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BUZZ-TOMATO: An Off-Grid Solar-Powered Mechanical Vibration System for *Biomimetic* Pollination and Fruit Uniformity in Commercial Tomatoes (*Solanum lycopersicum*)

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ABSTRACT

Tomatoes (*Solanum lycopersicum*) are a horticultural crop with high economic value, but the size and quality of the harvest are not always uniform. Variations in fruit development within a single plant can lead to differences in size and quality, resulting in a lower proportion of fruits that meet specific quality standards and potentially affecting the economic value of the harvest. One factor influencing the success of fruit formation and development is the pollination process. Tomato flowers have a porous anther structure that requires vibration to facilitate pollen release; therefore, vibration mechanisms can be utilized as a biomimetic approach to assist in the pollination process. To address these issues, this proposal introduces BUZZ-TOMATO, an off-grid, mechanical vibration-based pollination assistance system that uses photovoltaic (PV) panels and LiFePO₄ batteries as energy sources. The device operates by applying controlled mechanical vibrations to tomato flowers to facilitate pollen release and support a more consistent pollination process. Vibration parameters are controlled using Pulse Width Modulation (PWM), allowing the motor's operation to be adjusted according to the stimulation needs of the flowers. The PV panels serve as the primary energy source, while the LiFePO₄ batteries store energy, enabling the device to operate independently without relying on the electrical grid. Compared to manual pollination, BUZZ-TOMATO offers more consistent and controlled stimulation, operates independently of the electrical grid, and utilizes renewable energy, making it more environmentally friendly. This technology has the potential to be applied to both small-scale and commercial tomato cultivation, particularly in areas with limited access to electricity. The implementation of BUZZ-TOMATO is expected to reduce variations in fruit development, improve size uniformity, and increase the proportion of the harvest that meets quality standards, thereby providing greater economic value for farmers.

1. Introduction

Tomatoes (*Solanum lycopersicum*) are a horticultural commodity with high economic value and steadily increasing market demand, both for fresh consumption and the processing industry [1]. However, tomato yields do not always exhibit uniformity in size and quality. Although research on mechanical pollination has advanced considerably, several questions remain unanswered. The

vibration frequency of 324 Hz reported by Shi et al. was obtained solely through simulation and therefore requires validation using a physical prototype mounted on tomato plants [3]. Furthermore, the mechanical pollination method investigated by Xu et al. has not yet incorporated renewable energy sources into an off-grid system [2]. To date, the most commonly used indicators for evaluating pollination success are fruit weight and fruit set rate. Xu et al. reported fruit set rates of 90% for bumblebee pollination, 75.4% for vibrator pollination, 91.7% for ultrasonic devices, 74.1% for air blowers, and 82.81% for pulse airflow [2]. Regarding fruit weight, Cooley and Vallejo-Marín reported a 64.72% increase following pollination by vibrating stingless bees and an 85.37% increase following open pollination compared to conditions without pollination. Mechanical vibration increased fruit weight by only 30.13%, although this increase was not statistically significant [1]. One of the key factors influencing fruit formation and development is the success of the pollination process. Optimal pollination can promote more consistent fruit formation and development.

Tomatoes have a poricidal anther structure that releases pollen through small pores at the tips of the anthers [1]. This structure facilitates pollen release through buzz pollination, a mechanism that relies on vibrations, such as those generated by buzz-pollinating bees. Cooley and Vallejo-Marín demonstrated that both buzz pollination by bees and open pollination can increase fruit weight compared to conditions without pollination [1]. These findings suggest that mechanical vibrations have the potential to serve as a biomimetic approach to facilitating the pollination process in tomatoes.

The limited availability of natural pollinators, particularly in greenhouse cultivation and areas where pollinator populations are scarce, has driven the development of mechanical pollination methods [2]. These methods include vibrating wands, vibrating motors, ultrasonic devices, and airflow-based systems. Xu et al. demonstrated that vibration-based methods have considerable potential to facilitate pollen release and achieve fruit set rates comparable to those obtained through bumblebee pollination [2]. Furthermore, Shi et al. employed Discrete Element Method (DEM) simulations to determine an optimal vibration frequency of 324 Hz and demonstrated a positive correlation between vibration duration and the amount of pollen released [3].

Although research on mechanical pollination has advanced considerably, several research gaps remain. The optimal vibration frequency of 324 Hz identified by Shi et al. has yet to be validated experimentally using a physical prototype on tomato plants [3]. Furthermore, the mechanical pollination methods investigated by Xu et al. have not yet incorporated renewable energy sources into an off-grid system [2]. To date, the effectiveness of tomato pollination has primarily been evaluated based on fruit weight and fruit set rate. Xu et al. reported fruit set rates of 90% for bumblebee pollination, 75.4% for vibrator pollination, 91.7% for ultrasonic devices, 74.1% for air blowers, and 82.81% for pulse airflow [2]. Regarding fruit weight, Cooley and Vallejo-Marín reported increases of 64.72% following pollination by buzz-pollinating bees and 85.37% following open pollination compared to conditions without pollination. Mechanical vibration increased fruit weight by only 30.13%, although this increase was not statistically significant [1]. However, neither study considered fruit size uniformity as an indicator for evaluating the effectiveness of mechanical pollination.

To address these research gaps, this study proposes BUZZ-TOMATO, a mechanical vibration-based pollination assistance system developed as a physical prototype operating at a vibration frequency of 324 Hz and powered by photovoltaic (PV) panels and a LiFePO₄ battery. The system employs Pulse Width Modulation (PWM) to regulate the vibration stimulus and is designed to operate independently of the electrical grid (off-grid). The effectiveness of the proposed system is evaluated based on pollination success and fruit size uniformity as key yield indicators. This approach

aims to integrate the experimental validation of vibration parameters, the utilization of renewable energy, and the assessment of harvest uniformity into a single system.

