

EFFECT OF VIBRATION FREQUENCY ON ARTIFICIAL POLLINATION EFFICIENCY AND TOMATO (*SOLANUM LYCOPERSICUM* L.) YIELD UNDER HIGH TUNNEL CULTIVATION

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Abstract

Tomatoes are known for their quality and nutritional value all over the world. It provides approximately 40% of the daily-required vitamin C and vitamin A to support human health. This vegetable is usually grown in high tunnels, but in these structures, the natural pollinators (insects, birds, wind, and mammals, etc.) are not available, which badly affects the yield. To avoid this issue, an artificial pollinator handheld vibration device was used to mechanically transfer pollen by simulating the natural vibration to evaluate its performance at three different frequency levels (70, 85, and 100 Hz) for the Sahel hybrid cultivar. The proposed research performed a comparative analysis between natural and artificial pollination to explore the perspective of practical application. Considering the specific floral morphology and physiological characteristics of plant flowers during the pollination phase, the research scrutinizes the impact of artificial pollination. Results indicated that artificial pollination significantly improved crop performance over natural pollination in terms of fruit number by 40%, average fruit weight by 9.82 %, total fruit count by 34.5%, and yield up to 37.04%, respectively. Among the studied frequencies, the 85Hz frequency produced the highest yield (37kg). Average fruit weight of four treatments plants was close to each other, and remained relatively consistent ($\approx 115 \pm 8$ g) across treatments. A one-way ANOVA analysis demonstrated a significant impact of artificial pollination on the number of fruits, yield, and fruit conversion ($p < 0.01$). The suggested pollination frequency (85Hz) increased the fruit set of the crop. These findings contribute to a theoretical framework for artificial pollination methodology and demonstrate that artificial pollination, particularly at 85 Hz, effectively enhances fruit set and yield. The present study support the use of artificial pollination devices and their potential as an effective alternative for mimicking natural pollination.

Key words: Artificial pollination; Vibration frequency; Pollination efficiency; High tunnel; Precision Agriculture

Introduction

Agriculture is an important source for food, fiber, biofuel, and medical goods for sustaining and improving life. Agriculture is referred to as the backbone of human being, its play an important role in sustaining the world population. Agricultural products are very essential in economic and cultural factors, as a regular supply of food and raw materials is very essential for fulfilling human basic requirements for survival. For thousands of years, agriculture has been playing a vital role in economic development, forming societies and giving energy to the nations. However, the world population is increasing, and it will be approximately 9.7 billion by 2050; because of this, the demand for food is expected to increase by 70%, and this makes it necessary to increase agricultural production and yield (Peixoto *et al.*, 2022).

Pollination is mostly performed by insects such as bees, butterflies, and beetles, and this is important for the production of 75% of flowering plants and approximately 35% of worldwide food crops. Pollination is of different types, broadly classified into biological and mechanical types. Biological pollination involves pollinators such as bees, butterflies, and birds that transfer pollen from one flower to another. Among all these, pollinator bees are

considered the most efficient pollinators because of their behavior, movement, and body structure that enable bees to carry pollen (Kevan, 1999). According to (Garibaldi *et al.*, 2013), less pollen transfer can lead to a reduction in crop productivity and fruit set. Agriculture mostly depends upon insect pollination. Due to climate and environmental change, there is a decline in pollinators, and because of this, there is an alternative use of artificial pollination to meet the requirements in agricultural practices (Dingley *et al.*, 2022). It has shown that the distribution of some pollinator species, like bees, is affected due to climate change factors and with potential implications for crop yield in both temperate and tropical regions (Elias *et al.*, 2017).

Tomato (*Solanum lycopersicum* L.) is an important crop as it is a staple food for many cuisines and a key ingredient in many processed products such as sauces, juices, and paste (Ma *et al.*, 2025). In many countries like the United States, China, and India, tomatoes are a required part of both local and global agricultural economies (Yuan *et al.*, 2016). Pollination is a biological process for fruit and seed production in natural and agricultural systems (Zhang *et al.*, 2022). It involves the transfer of pollen from the male anther to the female stigma, which can occur in many different ways, such as biotic vectors like insects or abiotically by wind and by artificial methods using different inventions.

