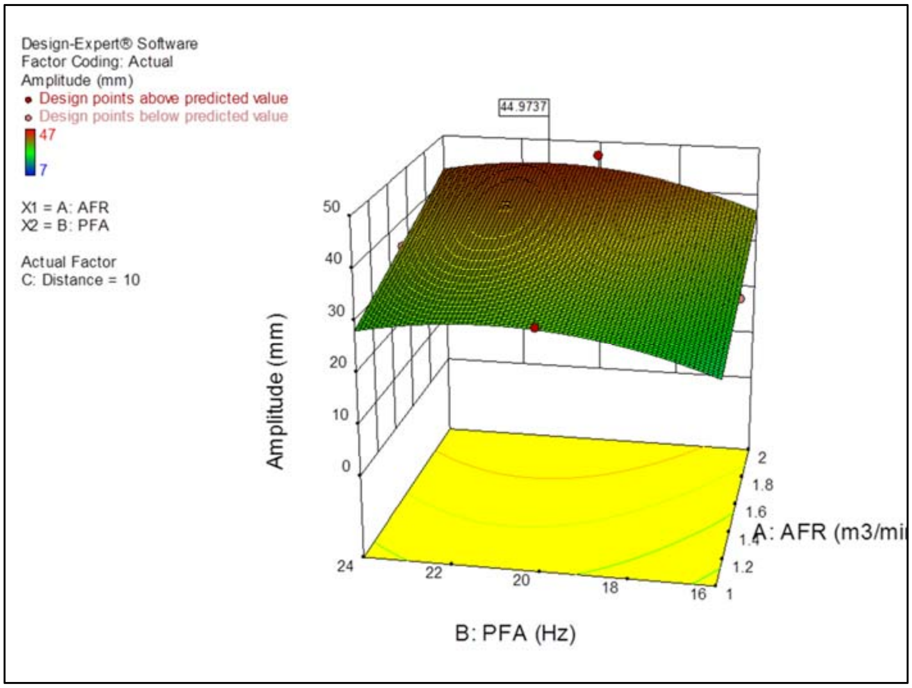


Fig. 4.3: Optimal solution of amplitude based on AFR and PFA after keeping distance at its optimum level

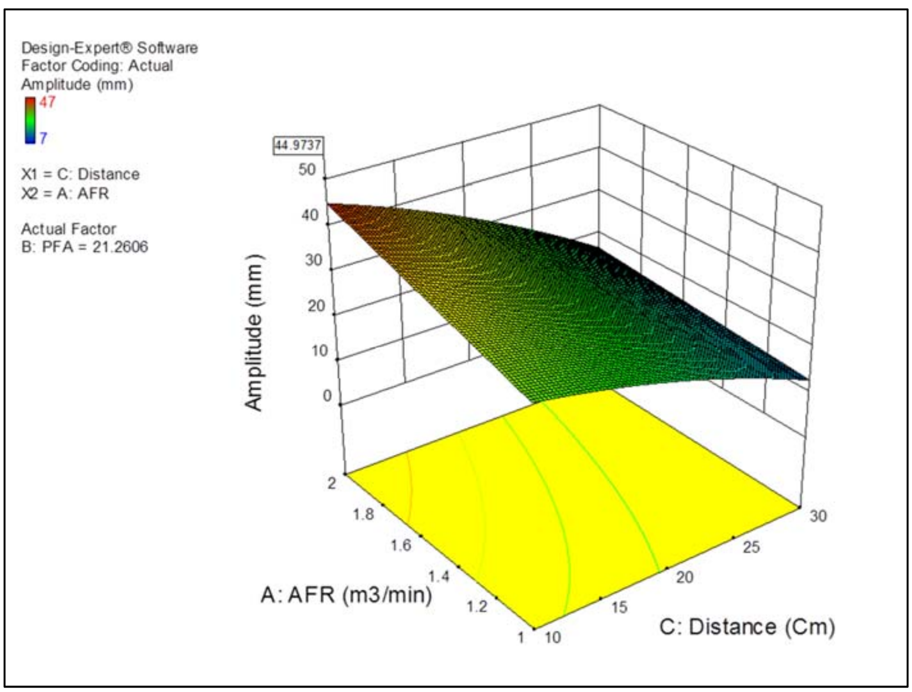


Fig. 4.4: Optimal solution of amplitude based on AFR and distance after keeping PFA at its optimum level

In Fig 4.4, optimal solution of amplitude of flowers based on air flow rate and distance at optimum level of PFA is given. Maximization of amplitude is indicated by red portion in the graph. The maximum amplitude of 44.97 mm was found at 2 m^3/min (AFR) and 100mm distance. Similarly, the effect of PFA and distance on amplitude of flower is shown in Fig. 4.5. Increasing distance between pollination unit and plant decreases amplitude of the flowers. Also, maximum amplitude was found at PFA of 21.26 Hz.

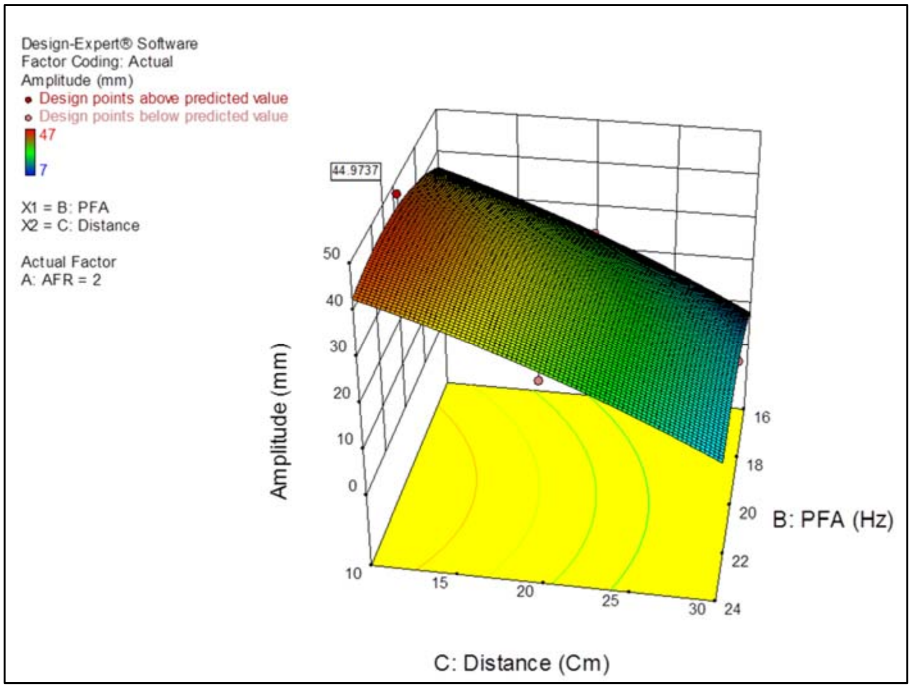


Fig.4.5: Optimal solution of amplitude based on PFA and distance after keeping AFR at its optimum level

4.4 Performance evaluation of the pollinator under field condition

4.4.1 Effect of air flow rate (AFR), pulse frequency of air (PFA) and exposure time (ET) on pollination efficiency

The experiment was conducted as per the research methodology. The data was analyzed using Box Behnken Design in the design expert software and ANOVA table for Response Surface Quadratic Model as given in Table 4.4.

From Table 4.4, it is observed that the model is significant 1% level of significance. Based, on the ANOVA, it can be seen that the linear effect of AFR and PFA are highly significant at 1 % level of significance whereas ET is significant at 5 % level of significance. The quadratic effect of PFA and ET are also significant at 5%

level of significance. Further, the interaction effect of PFA and ET is also significant at 10% level of significance.

Table 4.4: ANOVA for Pollination efficiency with respect to Air flow rate (AFR), Pulse frequency of air (PFA) and Exposure time (ET)

ANOVA for Response Surface Quadratic model						
Analysis of variance table [Partial sum of squares - Type III]						
Source of variance	**df**	**Sum of square**	**Mean Square**	**F Value**	**p-value (Prob > F)**	**Significance**
Model	9	1030.10	114.46	20.11	0.0003	*Significant ****
A-AFR	*1*	*714.04*	*714.04*	*125.45*	*< 0.0001*	*Significant ****
B-PFA	*1*	*116.83*	*116.83*	*20.53*	*0.0027*	*Significant ****
C-ET	*1*	*55.08*	*55.08*	*9.68*	*0.0171*	*Significant ***
AB	*1*	*0.033*	*0.033*	*5.800E-003*	*0.9414*	
AC	*1*	*2.69*	*2.69*	*0.47*	*0.5137*	
BC	*1*	*20.5*	*15.70*	*3.60*	*0.0997*	*Significant **
A^2	*1*	*0.51*	*0.51*	*0.090*	*0.7731*	
$\mathbf{B^2}$	*1*	*61.93*	*61.93*	*10.88*	*0.0131*	*Significant ***
$\mathbf{C^2}$	*1*	*57.16*	*57.16*	*10.04*	*0.0157*	*Significant ***
Residual	7	39.84	5.69	20.11		
Cor Total	16	1074.74				

(*significance at 10%, ** significance at 5%, * significance at 1%)**

A = Air flow rate (m^3/min), B = Pulse frequency of air (HZ) & C= Exposure time(sec)

The $\mathbf{R^2 = 0.9628}$ for the model indicates the model is able to explain 96.28% variability which is very high. The **adjusted** $\mathbf{R^2 = 0.9149}$ indicates the significant portions of variations explained by the model is about 91.49% which is also well desirable. It is to be noted here that, the adjusted R^2 will increase if only significant variables included in the model. Further, the **Adeq Precision value of 14.504** (value > 4 is desirable) is also high. Thus, all these criteria suggest that the model is an appropriate model for the given data set. Thus, based on analyzed results, the final fitted second order model is

$$Pollination\ Efficiency = -70.93882 + 8.88137 * AFR + 8.98890 * PFA + 2.47274 * ET + 0.045422 * AFR * PFA + 0.32820 * AFR * ET + 0.099061 * PFA * ET + 1.39405 * AFR^2 - 0.23969 * PFA^2 - 0.14738 * ET^2 \quad \text{…………….Eq. 2}$$

Based on the second order model, the optimal solution which results maximization of PE is

Table 4.5: Optimal solution for maximization of pollination efficiency

Solutions					
No.	**AFR (m^3/min)**	**PFA (Hz)**	**ET (seconds)**	**PE (%)**	**Desirability**
1	1.99	23.50	19.40	83.66	1

The desirability for the optimal solution is 1.00 which is the highest possible value and hence the optimum combination is highly recommended. The graphical representations for optimal solution of maximum amplitude is shown in Fig 4.6.