Table 1

Research Gaps in the Development of Mechanical Pollination Technology for Tomatoes

No.	Previous Research	Research Findings	Research Gap
1	Shi et al. [3]	Determining the optimal vibration frequency of 324 Hz using Discrete Element Method (DEM) simulation.	The 324 Hz parameter was obtained through simulation and needs to be validated using a physical prototype on tomato plants.
2	Xu et al. [2]	Examining various mechanical pollination methods, including the vibrating wand, ultrasonic, and airflow methods.	The development of mechanical pollination has not yet integrated renewable energy sources into off-grid systems.
3	Cooley dan Vallejo-Marín [1] & Xu et al. [2]	The success of pollination is evaluated primarily based on fruit weight and fruit set rate.	Fruit uniformity has not yet been widely used as an indicator in the evaluation of mechanical pollination.

2. Methodology

This study focuses on the design and development of BUZZ-TOMATO, a solar-powered mechanical pollination assistance system. The research methodology encompasses the development of a systematic research workflow, the design and operating principles of the proposed device, structural and material design, and mechanical and energy analyses to evaluate the performance and feasibility of the developed system.

2.1 Research Design

The BUZZ-TOMATO research project was structured into several stages encompassing the overall research process, design development, and operating mechanisms of the proposed device. Each stage was systematically organized to ensure a comprehensive design process, beginning with problem identification and progressing through to design evaluation. The research workflow, prototype development process, and operating mechanisms of the device are described in the following subsections.

2.1.1 Research Flowchart

The research workflow for the development of the BUZZ-TOMATO system is illustrated in Figure 1

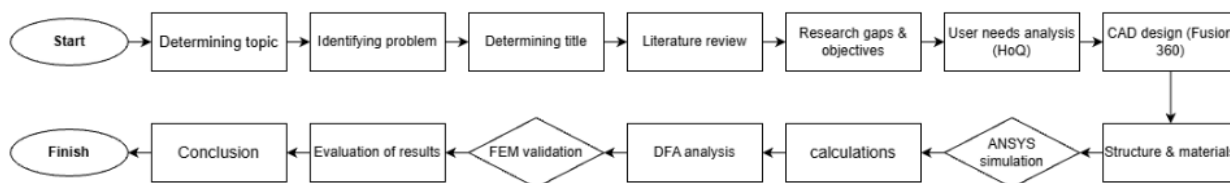


Fig. 1. Research Flowchart

2.1.2 Flowchart of the Process for Prototype Development

The BUZZ-TOMATO prototype development process is shown in Figure 2.

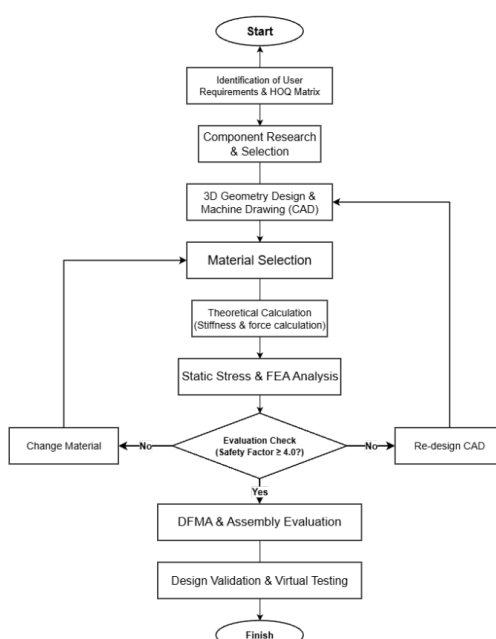


Fig. 2. Flowchart of the Process for Prototype Development

2.1.3 Flowchart of How the Device Works

The operating mechanism of BUZZ-TOMATO is shown in Figure 3.

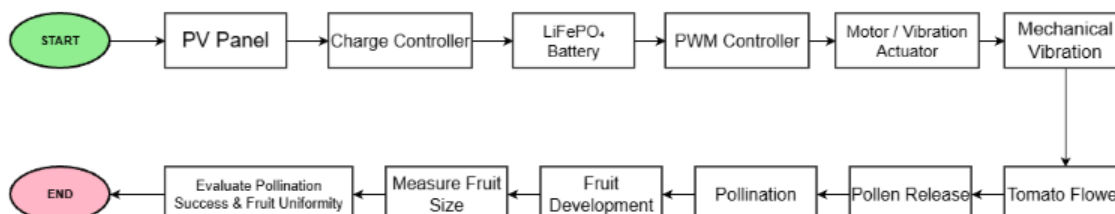


Fig. 3. Flowchart of How the Device Works

2.1.3 Sketch, Structural and Mechanical Design

The BUZZ-TOMATO design was developed to create a pollination assistance system capable of providing mechanical vibration stimulation to tomato flowers using solar energy. The design process included creating sketches and CAD models, determining the operating principles, designing the structure and materials, and analyzing the mechanical characteristics through modal analysis and static structural analysis.