Tomatoes are also self pollinated beside cross pollination. Studies have shown that pollination through bees, particularly bumblebees, provides good results in fruit set, better quality, and better fruit yield (Ma *et al.*, 2025). Increases in temperature and changes in precipitation patterns affect the presence and distribution of pollinators, resulting in disruption in the synchronization between plants and their pollinators. The decreasing number of pollinators, natural pollination is decreasing in crops, and small areas where farming depends on pollination could lead to food security (Wongnaa *et al.*, 2021). Artificial pollination necessitates the use of human-assisted force or mechanical devices for the transfer of pollen to facilitate fertilization in plants (Tn *et al.*, 2024). Methods such as using brushes or vibratory devices have been used to ensure artificial pollination for the reproduction of crops (Yuan *et al.*, 2016). These different pollination techniques have been successfully used to get good fruit set in tomato cultivation (Nazer *et al.*, 2003). Artificial pollinators play an important role in crop productivity and increase crop yield. In spite of tomato is a self-pollinated plant, but requires buzz pollination through bees to give maximum yield. Different kinds of tomato pollinator methods are developed to meet the specific requirements of the tomato crop. One of the methods involves a mechanical vibrator device that provides buzz-like pollination behavior similar to bees (Yuan *et al.*, 2016). Another technology that is used for artificial pollination is a drone. Drones are equipped with devices that carry the pollen and are designed to pollinate the crop. Drones can be operated in a controlled environment (Tn *et al.*, 2024). Artificial pollination devices help in increasing the reproductive potential of the plant by ensuring that each flower receives the necessary pollen (Eyles *et al.*, 2022).

(Eyles *et al.*, 2022) provided data about a mechanical pollination (MP) system, a compelling substitute for insect-based pollination in fruit and crops. (Akca *et al.*, 2024) cited that the effectiveness of drone-based artificial pollination obtained a 94.61% fruit setting rate in walnut trees, compared to control trees, which is 32.33%. This result shows a 62.28% increase in productivity by using an artificial pollination system. (Yuan *et al.*, 2016) examined the use of an artificial pollination robot that is developed for tomato flower treatment, which improved pollination efficiency and accuracy. This study shows that artificial pollination through a device shows productive results in tomato crop yield.

In this study, vibration-based artificial pollination was applied to the tomato crop. The primary objective was to evaluate the artificial pollination effectiveness with respect to natural pollination in tomato plants grown in a high tunnel. Tomato plants under uniform conditions were selected to ensure consistency in experimental results. The study is primarily about precision agriculture for pollination. The research involved the comparison of natural and artificial pollination as the key research parameter. The effectiveness of pollen release was measured in both methods for crop production improvement. The artificial pollination device was used for pollinating plant for mimicking natural pollination. Pollination is a compulsory process for the fruit production of the tomato. The pollination enhancement affects crop production. The field performance was tested by an experiment to verify the artificial pollination capability.

Materials and Methods

Study area: An artificial pollination study on tomato was conducted at the National Agricultural Research Centre (NARC) in Islamabad, Pakistan, during the cropping season of 2024-25. The geographical coordinates of the experiment area are located (Fig. 1) at 33°40'27.6"N, 73°07'42.4"E. This region falls in the zone of sub-humid to semi-arid climatic zone, characterized by hot summers, mild winters, and a monsoon-influenced rainfall pattern, with average annual precipitation ranged between 800- 1200 mm. The soil texture of the experiment site was loamy in texture and moderately fertile, making it suitable for vegetable production, especially for tomatoes. The tunnel cultivation was chosen because it provided a protected environment to minimize natural pollination and ensure the accurate evaluation of the artificial pollination technique.