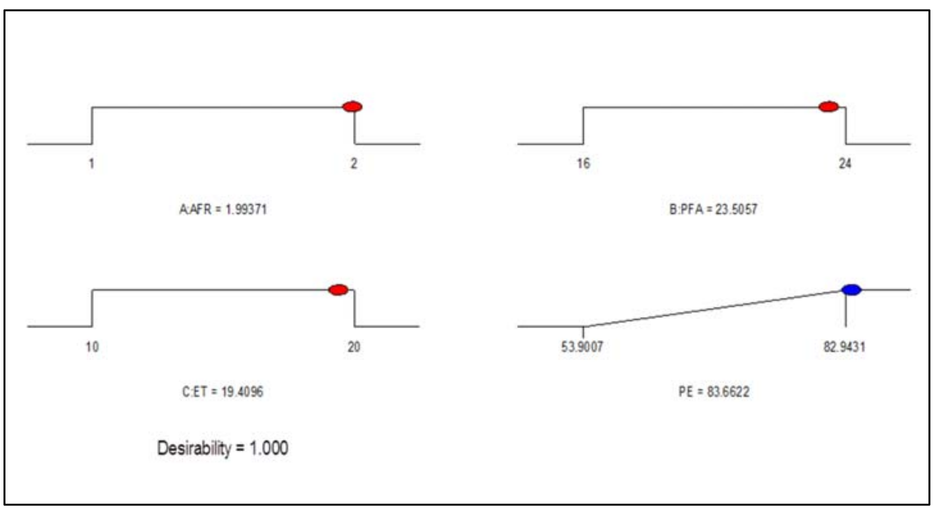


Fig 4.6: Optimal solution for maximization of pollination efficiency.

The effect of AFR and PFA on pollination efficiency is shown in Fig 4.7. Pollination efficiency was higher at air flow rate of 1.99 m^3/min and pulsation frequency of air of 23.50 Hz at optimum level of exposure time.

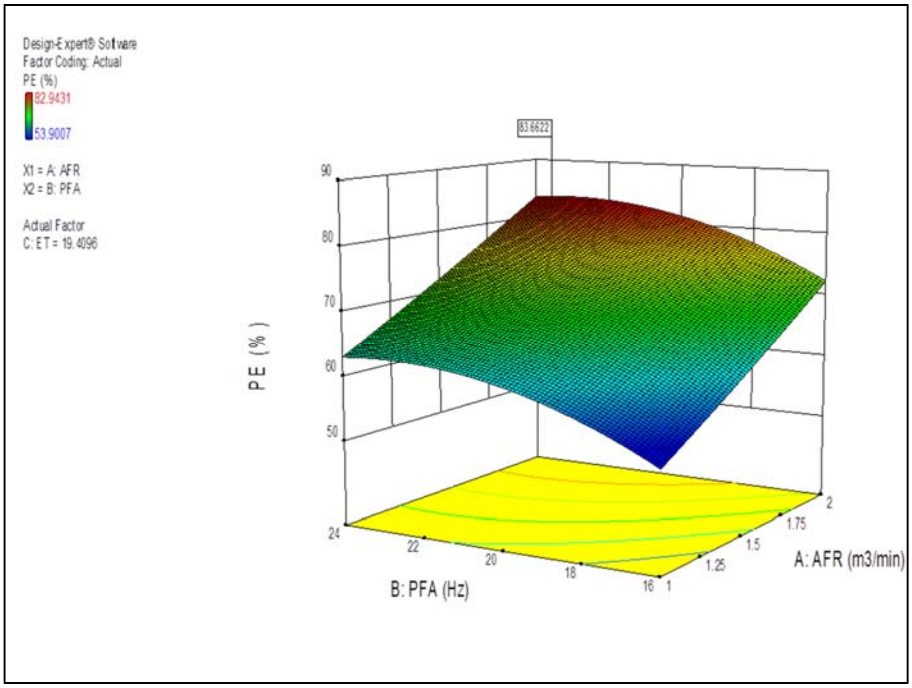


Fig 4.7: Optimal solution of PE based on AFR and PFA at optimum level of ET

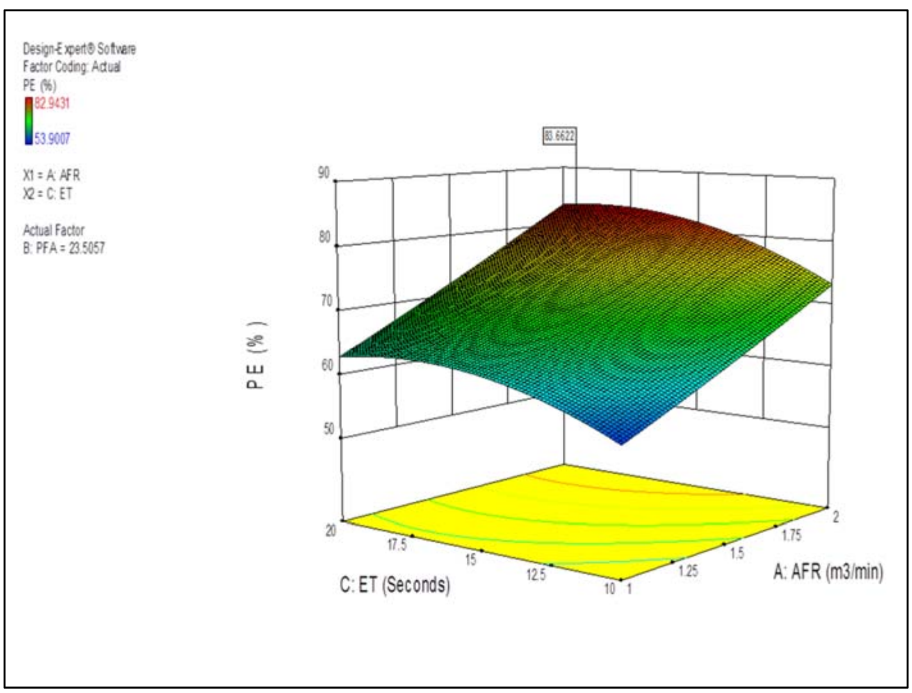


Fig 4.8: Optimal solution of PE based on AFR and ET at optimum level of PFA

Optimal solution of pollination efficiency based on air flow rate and pulse frequency of air at optimum level of exposure time is shown in Fig 4.8. Maximization of pollination efficiency is indicated by red portion in the graph. The maximum pollination efficiency of 83.66% was found at 1.99 m^3/min (AFR) and 23.50 Hz (PFA). Similarly, the effect of PFA and exposure time on pollination efficiency is shown in Fig 4.9. Increasing AFR increases pollination efficiency. Also, maximum pollination efficiency was found at PFA of 23.50 Hz. Maximum pollination efficiency of developed pollinator was 83.66% whereas manual hand pollination, pollination by blower and untreated plot had pollination efficiency of 79.48%, 64.82% and 50.93%, respectively.

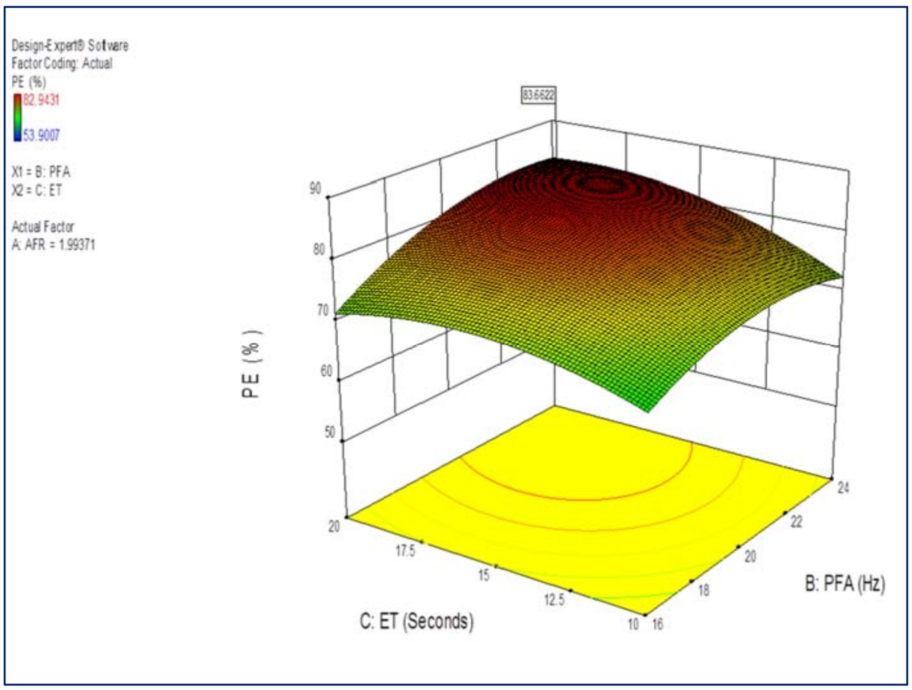


Fig 4.9: Optimal solution of PE based on PFA and ET at optimum level of AFR

4.4.2 Effect of air flow rate (AFR), pulse frequency (PF) and exposure time (ET) on yield

The data was analyzed using Box Behnken Design in the design expert software and ANOVA table for yield was calculated as given in Table 4.6. It was observed that, the overall model is significant 1% level of significance. Based, on the ANOVA, linear effect of AFR, PFA and Exposure time were highly significant at 1 % level of significance. The quadratic effect of PF and ET were also significant at 1% level of significance. On the other hand, the interaction effect of AFR and ET and also the interaction effects of PFA and ET were also significant at 10% level of significance.