2.1.4 CAD/Sketches & Working Principle

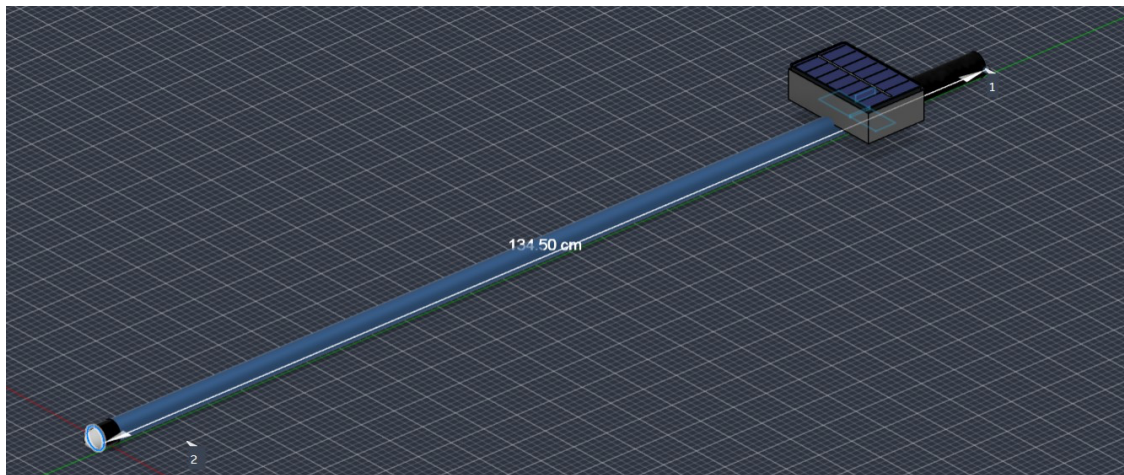


Fig. 3. Full-Body View Prototype

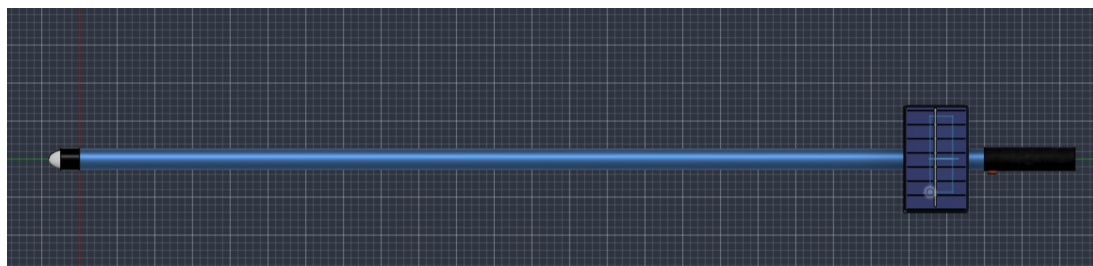


Fig. 4. Top View Prototype

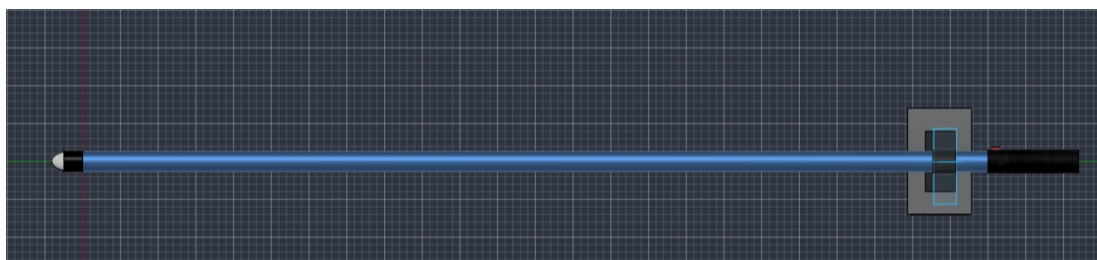


Fig. 5. View Prototype

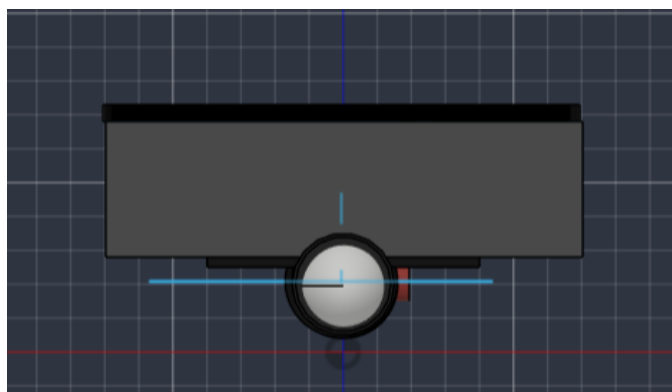


Fig. 6. View Prototype

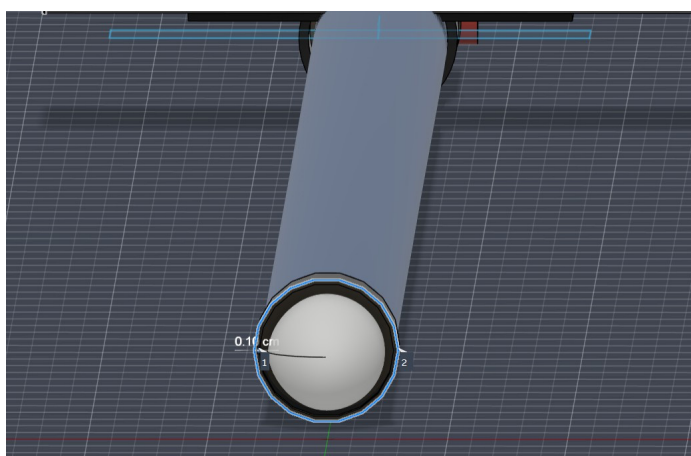


Fig. 7. View Prototype

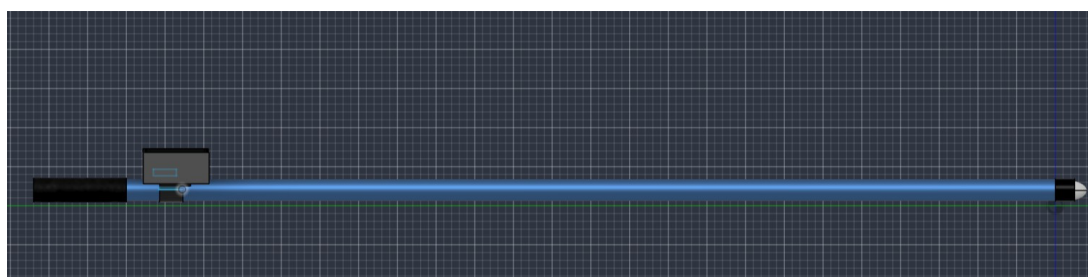


Fig. 8. View Prototype



Fig. 9. View Prototype

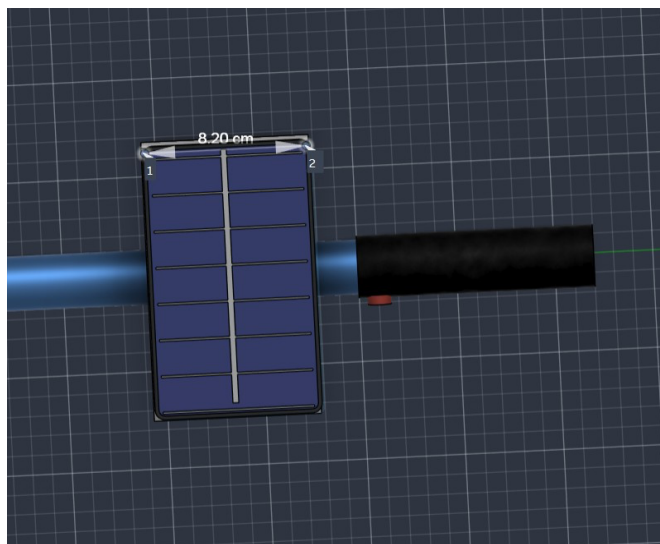


Fig. 10. View Prototype

2.1.5 Structural and Material Design

The mechanical structure of BUZZ-TOMATO is designed as a pole-shaped handheld device, enabling operators to reach tomato flowers without direct contact. The design approach is based on the House of Quality (HoQ) methodology, which translates eight user requirements into ten technical parameters. The weighting results indicate that the device's mass has the highest priority (13.4%), followed by the safety factor and number of components (12.8% each), displacement (11.3%), stress (10.8%), and material selection. Consequently, material selection and structural configuration focus on three key considerations: minimizing weight, ensuring adequate strength and stiffness, and reducing the number of components.