Tomato cultivation under high tunnel: In Pakistan, it is cultivated as a Rabi crop under high tunnel conditions to make it possible for optimal growth and extended harvesting periods. The Rabi season for the tomato crop (Table 1) typically spans from October to March. During the period of this season, daytime temperatures vary from 18-30°C, and the night temperature drops to 5-15°C, mostly in the winter months of December and January. The tunnel structures protect against extreme cold, frost, and pests. Allowing for consistent crop production and reliable evaluation of artificial pollination techniques. The cultivation of the tomato under a high tunnel was carefully prepared to enhance growth. The land that was used for the tunnel was first cleared, plowed, and leveled to ensure a uniform soil texture and proper drainage. Raised beds were formed inside the tunnel to enhance root aeration and irrigation efficiency. The organic manure and fertilizer were incorporated into the soil with a well-balanced ratio between them to improve soil fertility and structure. Tomato seeds were sown in nursery trays in early October 2024 in a separate tunnel to ensure healthy seedling development. After 35-40 days, the seedlings were transplanted into the prepared tunnel beds in the beginning days of December 2024. Flood irrigation was applied to the tomato to fulfill the crop water requirement. The tunnel structure protected the crop from the bad weather conditions and provided a suitable environment for evaluating the artificial pollination device and its impact on the tomato crop.

Artificial pollination device: The artificial pollinator device was employed for the current study. The use of artificial pollinators provides a comparison between natural and artificial pollination. The device was used for its versatility in artificial pollination of the crop. The device ensures the release of pollen from the stigma for effective pollination. It was precisely calibrated to work on three different frequencies. Collectively, the advance specification of the device make it easy to use in the field and for the experiment of the study. The technical specification of the artificial pollinator device is tabulated below (Table 2). During the device operation, the plants were selected for pollination only through an artificial technique. The air temperature and field humidity were the same for all the plants selected for the experimental study. The use of this device makes it easy to compare the natural and artificial pollination effects on tomato plants.

Test for the number of fruits under different vibration-based pollination: To evaluate the impact of an artificial pollination device on the tomato flowers compared to natural pollination, the number of fruits per plant was considered a key parameter. During the performance of the experimental setup, fruit set was recorded for each treatment group for both natural and artificial pollination conditions. Selected tomato plants for each treatment were monitored consistently during the experiment, and the total number of fruits produced per plant was counted at maturity. This parameter served as a measure of pollination success and reproductive efficiency. It shows the relative impact of pollination for quantitative assessment. Figure below (2) shows the stages of the tomato flower converting into fruit step by step.

Test on the effect of pollination on average fruit weight and yield.

To evaluate the effect of the artificial pollination method as compared to natural pollination, the average fruit weight was calculated for each treatment. The formula used for this calculation was:

Average fruit weight (g) =

Total weight of all fruits

Number of fruits

Table 1. Details of crop parameters.

Crop parameters	Details
Crop	Tomato
Variety	Indeterminate (Sahel hybrid)
Canopy features	Vertical trellis type
Height of crop (m)	1100-1200mm
Row to row spacing (m)	750mm
Plant to plant spacing (m)	500mm

Table 2. Technical parameters of the artificial pollination device.

Items	Parameters
Size	30cm × 5cm ×2.8 cm
Number of motors	1
Microcontroller	Arduino Nano
Motor driver	L298N dual H-bridge motor driver
Battery (type)	18650 lithium-ion cell
Battery (number)	2
Maximum vibration frequency	100 Hz
Medium vibration frequency	85 Hz
Minimum vibration frequency	70 Hz