Table 4.6: ANOVA for Yield with respect to Air flow rate (AFR), Pulse frequency (PF) and Exposure time (ET)

ANOVA for Response Surface Quadratic model						
Analysis of variance table [Partial sum of squares - Type III]						
Source of variance	**Df**	**Sum of square**	**Mean Square**	**F Value**	**p-value (Prob > F)**	**Significance**
Model	9	102.51	11.39	67.60	< 0.0001	*Significant ****
A-AFR	*1*	*18.40*	*18.40*	*109.19*	*< 0.0001*	*Significant ****
B-PFA	*1*	*3.47*	*3.47*	*20.57*	*0.0027*	*Significant****
C-ET	*1*	*30.75*	*30.75*	*182.48*	*< 0.0001*	*Significant ***
AB	*1*	*0.033*	*0.033*	*0.19*	*0.6725*	
AC	*1*	*0.78*	*0.78*	*4.61*	*0.0690*	*Significant **
BC	*1*	*0.62*	*0.60*	*3.65*	*0.0999*	*Significant **
A^2	*1*	*0.020*	*0.020*	*0.12*	*0.7382*	
$\boldsymbol{B^2}$	*1*	*10.32*	*10.32*	*61.23*	*0.0001*	*Significant ***
$\boldsymbol{C^2}$	*1*	*23.68*	*23.68*	*140.53*	*< 0.0001*	*Significant ***
Residual	7	1.18	0.17			
Cor Total	16	103.71				

***significance at 10%, ** significance at 5%, *** significance at 1%**

A = Air flow rate(m^3/min), B = Pulse frequency of air (HZ) and C = Exposure time(seconds)

The $\mathbf{R^2 = 0.9886}$ for the model indicates the model is able to explain 98.86% variability which is very high. The **adjusted** $\mathbf{R^2 = 0.9740}$ indicates the significant portions of variations explained by the model is about 97.40% which is also well desirable. It is to be noted here that, the adjusted R^2 will increase if only significant variables included in the model. Further, the **Adeq Precision value of 25.64** (value > 4 is desirable). Thus, all these criteria suggest that the model is an appropriate model for the given data set. Thus, based on analyzed results, the final fitted second order model is

Yield = -77.76147 + 9.63590 * AFR + 3.97541 * PF + 3.87195 * ET - 0.045250 * AFR * PF - 0.17620 * AFR * ET + 0.019387 * PF * ET - 0.27830 * AFR^2 - 0.097833 * PF^2 - 0.094853* ET^2 ………… *Eq. 3*

Based on the second order model, the optimal solution which results maximization of yield is

Table 4.7: Optimal solution for maximization of yield

Solutions					
No.	**AFR (m^3/min)**	**PFA (Hz)**	**ET (seconds)**	**Yield (kg)**	**Desirability**
1	1.99	22.25	15.78	19.49	0.99

The desirability for the optimal solution is 0.99 which is almost close to 1 and is well recommended. The representation for optimal solution of maximum yield is shown in fig 4.10

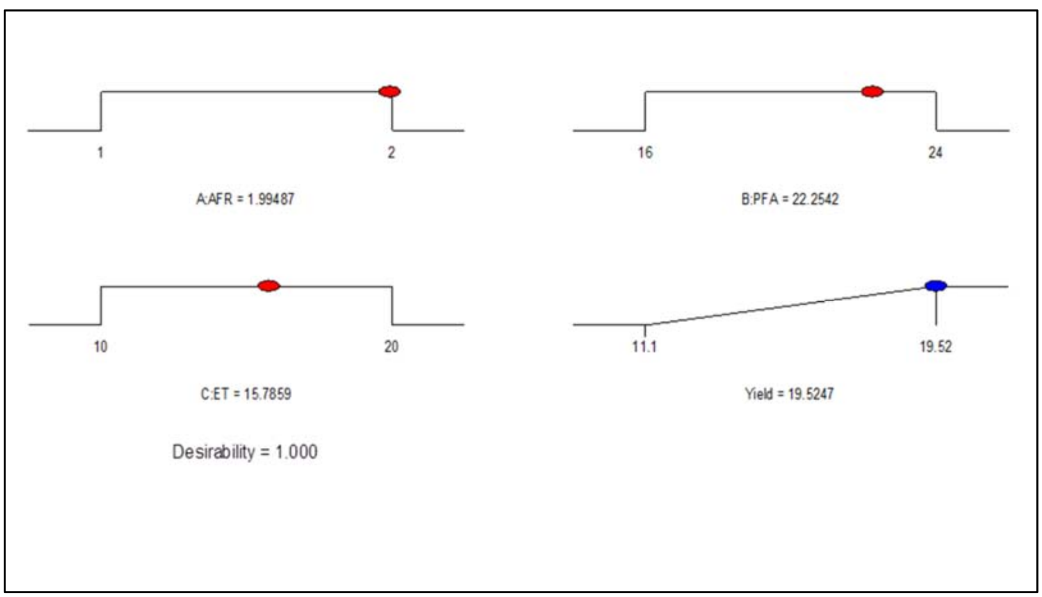


Fig 4.10: Optimal solution for maximization of Yield

Effect of air flow rate and pulsation frequency of air at optimum level of exposure time is shown in fig. 4.11. The optimal solution for maximum yield was at 1.99 m^3/min (AFR) and 22.25 Hz (PFA). The yield was higher at higher level of air flow rate. Pulsation frequency of air required for highest yield was lower than required for PE. This was due to lower fruit weight at maximum pollination efficiency than pollination efficiency at 22.25 Hz.

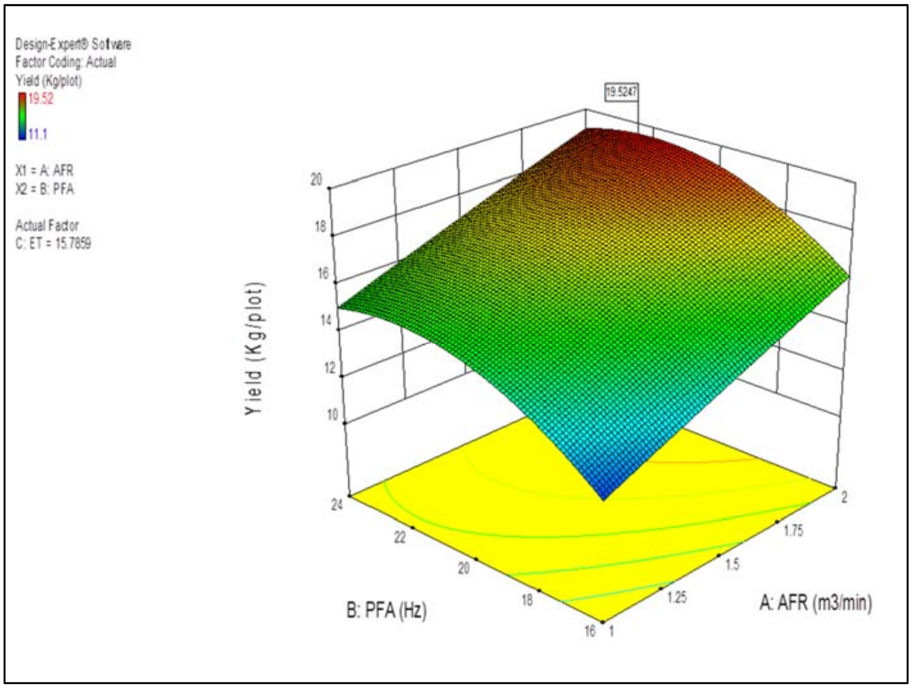


Fig. 4.11: Optimal solution of yield based on AFR and PFA at optimum level of ET

Optimal solution for yield based on AFR and ET is shown in Fig 4.12. This graph shows that maximum yield of 19.49 kg per number of selected flowers in 5 m^2 plot was at 1.99 m^3/min (AFR) and exposure time of 15.78 seconds. Similarly, effect of PFA and ET on yield is shown in Fig 4.13. The graph indicates that yield was highest at 22.25 Hz (PFA) and 15.78 seconds (ET) at optimum level of AFR. The yield was higher in case of developed pollinator at optimal solution of AFR, PFA and ET compared to manual hand pollination, pollination by blower and untreated plot (19.44, 14.29 and 9.97 kg per number of flowers selected in 5 m^2 plot, respectively).