Following the redesign process, the system comprises 15 components, as determined through Design for Assembly (DFA) analysis. The display screen and switch were removed and are therefore excluded from the final component count. The mechanical components include a pole, a silicone tip (BUZZ-TOMATO silicone tip), a trigger housing, a printed circuit board (PCB) enclosure, and a bracket. The electrical components include a 5 W solar panel, a controller PCB, a 12.8 V LiFePO₄ battery equipped with a 4S Battery Management System (BMS), a 5 V buck converter, an L9110S motor driver, a micro DC eccentric rotating mass (ERM) vibration motor, a trigger button, and cable connectors.

The pole serves as the primary load-bearing element and is fabricated from 6061 aluminum alloy, with a length of 1.345 m and a diameter of 20 mm. This material was selected for its high strength-to-weight ratio, corrosion resistance under outdoor and greenhouse conditions, and ease of fabrication, making it suitable for developing a lightweight yet structurally robust device. The grip is made of rubber to prevent slipping and attenuate vibrations transmitted to the operator's hand. The tip that comes into contact with the tomato flower is made of silicone rubber, allowing mechanical vibrations to be transmitted while minimizing the risk of damage to floral tissues, in accordance with the design requirement of preventing flower damage. The PCB enclosure, trigger housing, and bracket are fabricated from acrylonitrile butadiene styrene (ABS) plastic, which offers low weight, electrical insulation, and sufficient mechanical strength to protect the electronic components.

2.1.6 Modal Analysis

Modal analysis was performed to determine the natural frequencies of the BUZZ-TOMATO structure. The analysis considered multiple vibration modes to investigate the natural frequency characteristics and dynamic behavior of the structure. The natural frequencies obtained from the simulation are presented in Table 2.

Table 2
Results of the Modal Structure Analysis for BUZZ-TOMATO

Mode	Natural Frequency (Hz)
1	0,37
2	0,37
3	2,0
4	2,0
5	6,0
6	6,0
7	12,5
8	12,5
9	12,5
10	19,7

The simulation results indicate that the natural frequencies of the first 10 vibration modes range from 0.37 Hz to 19.7 Hz. The lowest natural frequencies are observed in modes 1 and 2, both at 0.37 Hz. Several vibration modes exhibit identical or nearly identical natural frequencies, particularly modes 3 and 4, as well as modes 5 and 6. These findings characterize the dynamic behavior and natural frequency distribution of the BUZZ-TOMATO structure based on modal simulations. The highest natural frequency among the first 10 modes is 19.7 Hz, whereas the proposed operating vibration frequency of the device is 324 Hz, as reported by Shi et al. [3]. This operating frequency is approximately 16 times higher than the highest natural frequency identified in the simulation. Therefore, the operating frequency does not coincide with any of the natural frequencies identified within the first 10 vibration modes, suggesting a low risk of resonance in the supporting pole. Based on these modal analysis results, the BUZZ-TOMATO structure is considered to have a low risk of resonance at the proposed operating frequency.

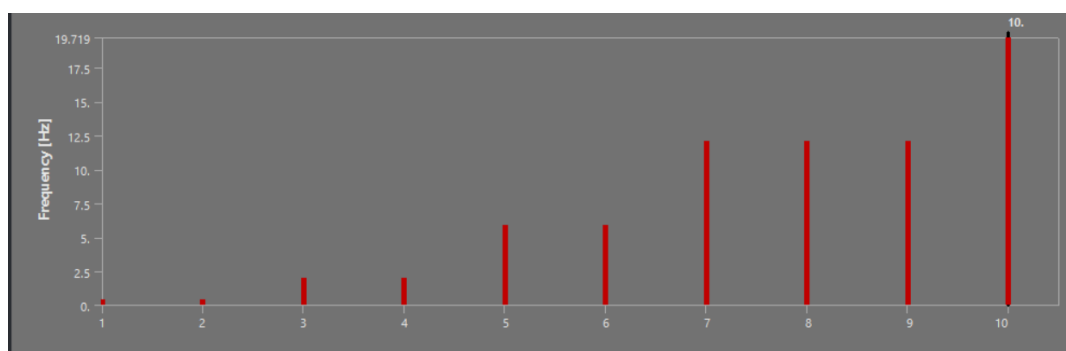


Fig. 11. Natural frequency graph

Figure 11 illustrates the variation in natural frequencies across different vibration modes of the BUZZ-TOMATO structure. The results indicate that the natural frequencies generally increase

with increasing vibration mode number. These findings provide an initial characterization of the dynamic behavior of the BUZZ-TOMATO structure and serve as a basis for evaluating its vibration characteristics.

2.1.7 Static Structural Analysis

Static structural analysis was performed to evaluate the response of the BUZZ-TOMATO structure under static loading conditions. The analysis aimed to determine the stress distribution, structural displacement, and safety factor of the proposed design. Prior to conducting the simulation, manual calculations were performed to estimate the applied force, maximum bending moment, second moment of area, bending stress, safety factor, and structural displacement. The results obtained from these manual calculations were subsequently compared with those generated through static structural simulations using Autodesk Fusion 360.