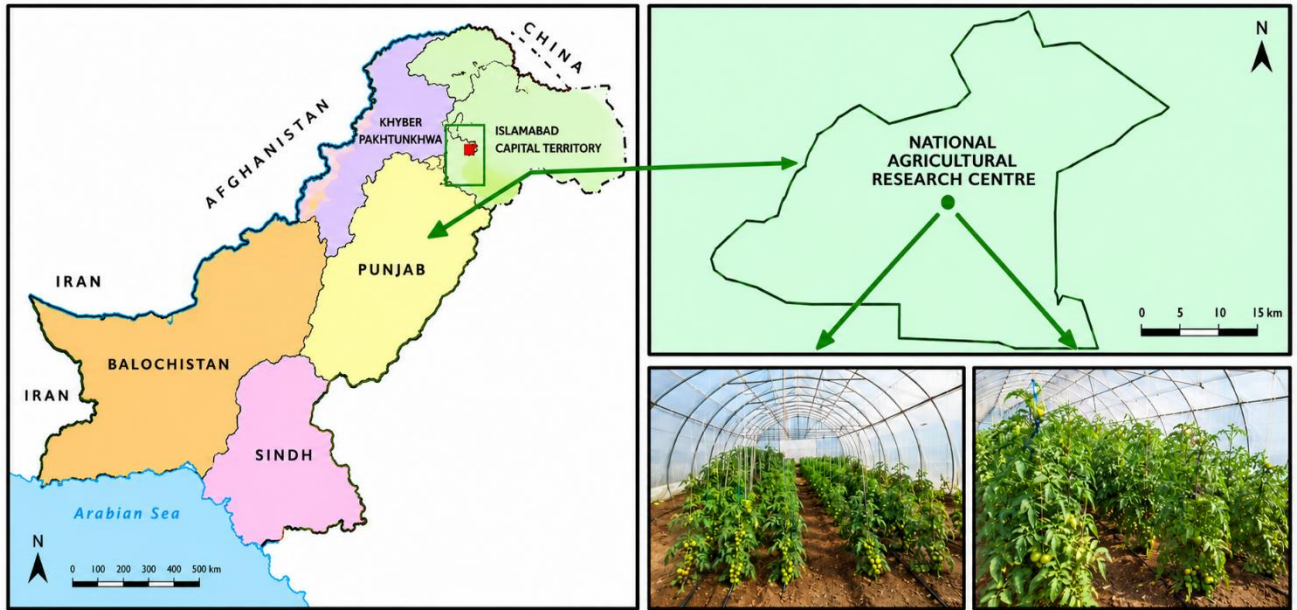


Fig. 1. Experimental site at National Agricultural Research Centre (NARC).

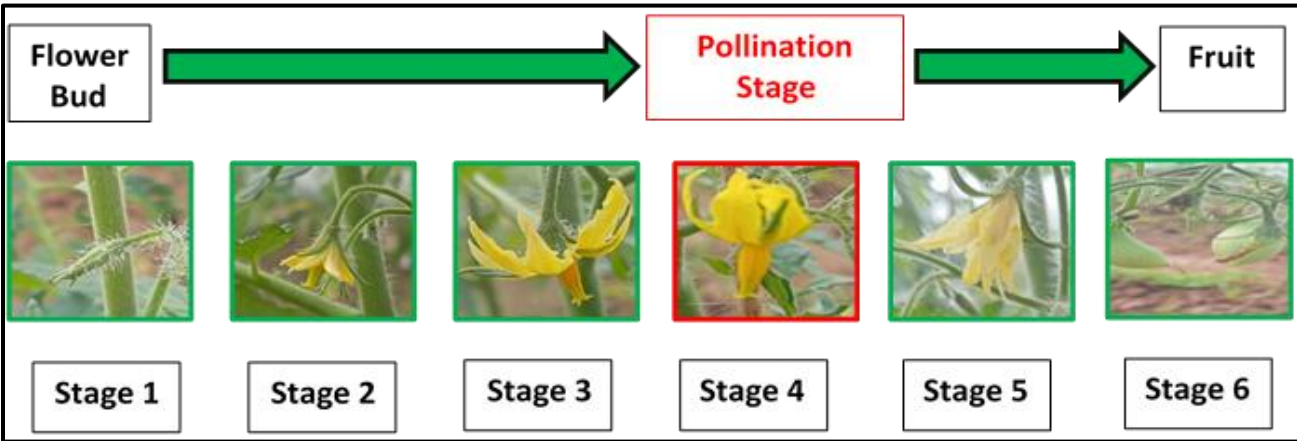


Fig. 2. Stepwise progression from tomato flowering to fruit set.