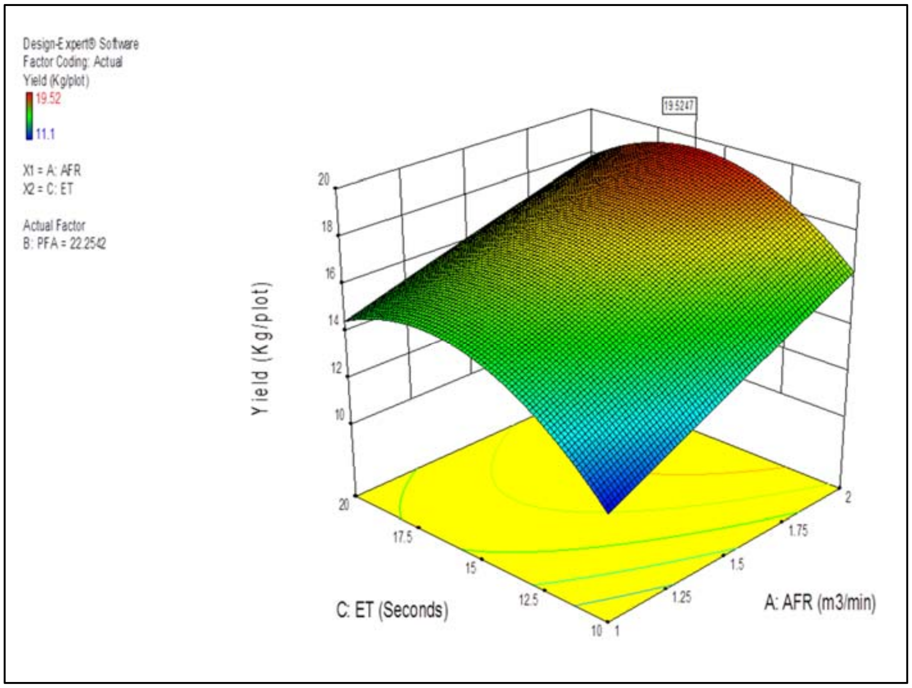


Fig. 4.12: Optimal solution of yield based on AFR and ET at optimum level of PFA

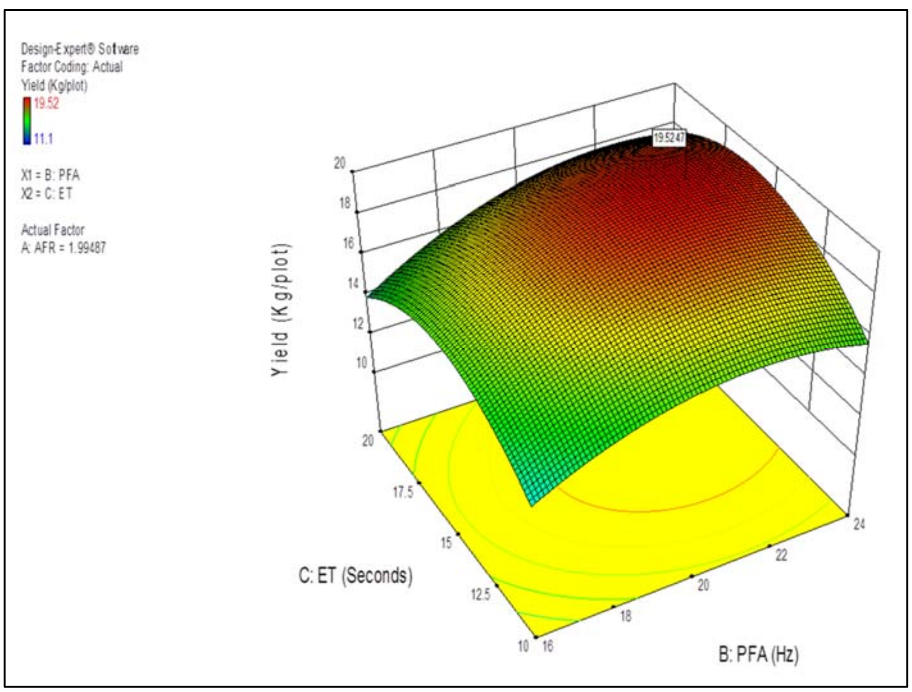


Fig. 4.13: Optimal solution of yield based on PFA and ET at optimum level of AFR

4.5 Ergonomic analysis of different pollination methods

Mean values of the ODS (Overall discomfort score) for 6 subjects pollinating with different methods namely Manual (hand) pollination, pollination with blower and pollination with developed pollinator were recorded. Mean values of ODS varied from 1.25-1.5 in case of manual hand pollination, 1.5-2 in case of pollination by blower and 1.75-2.25 in case of pollination by developed pollinator as shown in Fig 4.14. Statistical analysis of the data on the mean ODS was carried out by non-parametric Friedman's test in SPSS design software. The analysis is given in Appendix II.

The analysis indicated that there is a non-significant difference (P>0.05) between the mean Body Part Discomfort score obtained with different pollination methods. The minimum mean ODS was observed for Manual hand pollination (1.25). The maximum mean ODS was found at pollination by developed pollinator (2.25). The mean values of ODS is given in Appendix II.

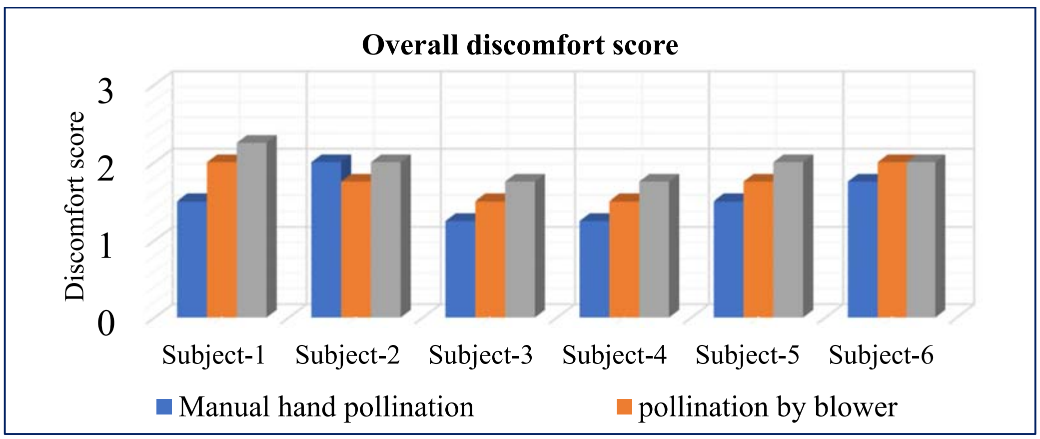


Fig. 4.14: Mean values of overall discomfort score for pollination methods with 6 subjects

Mean values of the BPDS (Body part discomfort score) for the six subjects pollinating with different methods were recorded. Mean values of BPDS varied from 9-18 in manual hand pollination, 24-30 of pollination by blower and 26-30 in pollination by developed pollinator.

The analysis (given in Appendix II) indicated that there is a non-significant difference (P>0.05) between the mean BPDS obtained at 3 different pollination methods. The minimum mean BPDS was observed at Manual hand pollination (9). The maximum mean BPDS was found in pollination by developed pollinator (30).

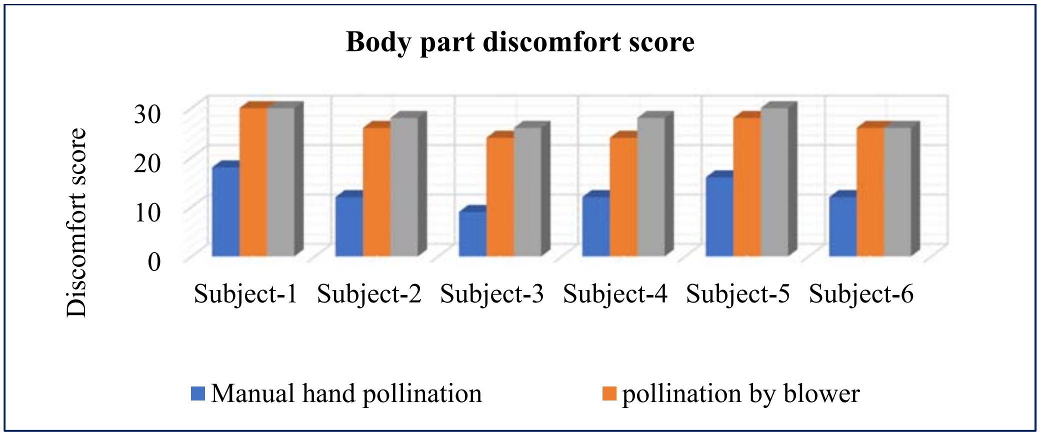


Fig. 4.15: Mean values of body part discomfort score for pollination methods with 6 subjects

Mean values of the HR (Heart rate) for the 3 subjects pollinating with different methods were recorded. Mean values of HR varied from 84.69-110.87 bpm in manual hand pollination, 86.48-118.51 bpm in pollination by blower and 90.99-127.65 bpm in pollination by developed pollinator as shown in Fig 4.16.

The analysis indicated that there is a non-significant difference (P>0.05) between the mean Body part discomfort score obtained at 3 different pollination methods. The minimum mean HR was observed for Manual hand pollination i.e. 84.69 bpm. The maximum mean HR was found at pollination by developed pollinator i.e. 127.65 bpm.

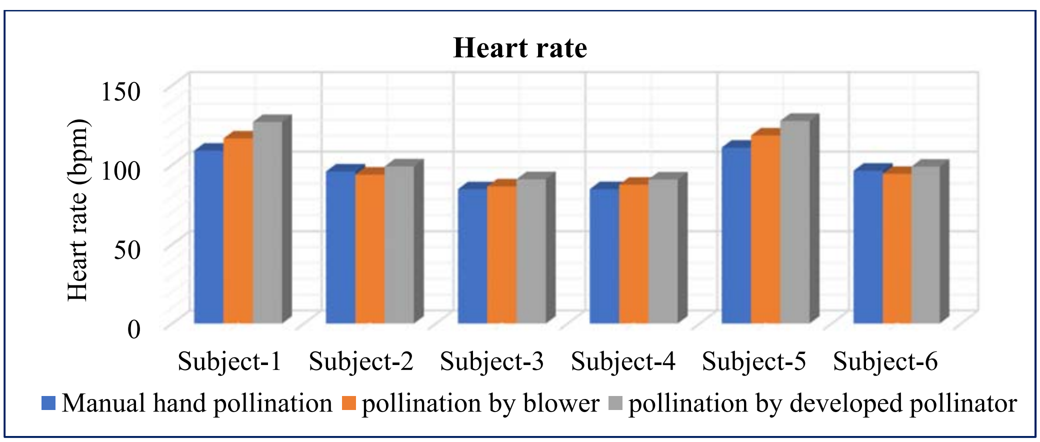


Fig. 4.16: Mean values of heart rate for pollination methods with 6 subjects

Mean values of the total energy expenditure in operation of 10 min time period for the 3 subjects pollinating with different methods were recorded. Mean values of total energy expenditure varied from 15.55-20.47 kcal in case of manual hand pollination, 18.96-28.35 kcal in case of pollination by blower and 22.35- 29.34 kcal in case of pollination by developed pollinator as shown in fig 4.17.

The analysis (given in Appendix II) indicated that there is a significant difference ($P<0.05$) between the mean total energy expenditure obtained at 3 different pollination methods. The minimum mean Total energy expenditure was observed at Manual hand pollination i.e.15.55 kcal. The maximum mean Total energy expenditure was found at pollination by developed pollinator i.e.29.34 kcal. The mean values of Total energy expenditure are given in Appendix II.

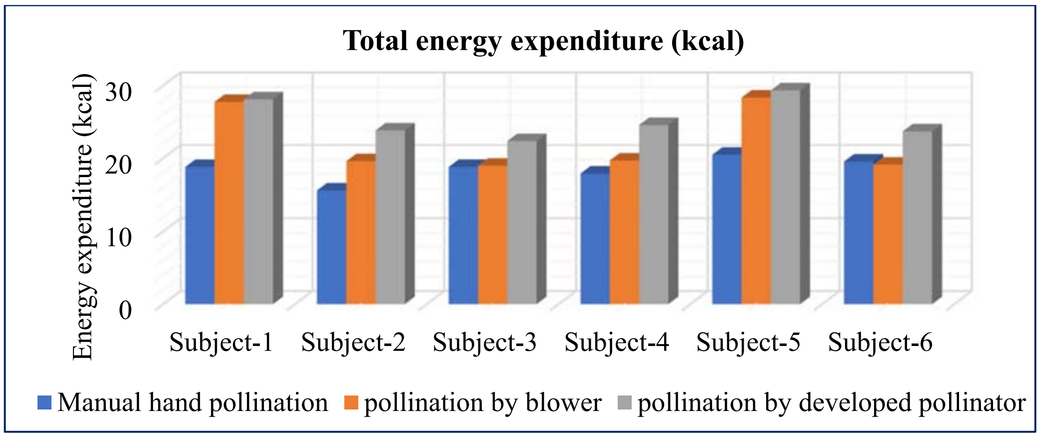


Fig. 4.17: Mean values of total energy expenditure (kcal) for pollination methods with 6 subjects

4.6 Cost economics of developed pollinator

The device was developed and evaluated as per the methodology given in chapter 3. The device is used for pollination tomatoes in greenhouse. The estimated cost of the developed pollinator was Rs 14600 (Appendix-IV) with operational cost of Rs 78.6/hour.Cost of manual hand pollination was approximately 1500 Rs/ha with operational cost of 400 Rs/ha. The breakeven point was 74.14 hours/year with a payback period of 2.2 years for the developed pollinator (Appendix V).