Manual Calculations

1) Mechanical Calculations

The applied load was determined based on a component mass of 0.5 kg. The corresponding gravitational force was calculated using the following equation:

$$F = mg$$

$$F = (0,5)(9,81)$$

$$F = 4,905 \text{ N}$$

The maximum bending moment was then calculated based on the applied load and the rod length of 1.345 m, using the following equation:

$$M_{\max} = FL$$

$$M_{\max} = 4,905(1,345)$$

$$M_{\max} = 6,596 \text{ N} \cdot \text{m}$$

The second moment of area of the rod's cross-section was determined by assuming a circular cross-section with a diameter of 0.02 m, as expressed in the following equation:

$$I = \frac{\pi D^4}{64}$$

$$I = \frac{\pi(0,02)^4}{64}$$

$$I = 7,854 \times 10^{-9} \text{ m}^4$$

The distance from the neutral axis to the outermost surface of the cross-section was calculated as follows:

$$y = \frac{D}{2}$$

The maximum bending stress was subsequently determined using the following equation:

$$\sigma_{\max} = \frac{M_{\max} y}{I}$$

$$y = \frac{0,02}{2} = 0,01 \text{ m}$$

By substituting the calculated values into the equation:

$$\sigma_{\max} = \frac{(6,596)(0,01)}{7,854 \times 10^{-9}}$$

$$\sigma_{\max} \approx 8,40 \text{ MPa}$$

The manual calculations yielded a maximum bending stress of 8.40 MPa.

The safety factor was then calculated based on the yield strength of 6061 aluminum alloy, which was taken as 275 MPa, using the following equation:

$$SF = \frac{\sigma_{\text{yield}}}{\sigma_{\max}}$$

$$SF = \frac{275}{8,40}$$

$$SF \approx 32,7$$

To determine the structural displacement resulting from the applied load, an additional calculation was performed to estimate the maximum beam deflection under the specified loading conditions. The maximum displacement was calculated using the following equation:

$$L_3 = (1,345)^3 = 2,433 \text{ m}^3$$

$$\delta_{\max} = \frac{FL^3}{3EI} = \frac{4.91 \times (2.433)^3}{3 \times 68.9 \times 10^9 \times 7.85 \times 10^{-9}} = 7.37 \times 10^{-3} \text{ m} = 7.37 \text{ mm}$$

Overall, the manual calculations yielded an applied load of 4.905 N, a maximum bending moment of 6.596 N·m, a maximum bending stress of 8.40 MPa, a safety factor of 32.7, and a maximum displacement of 7.35 mm. These results were subsequently used as reference values for comparison with the static structural simulation results obtained using Autodesk Fusion 360.

Electrical and Energy Calculations

The electrical requirements of the BUZZ-TOMATO system were determined based on the operating voltage, typical current consumption, and power requirements of each electrical component. These parameters were used to calculate the total electrical power consumption and estimate the energy

requirements of the proposed system. The specifications of the electrical components are presented in Table 3.

Table 3

Electrical Specifications and Power Consumption of BUZZ-TOMATO Components

No.	Component	Voltage (V)	Typical Current (A)	Power (W)
1	Solar Panel (5W)	17–18 Vmp	-	5W
2	Charge Controller (BMS 4S)	128	0.005 (Quiescent)	0.064
3	Buck Converter (12→5V)	12.8 → 5	0.01 (Idle draw)	0.05 (loss, 85% eff.)
4	Microcontroller (ESP32)	5	0.16 (WiFi active/0.02 idle)	0.8 / 0.1
5	Motor Driver (L9110S)	5	0.01 (Standby)	0.005
6	Actuator (Micro DC ERM)	3-5	0.08 (Running)	0.3-0.4

In addition to the mechanical calculations, electrical and energy calculations were performed to determine the power requirements and energy storage capacity of the BUZZ-TOMATO system. These calculations included the power consumption of individual electrical components, total system power consumption, battery energy capacity, estimated operating duration, and energy generation required to charge the battery using photovoltaic (PV) panels.

The total power consumption of the system was determined by considering the simultaneous operation of the microcontroller and actuator motor under active operating conditions. The total electrical power requirement was calculated using the following equation:

$$P_{\text{total}} = P_{\text{ESP32}} + P_{\text{driver}} + P_{\text{actuator}} + P_{\text{buck loss}}$$

$$P_{\text{total}} = 0.8 + 0.05 + 0.35 + 0.05 \approx 1.25 \text{ W}$$

Under idle/standby conditions, when the ESP32 microcontroller operates in sleep mode and the actuator motor is inactive, the estimated power consumption of the system is expressed as:

$$P_{\text{idle}} = 0.1 + 0.05 = 0.15 \text{ W}$$

The energy storage capacity of the 4S LiFePO₄ battery was calculated based on its nominal voltage of 12.8 V and rated capacity of 2 Ah, using the following equation:

$$E_{\text{battery}} = V \times C = 12.8 \text{ V} \times 2.0 \text{ Ah} = 25.6 \text{ Wh}$$

Based on a total active power consumption of 1.25 W, the theoretical operating duration of the system under active conditions was estimated using the following equation:

$$t_{\text{active}} = \frac{E_{\text{battery}}}{P_{\text{total}}} = \frac{25.6}{1.25} \approx 20.5 \text{ hours}$$

Similarly, the estimated operating duration under idle/standby conditions was calculated as follows:

$$t_{\text{idle}} = \frac{E_{\text{battery}}}{P_{\text{idle}}} = \frac{25.6}{0.15} \approx 170.7 \text{ hours} \approx 7.1 \text{ days}$$

To evaluate the energy generation capacity of the photovoltaic panel, the estimated daily electrical energy output was calculated by considering the rated power of the solar panel, effective daily sunlight hours, and overall system efficiency, as expressed in the following equation:

$$E_{\text{solar/day}} = P_{\text{panel}} \times t_{\text{sun}} \times \eta = 5 \text{ W} \times 4 \text{ h} \times 0.8 = 16 \text{ Wh/day}$$

$$t_{\text{charge full}} = \frac{E_{\text{battery}}}{E_{\text{solar/day}}} \times 24 \text{ h} = \frac{25.6}{16} \times 24 \approx 38.4 \text{ hours} \approx 1.6 \text{ hari terik penuh}$$

The electrical and energy calculations indicate that the BUZZ-TOMATO system requires approximately 1.25 W of electrical power during active operation. The LiFePO₄ battery, with a nominal energy capacity of 25.6 Wh, can theoretically support approximately 20.5 hours of continuous active operation and 170.7 hours, equivalent to approximately 7.1 days, under idle/standby conditions. Furthermore, a 5 W photovoltaic panel, assuming four effective sunlight hours per day and an overall system efficiency of 80%, is estimated to generate approximately 16 Wh of electrical energy per day. Based on this energy generation capacity, approximately 1.6 days would be required to generate an amount of energy equivalent to the nominal battery capacity. These estimates are based on theoretical calculations using the specified design parameters and operating assumptions.