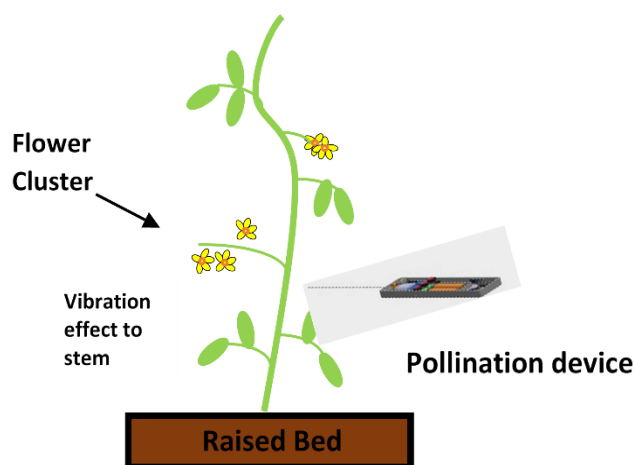


Fig. 3. Application of a developed artificial pollination device.

This parameter determined the effect of natural pollination and artificial pollination treatments at vibration frequencies of 70 Hz, 85 Hz, and 100 Hz. For this experiment, the total weight of all harvested fruits from the selected plants was recorded, and then the average weight of fruit from each plant was calculated. This parameter provided the result related to the influence of the pollination method on fruit development (Fig. 3).

The treatment-wise average yield was calculated to assess the productivity impact of pollination on tomato vegetables. The evaluation for this parameter was calculated by using the following formula:

$$\text{Average yield per treatment (g)} = \frac{\text{Total yield from all plants (g)}}{\text{Number of fruits}}$$

The total yield was calculated for each treatment of natural pollination and artificial pollination at different frequencies. All the selected plant yields were measured and divided by the number of plants to determine the average yield per treatment. This parameter approach enables a clear comparison of yield performance across treatments.

Table 3. The test treatment designs.

Treatment	Replication	Applied timing
T ₁ Natural pollination	15	Natural
T ₂ Artificial pollination (70 Hz)	15	5 sec
T ₃ Artificial pollination (85 Hz)	15	5 sec
T ₄ Artificial pollination (100 Hz)	15	5 sec

Fifteen different plants were selected for each artificial and natural pollination (Table 3). All plants were in the same atmospheric conditions. Table 3 also shows that the natural pollination for plants was through insects, birds, wind, and mammals, etc., and artificial pollination was provided through vibration to plants for 5 sec per cluster. Artificial pollination was carried out only during the flowering stage to each flower cluster with one-day intervals. The vibration frequency significantly affects the release of pollen and pollination efficiency in the tomato crop. Based on these findings, the frequencies of 70, 85, and 100 Hz were selected to evaluate the performance of the developed artificial pollination device.

Data statistics and processing: To determine significance of difference between the treatments and to validate the impact of artificial pollination compared with natural pollination, an appropriate statistical analysis was applied. The appropriate statistical analysis was applied to the collected data from the experiment. A Completely Randomized Design (CRD) was employed because of its suitability for experimental units entirely at random, mostly under field trials of experiments where environmental heterogeneity exists. The four pollination treatments were randomly assigned to the experimental units. Each treatment consisted of 15 plants, giving a total of 60 experimental plants. The experimental data included the following key parameters: number of fruits per plant, average fruit weight, and treatment-wise average yield, which were statistically analyzed using Analysis of Variance (ANOVA). This identifies the significant differences among all treatment of various vibration frequencies (70 Hz, 85 Hz, and 100 Hz) and natural pollination. The Tukey's Honest Significant Difference (HSD) post-hoc test was performed at the 95% confidence level to identify the significant differences. This compares treatment means and identifies significant differences among the pollination treatments. For the analysis and graphical representation of the data obtained from the experimental parameters, Minitab was utilized due to its user-friendly interface and robust statistical functions. The statistical approach makes it a reliable interpretation of data by enabling a comprehensive evaluation of the artificial pollination and natural pollination.

Result and Discussion

The experiment was conducted for the evaluation of the device, including its effectiveness and general functionality, and to establish baseline benchmarks for the device's real-world field application. This provides a comparison of the natural and artificial pollination effects on plants.