Chapter 5

DISCUSSION

Discussion of the results presented in Chapter 4 is made in this chapter. Supporting reasons for variation in the results are elaborated.

5.1 Effect of air velocity on pollination

The effect of air velocity on pollination efficiency was investigated for the effective range of velocity for pollination. The effect of air velocity on pollination efficiency at four levels (15, 30, 45 and 60 m/s), was studied. The combination of distance and air flow rate was able to vibrate flowers for pollen detachment. It was observed that the pollination efficiency increased with increase in air velocity up to certain limit and then deceased with further increase in air velocity. Increase in air velocity increases the amplitude of flowers which will release the pollens effectively up to certain threshold velocity. But beyond this limit, higher dispersion of pollens may occur and results in pollen dispersion out of flower causing wastage of pollens and decrease in pollination efficiency. The pollination efficiency was higher at 45m/s air velocity followed by 30 m/s, 60m/s and 15m/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 is 30-45 m/s on the basis of which blower was selected.

5.2 Developed pollinator

The pollinator was developed using principal of pulsating air jet for vibrating the flowers of tomato plant for pollination. The maximum pollination efficiency was found to be 83.67% at air flow rate of 1.99 m^3/min, Pulsation frequency of air of 23.50 Hz and exposure time of 19.4 seconds. Previous study carried out (Hanna, 2004) showed that pollination efficiency was higher at 22 Hz for cultivar of tomato in greenhouse field condition. Also, developed pollinator was provided with adjustable frame for pollinating flowers at desired height.

5.3 Effect of air flow rate (AFR), pulse frequency of air (PFA) and distance on amplitude of flowers

The effect of air flow rate (AFR), pulse frequency of air (PFA) and distance on amplitude of flowers was investigated under laboratory condition. It was observed that with increase in AFR from 1m^3/min to 2m^3/min, the amplitude of flowers increased. Higher amplitude was observed at 2 m^3/min. In case of pulse frequency, the results showed that increase in pulse frequency of air up to 21.26 Hz, amplitude of flowers increased. But it decreased with further increase in pulse frequency of air above 21.26 Hz. Higher amplitude of flowers observed at 21.26 Hz may be due to coincidence of resonance frequency of flowers. Distance of pollination unit from flower was inversely proportional to amplitude of flowers. Maximum amplitude was observed at lower distance 100mm. Various interaction effects of AFR, PFA and distance on amplitude were studied. The optimal solution for maximum amplitude was at 2m^3/min air flow rate, 21.26 Hz pulse frequency of air and 100mm distance.

5.4 Effect of air flow rate (AFR), pulse frequency of air (PFA) and exposure time (ET) on pollination efficiency (PE)

Effect of air flow rate (AFR), pulse frequency of air (PFA) and exposure time (ET)on pollination efficiency was investigated in greenhouse. It was observed that when the AFR increased from 1 m^3/min to 2 m^3/min, the pollination efficiency increased. Whereas higher amplitude was observed at 1.99 m^3/min. This might be due to increase in release of pollens as AFR increased up to 1.99 m^3/min. In case of pulse frequency, the results show that as pulse frequency of air increased up to 23.50 Hz, pollination efficiency increased. But it decreased with increase in pulse frequency of air above 23.50 Hz. Higher pollination efficiency was observed at 23.50 Hz due to occurrence of resonance at this frequency in field condition. Exposure time influenced pollination efficiency. With sufficient exposure time, maximum pollination efficiency was attained. Maximum pollination efficiency was observed at exposure time of 19.40 seconds. This exposure time infers the forward movement of machine at one km/hr, being manually driven, is very compatible for operator. Interaction effects of AFR, PFA and ET on pollination efficiency were also studied. The optimal solution for maximum pollination efficiency was at 1.99 m^3/min air flow rate, 23.50 Hz pulse frequency and exposure time of 19.40 seconds. The pollination efficiency was higher (83.67%) in developed pollinator at optimal solution of AFR, PFA and ET compared to manual hand pollination, pollination by blower and untreated plot with 79.48% ,64.82% and 50.93%, respectively.

5.5 Effect of air flow rate (AFR), pulse frequency of air (PFA) and exposure time (ET) on yield

The effect of air flow rate (AFR), pulse frequency of air (PFA) and exposure time (ET)on yield was investigated in greenhouse. Yield as number of flowers selected in 5 m^2 plot was measured. It was observed that as AFR increased from 1 m^3/min to 2 m^3/min, the yield increased. Highest yield was observed at 1.99 m^3/min. This might be due to the higher pollination efficiency at this AFR. In case of pulse frequency of air, the results showed that pulse frequency increased up to 22.25 Hz resulted in increased yield. But it decreased with pulse frequency of air increased above 22.25 Hz. Higher pollination efficiency was observed at 22.25 Hz. Exposure time also influenced yield. At sufficient exposure time, maximum yield was obtained. Maximum yield was observed at exposure time of 15.78 seconds. However, exposure time of 19.40 seconds gave higher pollination efficiency but somewhat less fruit weight. Whereas at exposure time of 15.78, lower pollination efficiency was observed but higher yield due to higher fruit size and weight. The various interaction effects of AFR, PFA and ET on yield was also studied. The optimal solution for maximum yield was at 1.99m^3/min air flow rate, 22.25 Hz pulse frequency of air and exposure time of 15.78 seconds. The yield was higher in case of developed pollinator at optimal solution of AFR, PFA and ET compared to manual hand pollination, pollination by blower and untreated plot had yield of 19.54, 14.29 and 9.97 kg per no of flowers selected in 5 m^2 plot, respectively.

5.6 Ergonomic data Analysis

The ergonomic data analysis for different pollination methods as detailed in result section for ODS, BPDS, HR and total energy expenditure for 10 min operation indicated that there was non-significant effect of pollination methods over ODS, BPDS and HR. But results indicated total energy expenditure by different subject was higher in case of developed pollinator. The total energy is function of physical work performed; in case of pollinator the pushing of machine is required which might increase the total physiological cost.

5.7 Cost economics

The cost of the developed pollinator was Rs 14600 and cost of operation per hour was Rs 78.65. Cost of manual hand pollination was approximately 1500 Rs/ha whereas pollination by pollinator was 400 Rs/ha. The breakeven point was 74.14 hours/year with a payback period of 2.2 years. The cost of operation decreased with reduction in time required for pollination per unit area than manual hand pollination.

Chapter 6

SUMMARY AND CONCLUSION

Greenhouse technology has been accepted worldwide to produce quality products and enhanced productivity even in off seasons. Greenhouse is the structure which is covered with the glass, acrylic, polythene etc. where the favourable condition for plant growth is maintained. Also, this protected structure provides protection to the plants from various factors such as diseases and external climatic condition. It offers a feasible solution for the round the year cultivation.

Cultivation of fruits and vegetables in greenhouse has become popular over the years due to its higher productivity, quality produce and higher economic returns compared to open field cultivation. Tomato is one of the major vegetable crops grown in greenhouse. Pollination plays an important role to increase the production of tomato in greenhouses. Tomato cultivation in greenhouses presents structural obstacle to natural pollinators such as birds, butterflies, bees and wind. In this case to improve pollination bumble bees are used in large greenhouse. But they create problems in small greenhouses by damaging stigma of flower due to repeated passes over same flowers. So, in small greenhouses manual hand pollination by shaking the flowers and hand held vibrator pollinator is used for effective pollination. These pollination methods are time consuming and tedious. Blowers are also used for pollination tomato crop in greenhouses but they are not cost effective. So, there is need to provide a device for effective pollination.

In this study basic principal used to pollinate the tomato crop is pulsating air jet which will vibrate the flower. This vibrating force is the force which will release the pollens from anther. To create pulsating air jet selected blower was equipped with blower extension accomdating 4 blade rotor, nema motor and control unit.

Design parameters were decided on the basis of results obtaind from lab experiments, previous work and crop parameters such as spacing, flowering band etc. from cultivation of tomato in greenhouse. Blower was selected on the basis of effective velocity range. Speed controller was used to provide various air flow rate (1, 1.5 and 2 m^3/min) from blower. Number of blowers depend upon flowering band which was 2 m wide, so 3 blowers were selected to cover the entire band. For creating pulsation of air, blower extension was developed where stepper motor was used to rotate 4 blade rotor in air tight enclosure of casing. Components of blower extension were designed on basis of blower dimensions and design parametes using 3D printer. Aurdino progrming was used to drive the stepper motor. Aurdino uno, easy driver, 10k resistors, push buttons and AC adapters were used for aurdino programming to control stepper motor with 3 buttons for 3 different speeds to provide required pulse frequency of air (16, 20 and 24 Hz). Pollinator frame was fabricated in the workshop considering the design parametes such as width of frame, height of farme required and angular movement of blower required. The developed pollinator was used for laboratory testing at three AFR (1, 1.5 and 2 m^3/min), three pulse frequency of air (16, 20 and 24 Hz) and three distance(100, 200 and 300 mm)for measure the amplitude of the flowers. The results were analysed using Box Behnken Design in design expert software. The pollinator was evaluated in greenhouse tomato field at three AFR (1, 1.5 and 2 m^3/min), three pulse frequency of air (16, 20 and 24 Hz) and three exposure time (10, 15 and 20 seconds) for observing effect on yield in each 5m plot and pollination efficiency. The results were anlysed using BBD in design expert software where analysis provide optimal solution for highest yield and pollination efficiency.

Ergonomic evaluation and cost economics were also carried out to assess ergonomic aspect and economic feasibility of developed pollinator.

Based on the research results analysis, following conclusions can be drawn

1. Optimal solution infers maximization of amplitude (44.97 mm) at AFR of 1.99 m^3/min, distance of 10 cm and Pulse frequency of 21.62 Hz
2. The maximum pollination efficiency of 83.67% was obtained at optimum values of AFR, Pulse frequency of air and Exposure timeof 1.99 m^3/min, 23.50 Hz and 19.40 seconds, respectively.
3. The pollination efficiency was higher (83.67%) in developed pollinator at optimal solution of AFR, PFA and ET as compared to manual hand pollination, pollination by blower and untreated plot with PE of 79.48% ,64.82% and 50.93%,respectively.
4. The maximum yield of 19.52 kg per no of flowers selected in 5 m^2 plot was obtained at optimum values of AFR, Pulse frequency of air and Exposure time is 1.9948 m^3/min, 22.25 Hz and 15.78 seconds, respectively.