Static Structural Simulation

The static structural simulation was conducted using Autodesk Fusion 360 to evaluate the mechanical response of the BUZZ-TOMATO structure under the specified loading conditions. The simulation model incorporated three materials: acrylonitrile butadiene styrene (ABS) plastic, silicone rubber, and 6061 aluminum alloy. Fixed constraints were applied to the structural components designated as supports to represent the prescribed boundary conditions. An external force of 4.91 N was applied to the structure, with a primary force component of 4.909 N acting along the Z-axis. Prior to conducting the simulation, the three-dimensional model was discretized into a finite element mesh to facilitate the numerical evaluation of the structural response.

Table 4
Comparison of Manual Calculations and Static Structural Simulation Results.

Parameter	Manual Calculation	Fusion 360
PCB Box Mass	0.5 kg	0,5 kg
Load type	4.905 N	4,91 N

Length of the stick	1.345 m	CAD Model
Diameter of the stick	0.02 m	CAD Model
Maximum bending moment	6.596 N.m	-
Moment of inertia	$7.854 \times 10^{-9} \text{ m}^4$	-
Bending stress	8.40 MPa	-
Von Mises stress	8.40 MPa	3.33 MPa
Yield strength aluminium	275 MPa	275 MPa
Safety factor	32.74	8.00
Displacement	7.35 mm	1.77 mm

The manual calculations yielded a maximum bending stress of 8.40 MPa and a safety factor of 32.74. In comparison, the Autodesk Fusion 360 simulation produced a maximum von Mises stress of 3.33 MPa, a minimum safety factor of 8.00, and a maximum total displacement of 1.77 mm.

Stress Simulation Results

The von Mises stress distribution obtained from the static structural simulation of the BUZZ-TOMATO structure is presented in Figure 12.

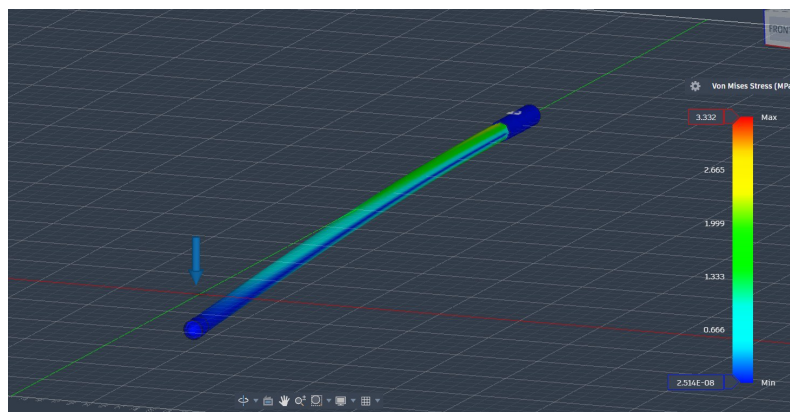


Fig. 12. Von Mises stress simulation results for the BUZZ-TOMATO structure

Based on the static structural simulation results, the maximum von Mises stress was determined to be 3.33 MPa. This value represents the highest equivalent stress experienced by the BUZZ-TOMATO structure under the specified loading and boundary conditions.

Displacement Simulation Results

In addition to stress analysis, the static structural simulation was performed to evaluate the displacement of the BUZZ-TOMATO structure under the applied loading conditions. The resulting total displacement distribution is illustrated in Figure 12.

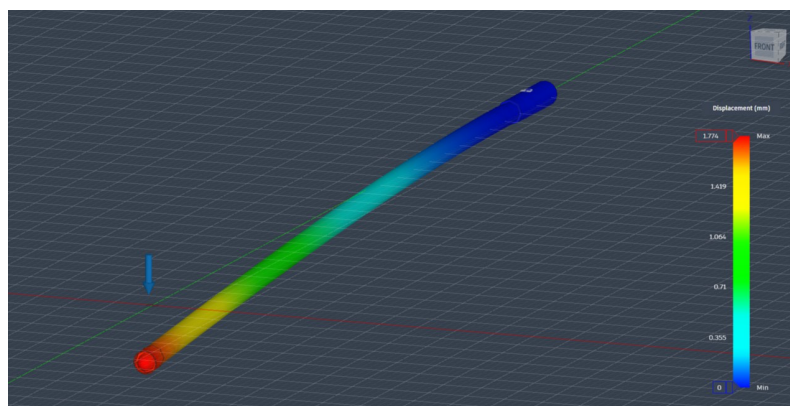


Fig. 13. Simulation results for the total displacement of the BUZZ-TOMATO structure

The simulation results indicate a maximum total displacement of 1.77 mm. This value represents the maximum deformation of the BUZZ-TOMATO rod structure relative to its initial position under an applied load of 4.91 N at the free end.

3. Discussion of Results

Based on the comparison presented in Table 4, the applied force used in the manual calculations (4.905 N) closely agrees with the force applied in the simulation (4.91 N). The manual calculations yielded a maximum bending stress of 8.40 MPa and a safety factor of 32.7, whereas the simulation produced a maximum von Mises stress of 1.442 MPa and a safety factor exceeding 8.00 throughout the rod, indicating that the structure falls within the "Above Target" safety range. The differences between the analytical and numerical results can be attributed to the simplified theoretical assumptions employed in the manual calculations, whereas the numerical simulation considers the complete three-dimensional (3D) geometry, boundary conditions, material properties, contact interactions, and load distribution.

The maximum displacement of 1.77 mm was observed at the free end of the rod, which is farthest from the fixed support and experiences the greatest deflection under the applied bending load. In contrast, the fixed end exhibited negligible displacement (approximately 0 mm). This displacement distribution is consistent with the expected mechanical behavior of a cantilever beam subjected to a concentrated load at its free end, where deflection progressively increases with distance from the fixed support.