Analyze the effect of pollination on the number of fruits, average fruit weight, and yield.: The bar chart showed the total number of fruits produced in each treatment group (Fig. 4). The medium and low frequencies showed greater results, and the 85 Hz frequency gave 308 fruits, higher than other treatments. However, the highest frequency (100 Hz) showed lesser number of fruits, not suitable for pollinating plants artificially. The chart provides a strong demonstration of the effectiveness of the 85 Hz vibrational frequency on fruit production.

The yield parameter showed the quality effect of the artificial pollination on the flower (Fig. 5). The data points on the bars of 27, 31, 37, and 22 kg relate to the treatment means of vibration-based pollination and natural pollination. The artificial pollination showed a greater effect on yield compared to natural pollination. But the high frequency of pollination showed lesser result compared to other treatments. High frequency disturbs the fruit quality. The 85 Hz treatment shows the maximum yield, followed by the other 70 Hz, Natural, and 100 Hz treatments.

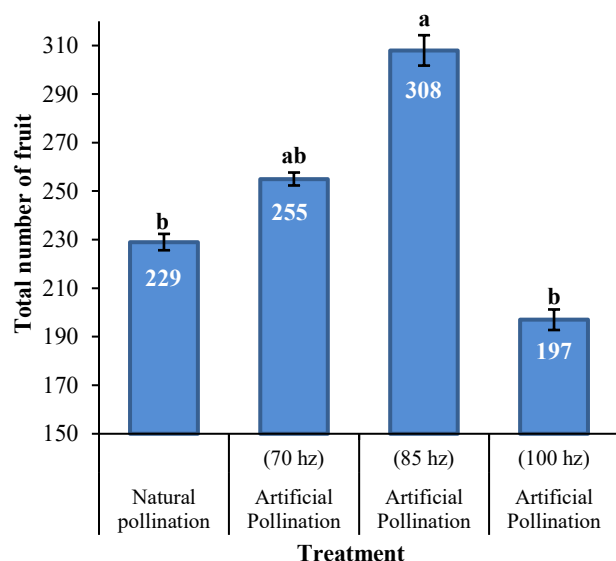


Fig. 4 Effect of pollination treatments on the number of fruits per plant.

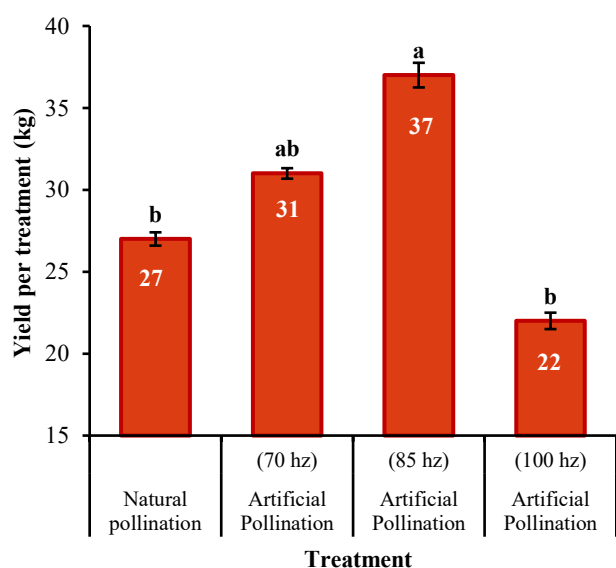


Fig. 5. Effect of vibration frequency on yield per treatment.

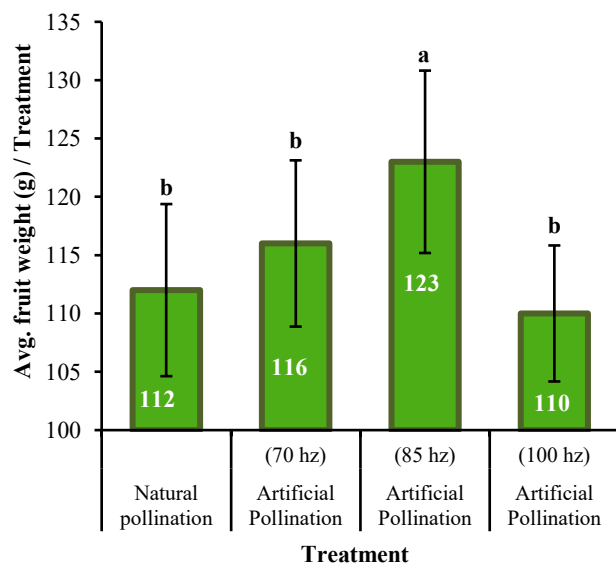


Fig. 6. Average fruit weight under different pollination treatments.