5. The yield was higher in case of developed pollinator at optimal solution of AFR, PFA and ET compared to manual hand pollination, pollination by blower and untreated plot Which has yield as 19.54, 14.29 and 9.97 kg per no of flowers selected in 5 m^2 plot, respectively.
6. The developed pollinator was ergonomically evaluated and ODS, BPDS and HR were similar in all the pollination methods (non significant). However, total energy expenditure was significantly difference for various pollination methods with higher value in case of pollinator.
7. Cost of developed pollinator was Rs 14607. Cost of operation per hour was Rs 78.65/ hour. The breakeven point and the payback period were found to be Rs 74.14 h/year and 2.2 years respectively for the developed pollinator.

Design and development of pollinator for greenhouse

ABSTRACT

Greenhouse technology has been accepted worldwide to produce quality products and enhance productivity. Greenhouse technology is popular for production of off-season vegetable and fruits. One of the major crops cultivated in greenhouses is tomato. Pollination of tomato crop in greenhouses is critical to enhance the production and productivity. Greenhouse provides desired climatic condition for tomato crop but at the same time has obstacles for natural pollinators. Hence, in large greenhouses bumble bee are used for pollination of tomatoes. But they have a constraint of damaging the stigma of flower in small greenhouses. So, other methods of pollination namely hand pollination, pollination with vibrating wand, pollination with blower and electric brush are practiced in the greenhouses. All these methods are time consuming and require human labour. So, with the objective of providing device for effective pollination, a pollinator for greenhouse tomatoes was developed. The pollinator was designed on the principal of pulsating air jet for tomato flowers vibration for pollination. The performance of developed pollinator was studied under varying combinations of Air flow rates, Pulsation frequencies of air and Exposure times. The performance was compared with other methods of pollination practiced in the greenhouses.

The effects of Air flow rates, AFR (1, 1.5 and 2 m^3/min), Pulsation frequencies of air, PFA (16, 20 and 24 Hz) and Exposure times, ET (10, 15 and 20 seconds) on pollination efficiency and yield were studied. The regression equations of Pollination efficiency (PE) and yield as functions of AFR, PFA and ET were obtained using Box Behnken Design of Response Surface Methodology. The optimum solution for highest PE (83.66%) was at 1.99 m^3/min of AFR, 23.50 Hz of PFA and ET of 19.40 seconds. Pollination efficiency was higher (83.67%) in developed pollinator at optimal solution of AFR, PF and ET as compared to manual hand pollination, pollination by blower and untreated plot with PE of 79.48%,64.82% and 50.93%, respectively. Similarly, optimum solution for highest Yield (19.52 kg per no of flowers selected in 5 m^2 plot) was at 1.99 m^3/min of AFR, 22.25 Hz of PFA and exposure time of 15.78 seconds. The yield was higher with developed pollinator at optimal solution of AFR, PF and ET compared to manual hand pollination, pollination by blower and untreated plot which had yield of 19.54, 14.29 and 9.97 kg per no of flowers selected in 5 m^2plot respectively. Total cost of developed pollinator is Rs. 14607 with operational cost of Rs. 78.65per hour. The cost economic analysis infers the payback period of 2.2 years with annual use of 74.14 hour.

Key words: Pollinator, Tomato pollinator, Greenhouse tomato pollination, Mechanical pollinator, Blower, Pulsating air jet

ग्रीनहाउस के लिए परागण यंत्र का प्रारूप और विकास

सारांश

ग्रीनहाउस प्रौद्योगिकी को गुणवत्ता और उत्पादकता बढ़ाने के लिए दुनिया भर में स्वीकार किया गया है। ग्रीनहाउस तकनीक बे-मौसमी सब्जी और फलों के उत्पादन के लिएभी लोकप्रिय है। ग्रीनहाउस में खेती की जाने वाली प्रमुख फसलों में से टमाटर एक है। ग्रीनहाउस में टमाटर की फसल का उत्पादन और उत्पादकता बढ़ाने के लिए उसकापरागण बहुत ही महत्वपूर्ण है। ग्रीनहाउस टमाटर की फसल के लिए वांछित जलवायु स्थिति प्रदान करता है, लेकिन साथ ही प्राकृतिक परागणकर्ताओं के लिए बाधाएं भी पैदा करता है। इसलिए, टमाटर के परागण के लिए बड़े ग्रीनहाउस में भौंरा मधुमक्खी का उपयोग किया जाता है। लेकिन, छोटे ग्रीनहाउस में वे फूलों के योनि-छत्र को नुकसान भी पहुँचाते हैं। इसलिए, परागण के अन्य तरीके अर्थात् हस्त परागण, हिलती हुई छड़ी के साथ परागण, धौंकनी (ब्लोअर) के साथ परागण और इलेक्ट्रिक ब्रश का उपयोग ग्रीनहाउस में किया जाता है। इन सभी विधियों में अधिकसमय और मानव श्रम की आवश्यकता होती है। इसलिए, प्रभावी परागण के लिए उपकरण प्रदान करने के उद्देश्य से, ग्रीनहाउस टमाटर के लिए एक परागणक विकसित किया गया। परागण के लिए परागणक को टमाटर के फूलों के कंपन के लिए स्पंदित वायु जेट के सिद्धांत पर डिज़ाइन किया गया। विकसित परागणक के प्रदर्शन का अध्ययन वायु प्रवाह दर(एएफआर), वायु के स्पंदन आवृत्तियों (पीऍफ़ये) और अनावृत काल (ईटी)के अलग-अलग संयोजनों के तहत किया गया। परागणक केप्रदर्शन की तुलना ग्रीनहाउस में प्रचलित परागण के अन्य तरीकों से की गई थी।

वायु प्रवाह दर (1, 1.5 और 2मी.^{3}/ मिनट), हवा की स्पंदनआवृत्तियों(16, 20 और 24 हर्ट्ज) और अनावृत काल(10, 15 और 20 सेकंड) पर परागण दक्षता और उपज का अध्ययन किया गया। परागण दक्षता (पीई) एवं उपज के लिए प्रतिगमन समीकरण वायु प्रवाह दर, हवा की स्पंदनआवृत्तियोंऔर अनावृत कालके रूप में, रिस्पांस सरफेस मेथडोलॉजी के बॉक्स बेकन डिजाइन का उपयोग करके प्राप्त किए गए। उच्चतम परागण दक्षता (83.66%) का इष्टतम मान वायु प्रवाह कीदर 1.99 मी.^{3}/ मिनट, हवा की स्पंदनआवृति 23.50 हर्ट्ज और 19.40 सेकंड केअनावृत काल परपायागया। एएफआर, पीएफ और ईटी के इष्टतम समाधान पर विकसित परागणकर्ता में परागण दक्षता (83.67%)थी जो कि हस्त परागण,धौंकनी (ब्लोअर) के साथ परागण, और अनुपचारित भूखंड मेंपरागणसे अधिक थी जो क्रमशः 79.48%, 64.82% और 50.93% पाई गयी। इसी प्रकार, उच्चतम उपज की इष्टतम मात्रा(19.52 किलोग्राम/5 मी.^{2}केप्लॉट मेंचयनित फूलों में) एएफआर का 1.99 मी.^{3}/ मिनट, पीएफए का 22.25 हर्ट्ज और 15.78 सेकंड का अनावृत कालपरथा। एएफआर, पीएफ और ईटी के इष्टतम समाधान पर विकसित परागणकर्ता के साथ पैदावार हस्त परागण,धौंकनी (ब्लोअर)के साथ परागण, और अनुपचारित भूखंड मेंपरागणकी तुलना में अधिक थी, जिसमें क्रमशः 19.54, 14.29 और 9.97 किलोग्राम/5 मी.^{2}केप्लॉट मेंचयनित फूलों में पाई गयी। विकसित परागणक की कुल लागत 14607 रुपये है।वहीं परिचालन लागत 78.65 प्रति घंटा थी। लागत का आर्थिक विश्लेषण करने पर 74.14 घंटे के वार्षिक उपयोग के साथ 2.2 साल में परागणक के लागत की मूल्य वापसी की जा सकती है।

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Appendix-I

Microcontroller program for controlling speed of stepper motor with 3 pushbuttons

```
#include <Stepper.h>

volatile int rpm = 0;
const int stepsPerRevolution = 2300;
Stepper myStepper (stepsPerRevolution, 2, 3, 4, 5);

const int button1 = 9;
const int button2 = 10;
const int button3 = 11;

int buttonState1 = 0;
int buttonState2 = 0;
int buttonState3 = 0;

void setup () {
Serial.begin(9600);
pinMode (button1, INPUT);
pinMode (button2, INPUT);
pinMode (button3, INPUT);
}

void loop () {

buttonState1 = digitalRead(button1);
buttonState2 = digitalRead(button2);
buttonState3 = digitalRead(button3);
```

```
if (buttonState1 == HIGH)
{
rpm = 300;
Serial.println("300 rpm");
}
else if (buttonState2 == HIGH)
{
rpm = 400;
Serial.println("400 rpm");
}
else if (buttonState3 == HIGH)
{
rpm = 500;
Serial.println("500 rpm");
}
for (int y = 0; y < rpm / 4; y++)
{
myStepper.setSpeed(y * 4);
myStepper.step(y);
}
myStepper.setSpeed(1 * rpm);
myStepper.step(1000);
for (int y = rpm; y > 0; y)
{
myStepper.setSpeed(y * 1);
myStepper.step(y);
}
myStepper.setSpeed(rpm);
}
```

Appendix-II

Performa for Subjective Evaluation (Ergonomic evaluation)

Experiment No.: **Date:**

Subject:

Replication:

Table D-1 Performa for calculation of overall discomfort score

Assessment of overall discomfort rating				
Tiredness level	At start	After 5 min	After 10 min	After 15 min
1 (No discomfort)				
2 (Very little discomfort)				
3 (Mild discomfort)				
4 (Great discomfort)				
5 (Extreme discomfort)				

Table D-2 Performa for calculation of body part discomfort score

Serial No.	Category	Body part(s)	No. of parts	Rating	Score
Total					

1. Assessment of overall discomfort rating

Assessment of overall discomfort rating (manual pollination)						
Tiredness level	Sub-1	Sub-2	Sub-3	Sub-4	Sub-5	Sub-6
At start	1	2	1	1	1	1
After 5 min	1	2	1	1	1	2
After 10 min	2	2	1	1	2	2
After 15 min	2	2	2	2	2	2