Overall, the static structural analysis provides an assessment of the mechanical response of the BUZZ-TOMATO structure under the specified loading conditions. The resulting von Mises stress, total displacement, and safety factor provide useful indicators for evaluating structural integrity and supporting design verification before prototype fabrication.

3.1 Material Comparison Based on ANSYS

Material selection was conducted based on the mechanical properties required to ensure the structural performance and functionality of the BUZZ-TOMATO system. The materials considered in the simulation included acrylonitrile butadiene styrene (ABS) plastic, silicone rubber, and 6061

aluminum alloy. Each material exhibits distinct mechanical characteristics, particularly in terms of density, Young's modulus, Poisson's ratio, yield strength, and ultimate tensile strength. The material properties used in the numerical simulation are summarized in Table 5.

Table 5
Material Characteristics of BUZZ-TOMATO

Material	Density (kg/mm ³)	Young's Modulus (MPa)	Poisson's Ratio	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)
ABS Plastic	1.060×10^{-6}	2.240	0.38	20.00	29.60
Rubber Silicone	1.250×10^{-6}	3.00	0.49	10.34	10.34
Aluminum 6061	2.700×10^{-6}	68.900	0.33	275.00	310.00

Based on the material properties presented in Table 5, the selected materials exhibit distinct mechanical characteristics. Aluminum 6061 has a higher Young's modulus and yield strength than acrylonitrile butadiene styrene (ABS) plastic and silicone rubber, indicating greater stiffness and resistance to mechanical deformation. In contrast, ABS plastic and silicone rubber exhibit lower Young's modulus values, resulting in different stiffness characteristics. These variations in mechanical properties were considered when selecting suitable materials for the individual components of the BUZZ-TOMATO system. In the static structural analysis, all three materials were assigned to their respective components according to the proposed design configuration. The simulation results indicated a maximum von Mises stress of 3.33 MPa, a maximum total displacement of 1.77 mm, and a minimum safety factor of 8.00.

3.1 Results

The House of Quality (HoQ) analysis identified device mass as the highest-priority design parameter, with a weighting of 13.4%, followed by the safety factor and number of components, each contributing 12.8%. The static structural simulation of BUZZ-TOMATO yielded a maximum von Mises stress of 3.33 MPa, a maximum displacement of 1.77 mm, and a minimum safety factor of 8.00, indicating that the proposed structure satisfies the safety requirements under the specified loading conditions. Furthermore, the final design comprises 15 components, following the removal of the display and switch to simplify the assembly process and reduce design complexity.

3.2 House of Quality and DFA Results

The House of Quality (HoQ) analysis revealed that device mass was the most critical design parameter, accounting for 13.4% of the total priority weighting. This was followed by the safety factor and number of components, each with a weighting of 12.8%, displacement (11.3%), and stress (10.8%). These findings indicate that minimizing device weight and ensuring structural reliability were the primary considerations in the design and development of BUZZ-TOMATO. The results provided a basis for determining the structural configuration, material selection, and component arrangement of the proposed system. Based on these design priorities, a Design for Assembly (DFA) analysis was

subsequently conducted to simplify the assembly process and minimize the number of components. The analysis resulted in a final design comprising 15 components, following the removal of the display and switch, which were identified as non-essential elements. The remaining mechanical and electrical components were arranged according to the specified design configuration to support the intended functionality and assembly requirements of the BUZZ-TOMATO system.

Table 6

House of Quality (HOQ) of BUZZ-TOMATO

CUSTOMER REQUIREMENTS (WHATs)			TECHNICAL REQUIREMENTS (HOWs)									
Code	User Needs	Importance (Ii)	H1 Mass	H2 Power	H3 Freq	H4 Amp	H5 Mat	H6 Stress	H7 SF	H8 Disp	H9 Comp	H10 Energy Percentage
W1	Light Equipment	5	9	1	-	-	1	-	1	-	3	-
W2	Easy to use	5	3	1	3	1	1	-	1	1	9	-
W3	Easy to transport to the field	4	9	-	-	-	1	-	1	-	3	-
W4	Energy-saving	4	1	9	3	3	-	-	-	-	1	9
W5	Effective pollination process	5	1	3	9	9	3	3	3	3	1	1
W6	Does not damage flowers	5	1	1	3	3	3	9	9	9	1	-
W7	Safe and durable in use	5	3	1	1	1	9	9	9	9	3	-
W8	Easy to maintain	3	3	1	-	-	3	1	3	1	9	-
Technical Priority (Pj)			134	74	92	82	98	108	128	113	128	41
Relative Weight (%)			13.4%	7.4%	9.2%	8.2%	9.8%	10.8%	12.8%	11.3%	12.8%	4.1%

Notes

Customer Importance Scale:

- 5 = Very High/Critical Importance: Essential user requirements that represent the highest priorities, such as a lightweight design, ease of use, effectiveness, and safety.
- 4 = High Importance: Important requirements that users strongly expect, such as energy efficiency and ease of transportation to the field.
- 3 = Moderate Importance: Requirements of moderate importance, such as ease of maintenance.
- 2 = Low Importance: Secondary requirements that have limited influence on user decisions.
- 1 = Very Low Importance: Requirements considered to have the lowest priority.

Relationship Matrix Scale:

- 9 = Very Strong Relationship: Changes in technical specifications have a direct and significant impact on user requirements (e.g., the relationship between tool mass, H1, and the lightweight design requirement, W1).
- 3 = Moderate Relationship: Technical specifications have a moderate or indirect influence on user requirements.
- 1 = Weak Relationship: Technical specifications have a minor or minimal influence on user requirements.
- 0 (or -) = No Relationship: Technical specifications have no influence on the corresponding user requirements.

Table 6 presents the results of the Design for Assembly (DFA) analysis of the BUZZ-TOMATO structure. The analysis evaluates each component based on several assembly-related parameters, including the number of parts (Np), number of interfaces (NI), potential for standardization, cost, and handling difficulty, particularly in terms of orientation, alignment, and tooling requirements. These parameters were used to identify components that could be simplified, standardized, or eliminated to improve assembly efficiency and reduce design complexity. Consequently, the DFA analysis resulted in a final BUZZ-TOMATO design comprising 15 components, as described in Section 3.1.