The average fruit weight result is presented in Fig. 6. Average fruit weight shows the quantity of the fruit. As the fruit weight shows the nutrients of the product. The pollination method did not show any major effects on the quality of the fruit's weight. All the treatment results are close to each other with minor differences in grams compared to each other. Average fruit weight remained relatively consistent ($\approx 115 \pm 8$ g) across all treatments. The 85Hz treatment led to the highest average fruit weights compared to natural pollination and other vibration frequencies. This suggests that artificial pollination can mimic natural pollination for increasing average fruit weight and maximum yield. The 85Hz vibration frequency provides optimum results in pollination.

Table 4. Analysis of Variance for number of fruit, average fruit weight and yield.

Effect and interaction	df	F-Ratio	p-Value	Significance
Number of fruit	3	7.76	$p < 0.001$	**
Average fruit weight	3	9.84	$p < 0.001$	**
Yield	3	8.37	$p < 0.001$	**

Statistical analysis of yield parameters

One-way ANOVA analysis was used to verify the significant effect on the number of fruit, average fruit weight, and yield obtained from the treatment (Table 4). The parameter of the research showed a significant effect.

Tukey's Honest Significant Difference (HSD) test was used to identify which specific groups differ from one another (Table 5). The test was conducted on three experimental parameters: total number of fruits, yield per treatment, and average fruit weight. For each parameter, the treatment mean and corresponding grouping letters are presented in the above table. Treatments with the same grouping letter are not significantly different at the 95% confidence level. Whereas treatments with different letters indicate significant differences. The results revealed that the 85 Hz treatment consistently recorded the highest mean values for total number of fruits (20.53), yield per treatment (2464), and average fruit weight (123.60 g). The 85 Hz treatment was assigned to Group A for all parameters. In comparison to the other 70 Hz, natural pollination, and 100 Hz treatments were grouped under Group B or AB. This indicated that there is no significant difference among them. The statistical outcomes, including mean values and confidence intervals, indicate a significant effect of vibration frequency on yield parameters, with 85 Hz showing the highest performance consistently.

Discussion

(Chautá-Mellizo *et al.*, 2012) state that natural pollination is required for fruit size, seed set, and germination rates, but natural pollination due to deposition of pollen and climate change reduces fruit set and fitness. The article by (Broussard *et al.*, 2023) states that comprehensive work is required for understanding the artificial pollination technologies and the requirement of research in this field; it involves parameters that identify the assessment of mechanical pollination systems, evaluation of pollen collection and application methodologies, and technological efficacy in different crops. Artificial pollination contains potential in ensuring crop productivity.

(Özer & Kandemir, 2016) study provides information that adopting advanced cultivation methods is also required for maximum yields. Artificial pollination often aligns with techniques that optimize plant performance in a controlled environment. (Arroyo-Correa *et al.*, 2019) said that tomato plants have poricidal anthers that release pollen when get vibrated through some external source. This mechanism involves bees, wind, and vibration to release pollen. (Tayal *et al.*, 2020) defined the important role of vibration pollination for the tomato crop for its production. Buzz pollination is a requirement for the plant because, with poricidal anthers such as tomato, pollen is held inside tubular anthers and can only be effectively released by artificial vibration. (Yuan *et al.*, 2016) examined the use of an artificial pollination robot that was developed for tomato flower treatment, which improved pollination efficiency and accuracy.