Assessment of overall discomfort rating (pollination by blower)						
Tiredness level	Sub-1	Sub-2	Sub-3	Sub-4	Sub-5	Sub-6
At start	1	1	1	1	1	1
After 5 min	2	2	1	1	2	2
After 10 min	2	2	2	2	2	2
After 15 min	3	2	2	2	2	3

Assessment of overall discomfort rating (pollination by developed pollinator)						
Tiredness level	Sub-1	Sub-2	Sub-3	Sub-4	Sub-5	Sub-6
At start	1	1	1	1	1	1
After 5 min	2	2	1	1	2	2
After 10 min	3	2	2	2	2	2
After 15 min	3	3	3	3	3	3

2. Assessment of overall discomfort rating

I. For Pollination by pollinator

Subject-1					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	3	1	4*6/4=6	6
2.	II	2,5	2	3*6/4=4.5	9
3.	III	6,7,4,9	4	2*6/4=3	12
4.	IV	14,15	2	1*6/4=1.5	3
5.	V	-			
6.	VI	-			
Total					30

Subject-2					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	2,3	2	3*6/3=6	12
2.	II	4,5	2	2*6/3=4	8
3.	III	6,7,14,15	4	1*6/3=2	8
4.	IV	-			
5.	V	-			
6.	VI	-			
Total					28

Subject-3					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	2,3	2	3*6/3=6	12
2.	II	4,5	2	2*6/3=4	8
3.	III	6,7,15	3	1*6/3=2	6
4.	IV	-			
5.	V	-			
6.	VI	-			
Total					26

Subject-4					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	2,3	2	3*6/3=6	12
2.	II	4,5	2	2*6/3=4	8
3.	III	6,7,14,15	4	1*6/3=2	8
4.	IV	-			

5.	V	-			
6.	VI	-			
Total					28

Subject-5					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	3	1	4*6/4=6	6
2.	II	2,5	2	3*6/4=4.5	9
3.	III	6,7,4,9	4	2*6/4=3	12
4.	IV	14,15	2	1*6/4=1.5	3
5.	V	-			
6.	VI	-			
Total					30

Subject-6					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	2,3	2	3*6/3=6	12
2.	II	4,5	2	2*6/3=4	8
3.	III	6,14,15	4	1*6/3=2	6
4.	IV	-			
5.	V	-			
6.	VI	-			
Total					26

II. For Pollination by blower

Subject-1					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	4,5	2	3*6/3=6	12
2.	II	6,7	2	2*6/3=4	8
3.	III	13,14,12,15,11	5	1*6/3=2	10
4.	IV	-			
5.	V	-			
6.	VI	-			
Total					30

Subject-2					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	4,5	2	3*6/3=6	12
2.	II	6,7	2	2*6/3=4	8
3.	III	13,14,15	3	1*6/3=2	6
4.	IV	-			
5.	V	-			
6.	VI	-			
Total					26

Subject-3					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	4,5	2	3*6/3=6	12
2.	II	6,7	2	2*6/3=4	8
3.	III	13,15	2	1*6/3=2	4
4.	IV	-			
5.	V	-			
6.	VI	-			
Total					24

Subject-4					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	4,5	2	3*6/3=6	12
2.	II	6,7	2	2*6/3=4	8
3.	III	13,15	2	1*6/3=2	4
4.	IV	-			
5.	V	-			
6.	VI	-			
Total					24

Subject-5					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	4,5	2	3*6/3=6	12
2.	II	6,7	2	2*6/3=4	8
3.	III	13,14,15,11	3	1*6/3=2	6

4.	IV	-			
5.	V	-			
6.	VI	-			
Total					28

Subject-6					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	4,5	2	3*6/3=6	12
2.	II	6,7	2	2*6/3=4	8
3.	III	13,14,15	5	1*6/3=2	6
4.	IV	-			
5.	V	-			
6.	VI	-			
Total					26

III. For Manual pollination

Subject-1					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	6,7	2	2*6/2=6	12
2.	II	14,15	2	1*6/2=3	6
3.	III	-			
4.	IV	-			
5.	V	-			
6.	VI	-			
Total					18

Subject-2					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	6	1	2*6/2=6	6
2.	II	13,15	2	1*6/2=3	6
3.	III	-			
4.	IV	-			
5.	V	-			
6.	VI	-			
Total					12

Subject-3					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score

7.	I	7	1	2*6/2=6	6
8.	II	15	1	1*6/2=3	3
9.	III	-			
10.	IV	-			
11.	V	-			
12.	VI	-			
Total					9

Subject-4					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	6	1	2*6/2=6	6
2.	II	13,15	2	1*6/2=3	6
3.	III	-			
4.	IV	-			
5.	V	-			
6.	VI	-			
Total					12

Subject-5					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	6	1	3*6/3=6	6
2.	II	7,15	2	2*6/3=4	8
3.	III	14	1	1*6/3=2	2
4.	IV	-			
5.	V	-			
6.	VI	-			
Total					16

Subject-6					
Serial No.	Category	Body part(s)	No. of parts	Rating	Score
1.	I	6	1	2*6/2=6	6
2.	II	13,15	2	1*6/2=3	6
3.	III	-			
4.	IV	-			
5.	V	-			
6.	VI	-			
Total					12

1. Overall discomfort score of the subjects for different pollination methods

Pollination methods	Subjects					
	Sub-1	Sub-2	Sub-3	Sub-4	Sub-5	Sub-6
Manual hand pollination	1.5	2	1.25	1.25	1.5	1.75
Pollination by blower	2	1.75	1.5	1.5	1.75	2
Pollination by developed pollinator	2.25	2	1.75	1.75	2	2

2. BPDS of the subjects for different pollination methods

Pollination methods	Subjects					
	Sub-1	Sub-2	Sub-3	Sub-4	Sub-5	Sub-6
Manual hand pollination	18	12	9	12	16	12
Pollination by blower	30	26	24	24	28	26
Pollination by developed pollinator	30	28	26	28	30	26

3. Heart rate (in bpm) of the subjects for different pollination methods

Pollination methods	Subjects					
	Sub-1	Sub-2	Sub-3	Sub-4	Sub-5	Sub-6
Manual hand pollination	108.94	95.84	84.69	84.74	110.87	96.32
Pollination by blower	116.58	93.84	86.48	87.55	118.51	94.38
Pollination by developed pollinator	126.92	99.03	90.99	90.82	127.65	98.86

4. Total Energy expenditure (in kcal) for different pollination methods

Pollination methods	Subjects					
	Sub-1	Sub-2	Sub-3	Sub-4	Sub-5	Sub-6
Manual hand pollination	18.78	15.55	18.79	17.88	20.47	19.53
Pollination by blower	27.75	19.58	18.96	19.67	28.35	19.11
Pollination by developed pollinator	28.1	23.82	22.35	24.56	29.34	23.69

1. Ergonomic analysis by non-parametric Friedman's test using SPSS software

i. Test statistics for ODS

Test Statistics[a]	
N	6
Chi-square	3.455
df	2
Asymp. Sig.	0.178

ii. Test statistics for Total energy expenditure

Test Statistics[a]	
N	6
Chi-square	6.000
df	2
Asymp. Sig.	**0.050**

iii. Test statistics for Heart Rate

Test Statistics[a]	
N	6
Chi-square	4.667
df	2
Asymp. Sig.	0.097

iv. Test statistics for BPDS

Test Statistics[a]	
N	6
Chi-square	5.636
df	2
Asymp. Sig.	0.060

2. Mean Values of ODS, BPDS, HR and Total Energy Expenditure

I. Mean values of ODS

Descriptive Statistics		
Methods of pollination	**N**	**Mean**
Manual Hand pollination	6	1.54
Pollination by blower	6	1.75
Pollination by developed pollinator	6	1.96

II. Mean values of BPDS

Descriptive Statistics		
Methods of pollination	**N**	**Mean**
Manual Hand pollination	6	13.16667
Pollination by blower	6	26.3333
Pollination by developed pollinator	6	28.0000

III. Mean values of Total energy expenditure

Descriptive Statistics		
Methods of pollination	**N**	**Mean**
Manual Hand pollination	6	18.50
Pollination by blower	6	22.23667
Pollination by developed pollinator	6	25.3100

IV. Mean values of Heart Rate

Descriptive Statistics		
Methods of pollination	**N**	**Mean (bpm)**
Manual Hand pollination	6	96.900
Pollination by blower	6	99.55667
Pollination by developed pollinator	6	105.7117

Appendix-III

1. Result data from experimental set up

Air velocity (m/s)	No of flowers	No of fruits	Pollination efficiency
15	13	7	53.85
30	14	9	64.29
45	12	8	66.67
60	12	7	58.33

2. Result data of laboratory evaluation

Replication	Run	AFR (m^3/min)	PFA (Hz)	Distance (cm)	Amplitude (mm)
1	1	2	24	20	29
1	2	2	20	20	33
1	3	2	16	20	24
1	4	1.5	24	20	25
1	5	1.5	20	20	28
1	6	1.5	16	20	22
1	7	1	24	20	22
1	8	1	20	20	25
1	9	1	16	20	18
1	10	2	24	30	14
1	11	2	20	30	16
1	12	2	16	30	10
1	13	1.5	24	30	15
1	14	1.5	20	30	18
1	15	1.5	16	30	7
1	16	1	24	30	8
1	17	1	20	30	10
1	18	1	16	30	5
1	19	2	24	10	40
1	20	2	20	10	47
1	21	2	16	10	33

1	22	1.5	24	10	35
1	23	1.5	20	10	38
1	24	1.5	16	10	28
1	25	1	24	10	27
1	26	1	20	10	31
1	27	1	16	10	25
2	1	2	24	20	30
2	2	2	20	20	36
2	3	2	16	20	25
2	4	1.5	24	20	27
2	5	1.5	20	20	28
2	6	1.5	16	20	23
2	7	1	24	20	24
2	8	1	20	20	28
2	9	1	16	20	18
2	10	2	24	30	15
2	11	2	20	30	17
2	12	2	16	30	8
2	13	1.5	24	30	13
2	14	1.5	20	30	15
2	15	1.5	16	30	8
2	16	1	24	30	10
2	17	1	20	30	12
2	18	1	16	30	7
2	19	2	24	10	42
2	20	2	20	10	43
2	21	2	16	10	35
2	22	1.5	24	10	37
2	23	1.5	20	10	40
2	24	1.5	16	10	30
2	25	1	24	10	28
2	26	1	20	10	28

2	27	1	16	10	24
3	1	2	24	20	28
3	2	2	20	20	35
3	3	2	16	20	26
3	4	1.5	24	20	26
3	5	1.5	20	20	29
3	6	1.5	16	20	22
3	7	1	24	20	23
3	8	1	20	20	26
3	9	1	16	20	20
3	10	2	24	30	14
3	11	2	20	30	19
3	12	2	16	30	12
3	13	1.5	24	30	13
3	14	1.5	20	30	16
3	15	1.5	16	30	10
3	16	1	24	30	7
3	17	1	20	30	9
3	18	1	16	30	5
3	19	2	24	10	42
3	20	2	20	10	46
3	21	2	16	10	36
3	22	1.5	24	10	36
3	23	1.5	20	10	41
3	24	1.5	16	10	31
3	25	1	24	10	27
3	26	1	20	10	30
3	27	1	16	10	22

3. Result data of field evaluation

i. Pollination by developed pollinator

Replication	Run	Air Flow Rate (m3/min)	Pulse Frequency	Exposure Time (seconds)	No of Flowers	No. of Fruits	Fruit weight (Kg)	Fruit diameter (mm)	Yield (kg/5m plot)	Pollination Efficiency (%)
1	1	2	24	15	296	237	81	56.9	19.197	80.06757
1	2	1.5	16	20	266	185	73	45.28	13.505	69.54887
1	3	1.5	24	20	281	201	83	47.15	16.683	71.53025
1	4	1	20	10	252	141	76	46.61	10.716	55.95238
1	5	2	16	15	269	194	77	48.41	14.938	72.11896
1	6	1.5	20	15	282	200	85	48.2	17	70.92
1	7	1	24	15	297	193	78	46.81	15.054	64.98316
1	8	1.5	20	15	278	202	86	47.93	17.372	72.66187
1	9	1.5	20	15	290	210	88	48.9	18.48	72.41
1	10	2	20	20	276	220	80	48.39	17.6	79.71014
1	11	1.5	24	10	258	172	79	49.91	13.588	66.66667
1	12	2	20	10	269	209	77	51.9	16.093	77.69517
1	13	1	20	20	301	172	75	45.69	12.9	57.14286

1	14	1.5	20	15	278	212	89	49.6	18.868	76.25
1	15	1	16	15	294	163	72	45.53	11.736	55.44218
1	16	1.5	20	15	285	205	84	48.1	17.22	71.92
1	17	1.5	16	10	250	146	75	43.42	10.95	58.4
2	1	2	24	15	299	248	77	56.06	19.096	82.94314
2	2	1.5	16	20	282	176	69	42.92	12.144	62.41135
2	3	1.5	24	20	273	202	77	46.49	15.554	73.99267
2	4	1	20	10	241	144	77	46.3	11.088	59.75104
2	5	2	16	15	265	199	76	45.7	15.124	75.09434
2	6	1.5	20	15	286	207	86	49.2	17.802	72.377
2	7	1	24	15	303	186	80	46.3	14.88	61.38614
2	8	1.5	20	15	280	200	83	47.5	16.6	71.42
2	9	1.5	20	15	284	204	84	48.44	17.136	71.83099
2	10	2	20	20	279	220	80	52.49	17.6	78.85305
2	11	1.5	24	10	270	168	76	49.08	12.768	62.22222
2	12	2	20	10	263	196	78	48.47	15.288	74.52471
2	13	1	20	20	301	183	72	45.34	13.176	60.79734
2	14	1.5	20	15	288	199	82	48.2	16.318	69.09
2	15	1	16	15	282	152	73	44.4	11.096	53.90071

2	16	1.5	20	15	281	209	81	48.48	16.929	74.37
2	17	1.5	16	10	251	147	78	47.33	11.466	58.56574
3	1	2	24	15	297	244	80	55.74	19.52	82.15488
3	2	1.5	16	20	264	173	72	46.23	12.456	65.5303
3	3	1.5	24	20	271	201	78	48.8	15.678	74.16974
3	4	1	20	10	257	150	74	47.43	11.1	58.36576
3	5	2	16	15	279	211	76	47.23	16.036	75.62724
3	6	1.5	20	15	280	207	84	50.3	17.38	73.92
3	7	1	24	15	319	192	78	48.75	14.976	60.18809
3	8	1.5	20	15	273	201	85	49.79	17.085	73.62
3	9	1.5	20	15	276	205	83	49.72	17.015	74.27536
3	10	2	20	20	278	221	78	51.46	17.238	79.4964
3	11	1.5	24	10	254	171	76	52.23	12.996	67.32283
3	12	2	20	10	283	200	80	47.7	16	70.67138
3	13	1	20	20	299	188	75	44.46	14.1	62.87625
3	14	1.5	20	15	287	206	82	49.11	16.892	71.77
3	15	1	16	15	285	159	70	45.2	11.13	55.78947
3	16	1.5	20	15	284	211	80	48.63	16.88	74.29
3	17	1.5	16	10	248	151	75	46.22	11.325	60.8871

ii. **Manual pollination**

Replication	No of Flowers	No. of Fruits	Fruit weight (Kg)	Fruit diameter (mm)	Yield (kg/5m plot)	Pollination Efficiency (%)
1	282	225	84	53	18.9	79.78
2	297	236	83	55	19.588	79.46
3	279	221	87	56	19.227	79.21

iii. **Pollination by blower**

Replication	No of Flowers	No. of Fruits	Fruit weight (Kg)	Fruit diameter (mm)	Yield (kg/5m plot)	Pollination Efficiency (%)
1	289	193	77	49	14.861	66.78
2	279	177	76	48	13.452	63.44
3	291	187	78	47	14.586	64.26

iv. **Untreated Plot**

Replication	No of Flowers	No. of Fruits	Fruit weight (Kg)	Fruit diameter (mm)	Yield (kg/5m plot)	Pollination Efficiency (%)
1	276	136	73	42	9.928	49.27
2	259	133	76	43	10.108	51.35
3	253	132	75	41	9.9	52.17

Appendix-IV

Calculations of the total cost of the pollinator

Sr. no.	Name of component	Material used for construction	Specification/ Dimensions	Quantity	Rate in Rs.	Cost in Rs.
1.	Base Frame	MS square pipe	3300×40×40×4mm	16.58 kg	46/kg	762.64
2.	Male female arrangement	MS square pipe	3100×25×25×2mm 2600×20×20×2mm	4.86 kg 3.26 kg	46/kg	223.56 149.96
3.	Pipe for handle	MS pipe	3400×20mm	4.67	107/kg	499.69
4.	Ground wheels	Rubber		4	150	600
5.	Cheston Blower	Plastic	550 W	3	699	2097
6.	Nema17 motor			3	875	2625
7.	Speed controller		50-220 V	3	296	888
8.	Arduino Uno			3	400	1200
9.	Ac adapter		240 V to 12 V	4	199	796
10.	Easy driver		5 to 12 V	3	399	1197
11.	Wiper motor		5 to 24 V	1	700	700
12.	Extension board		8 plugs	1	500	500
13.	Plain bearings		6202	6	50	300
14.	Nut, bolts, and washers	Steel alloy		1 Kg	100/kg	100
15.	Wanhao printer filament	PLA filament		1 Kg	1249/ Kg	1249
16.	LN bolts and nuts	Steel alloy	5×90cm 3×50cm	12 12	40 20	480 240
Total cost of the pollinator						14607.8

Appendix-V

Calculations of the cost of operation of the developed pollinator

1.Assumptions

A. Fixed cost

i. Average annual use, h= 100 hours per year

ii. Life of machine, years= 7 years

iii. Salvage value@10% of initial cost

iv. Rate of interest @12% of capital cost

v. Housing, taxes and insurance cost @ 3% of initial investment per year

vi. Initial investment on the platform =Rs 13208

B. Variable cost

i. Labour cost per day= Rs 250

ii. Repair and maintenance cost@ 10% of the initial investment per year

2. Cost of operation of the variable height platform

A. Fixed cost

Initial cost of the designed pollinator = Rs 13208,

Depreciation, Rs/h=$\frac{C-S}{L\times H}$ = (14607-1460.7)/ (100×7) = 18.78 Rs/h

Interest, Rs/h= $\frac{C+S}{2}\times\frac{I}{H}=\frac{14607+1460.7}{2}\times\frac{12}{100\times100}$ = 9.64Rs/h

Housing, taxes and insurance cost@ 3% of initial investment per year, Rs/ h= $\frac{3\times14607}{100\times100}$= 4.38 Rs/hour

Fixed cost of the designed pollinator, Rs/h= 18.78 + 9.64 + 4.38 = 32.8 Rs/hour

B. Variable cost

Wages of labour @ Rs250 per day of 8 hours = 31.25 Rs/hour

Repair and maintenance cost @ 10% of the initial investment per year, $= \frac{10 \times 14607}{100 \times 100} =$ 14.60 Rs/hour

Variable cost of the designed platform, Rs/h= 31.25+ 14.60 = 45.85 Rs/hour

3.Cost in the operation of variable height platform

Total cost of the platform= Fixed cost + Variable cost= 32.8 Rs/hour + 45.85 Rs/hour

Total cost = 78.65 Rs/ hour

By using pollinator1 ha land can be covered in 5 hrs (at 1 km/hr speed while operating at both ends)

So, rate of pollination in 1 ha = 393.25 Rs/ ha

4. Cost involved in the manual pollination

Manually pollination depends upon skill of workers. Usually 5-6 labours are required to pollinate 1 ha/ day

So, Rate of manual pollination = 6×250 = 1500 Rs/ ha

BEP (Breakeven point, **h/year)** $= \frac{FC}{CH-C} = \frac{32.8 \times 100}{122.89-78.65} =$ 74.14 h/year

Where FC = fixed cost = 32.8 × 100 = 3280 Rs/year

CH= custom hiring charges, Rs/ hour

= (cost of operation per hour +25% of overhead charges) × 25% profit over new cost

= (78.65+0.25×78.65) ×1.25

= 122.89 Rs/ hour

C= Operating cost= 78.65 Rs/ hour

Hence,

BEP=74.14 h/year × 0.2ha/h= 14.82ha/year

Annual utility = 0.2ha/h×100 hours/year = 20ha/year

So BEP is achieved at 74.14 % of annual utility of 100 hours of pollinator.

Payback period

IC=Initial cost=Rs. 14607

ANP is Average net annual profit, Rs/year = (CH-C) × AU= (122.89 – 78.65) ×150

= Rs 6636

Payback period=$\frac{IC}{ANP} = \frac{14607}{6636} =$ 2.2 years