A study revealed that using the bee pollination method provided better results than artificial pollination (Sáez *et al.*, 2019). Bee pollination produced 40% more fruits with 34% more seeds compared to artificially pollinated plants. (Ahi Koşar *et al.*, 2023) investigated that UAV-based artificial pollination increased walnut fruit set by about 20%, providing a viable solution to frost-damaged catkins and climate change challenges. UAV method of pollination precisely pollinated 120 walnut trees per hour without affecting fruit quality, and it improved fruit weight, thickness, and length.

(Dingley *et al.*, 2022) reported that applying pollination through mechanical and acoustic methods showed an increasing result in crop production compared to natural pollination. (Zafar *et al.*, 2026) experiment found that applying vibration-based pollination through an artificial pollinator increased the fruit conversion in tomato plants. (Liu *et al.*, 2022) study explains mechanical vibration-based supplementary pollination for greenhouse tomatoes, focusing on the release and motion dynamics of pollen from the flower. It was reported that using the

coupled method of vibration and airflow improved pollen movement in the tomato crop (Liu *et al.*, 2024). The airflow method of pollen movement shows a higher coverage rate of 85.85% on the stigma as compared to the vibration pollination method alone. The numerical simulation model closely matched actual observations, validating its reliability.

(Aragon-Rodriguez *et al.*, 2022) examined the use of an artificial pollination device in pistachio trees that can mitigate the yield losses caused by adverse weather conditions. The vibrational response of the artificial pollination device ensures efficient pollen capture and distribution that increases fruit productivity. (Mahmood *et al.*, 2017) managed orchards produced 214-219 fruits per tree with higher fruit weight (125-127 g) and yields of 29-32 kg per tree, whereas unmanaged orchards yielded only 146-165 fruits per tree, lower fruit weight (104-112 g), and reduced yields of 17-22 kg per tree. (Urairi *et al.*, 2026) examine that pollination between 15-50 Hz vibrations showed lower results as compared to 100 Hz, but the (Sekine *et al.*, 2023) study shows that higher vibration frequency provides less effective results in pollination as compared to non-vibrational plots.

These results highlight the effectiveness of controlled pollination in enhancing both fruit quality and overall productivity. (Wang *et al.*, 2024) study demonstrates that the UAV-based liquid pollination method is effective and efficient, an alternative to manual and natural pollination. These findings support the adoption of advanced pollination methods as a practical strategy for enhancing production. (Liu *et al.*, 2023) Research finds that a comprehensive approach to enhancing tomato crop pollination through a vibration-based system. (Sekine *et al.*, 2023) reported that substrate-borne vibration was an effective technique for enhancing pollination. Vibrations at 30 Hz and 300 Hz were applied in a greenhouse, where 30Hz significantly increased tomato fruit set, showing effectiveness comparable to conventional plant growth methods.

Table 5. Tukey's HSD grouping of treatment means for experimental parameters.

Vibration (Hz)	N	Total number of fruit		Yield per treatment		Avg. fruit weight	
		Mean	Grouping	Mean	Grouping	Mean	Grouping
85 Hz	15	20.53	A	2464	A	123.6	A
70 Hz	15	17	A	2040	A	115.93	B
Natural	15	15.267	B	1833	B	112.13	B
100 Hz	15	13.13	B	1539	B	110.87	B

Conclusion

In the present study, the effects of different vibration frequencies and their results were compared to natural pollination. Artificial pollination was exerted on a tomato plant under a high tunnel through a vibration-based device. Fruit production in the tomato depends on effective pollen release and transfer. Vibration-based pollination showed notable enhancement in crop productivity. Results demonstrated that vibration-based pollination device significantly improved fruit set, yield, and overall crop productivity compared with natural pollination. This showed that the study increased crop productivity. The optimized vibration frequency of 85 Hz consistently produced effective results. The second-best result was noted at 70Hz while the lowest performance of the machine was observed at 100 Hz,

which is even below the natural pollination. Precision agriculture advancement offers a sustainable solution to improve tomato productivity. This device could enhance the farmer's economic returns by increasing marketable yield. The dependence of farmers on natural pollinator get reduced, also suitable for protected agriculture.

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