Table 7
Design for Assembly (DFA) of BUZZ-TOMATO

No	Part Name	Np	NI	Std	Cost	Wrong Way	Tangle	Flexible	Tools	Difficult Align	Hold Down	Resistance	Obstructed	Reorient	Screw/ Drill	Weld	Solder	Test
1	POLE	1	2	N	M	N	N	N	Y	Y	Y	N	N	Y	Y	N	N	Y
2	PCB Box	1	1	N	M	Y	N	N	Y	Y	Y	N	Y	Y	Y	N	N	Y
3	Silicon Buzz Tomato	1	1	N	L	Y	N	Y	N	Y	Y	Y	N	Y	Y	N	N	Y
	Trigger Housing / Body	1	2	N	M	Y	N	N	Y	Y	Y	N	N	Y	Y	N	N	Y
5	Bracket	1	2	N	L	Y	N	N	Y	Y	Y	N	N	Y	Y	N	N	Y
6	PV 5 W	1	1	Y	M	Y	N	Y	Y	Y	Y	N	N	Y	Y	N	N	Y
7	PCB Controller	1	5	Y	M	Y	N	N	Y	Y	Y	N	Y	N	Y	N	Y	Y
8	Battery LiFePO4 12.8 V	1	2	Y	M	Y	N	N	Y	Y	Y	N	Y	N	Y	N	Y	Y
9	L9110S Motor Driver	1	2	Y	L	Y	N	N	Y	Y	Y	N	Y	N	N	N	Y	Y
10	Micro DC ERM Motor	1	1	Y	L	Y	N	Y	Y	Y	Y	N	N	Y	Y	N	Y	Y
11	PWM Control	1	1	Y	L	Y	N	N	Y	Y	Y	N	Y	N	N	N	Y	Y
12	Trigger Button	1	2	Y	L	Y	N	N	Y	Y	Y	N	N	N	Y	N	Y	Y
13	BMS LiFePO4 4S	1	2	Y	L	Y	N	N	Y	Y	Y	N	Y	N	N	N	Y	Y
14	Cable Connector	1	2	Y	L	Y	Y	Y	Y	N	N	N	Y	Y	N	N	Y	Y
15	Buck Converter 5V	1	2	Y	L	N	N	N	Y	Y	Y	N	Y	N	N	N	Y	Y

Notes

1. Np (Number of Parts): Refers to the total number of individual parts or components included in the assembly.
2. NI (Number of Interfaces): Refers to the number of connections or contact points between a component and other components within the assembly.
3. Std (Part Can Be Standardized): Indicates whether a component can be manufactured or selected using standardized dimensions or geometries.
4. Cost: Indicates the relative cost associated with an individual component.
5. Wrong Way Around: Indicates the possibility of installing a component in an incorrect direction or orientation.

6. Tangle/Nest/Stick Together: Indicates the tendency of components to become tangled, nested, or stuck together during handling or assembly.
7. Flexible/Fragile/Sharp/Slippery: Refers to the physical characteristics of a component that may increase handling difficulty during assembly.
8. Pliers/Tweezers/Magnifying Glass: Indicates whether specialized tools are required to handle or assemble a component.
9. Difficult to Align/Locate: Indicates the degree of difficulty associated with aligning or positioning a component correctly during assembly.
10. Holding Down Required: Indicates whether a component must be held in position during the assembly process.
11. Resistance to Insertion: Indicates whether resistance is encountered when inserting or fitting a component into its designated position.
12. Obstructed Access/Visibility: Indicates whether access to or visibility of the assembly area is restricted during component installation.
13. Re-oriented Workpiece: Indicates whether the workpiece must be rotated or repositioned during the assembly process.
14. Weld/Solder/Glue: Indicates whether component connections require welding, soldering, or adhesive bonding.
15. Paint/Lube/Heat/Apply Liquid or Gas: Indicates whether additional assembly processes, such as painting, lubrication, heating, or the application of liquids or gases, are required.
16. Test/Measure/Adjust: Indicates whether individual components or the assembled product require testing, measurement, or adjustment.

Classification Codes:

- Y = Yes; N = No.
- L = Low; M = Medium; H = High.
- Np = Number of Parts: Represents the number of individual parts or components (e.g., Np = 1 indicates one component, while Np = 2 indicates two components).
- NI = Number of Interfaces: Represents the number of connections between a component and other components (e.g., NI = 1 indicates one connection, NI = 2 indicates two connections, NI = 3 indicates three connections, NI = 4 indicates four connections, and NI = 5 indicates five connections).

3.3 Static Structural and Stress Analysis

Static structural analysis was performed on the mechanical components of the BUZZ-TOMATO pollinator pole using the Finite Element Analysis (FEA) method in Autodesk Fusion 360. The primary objective of this analysis was to evaluate and validate the mechanical strength and structural integrity of the proposed design under the applied loading conditions during device operation.

3.4 Modeling Parameters and Boundary Conditions

The structural model incorporates three principal materials: Aluminum 6061 for the supporting frame components (POLE KIRB), acrylonitrile butadiene styrene (ABS) plastic for the internal housing, and silicone rubber for the pollinator contact tip. The boundary conditions were defined by applying a fixed constraint at the base of the rod and an external force of 4.91 N,

representing the installation load, in the negative Z-axis direction at the working area of the pollinator tip. The finite element mesh consisted of 6,430 nodes and 3,416 parabolic elements to support the accuracy and numerical convergence of the simulation.

3.4.1 Results of Stress, Strain, and Safety Factor Distribution

The numerical simulation based on the von Mises stress criterion yielded a maximum equivalent stress of 3.332 MPa, concentrated near the base support region of the structure. This stress value is substantially lower than the yield strengths of Aluminum 6061 (275 MPa) and PPS plastic (68.90 MPa).

$$\sigma_{max} = 3.332 \text{ MPa} \ll \sigma_{yield} = 275 \text{ MPa}$$

The displacement contour results indicated a maximum structural displacement of 1.774 mm at the free end of the pole. Furthermore, the structural integrity analysis yielded a minimum safety factor (SF) exceeding the specified safety threshold. These findings indicate that the proposed structure is capable of withstanding the applied operational loads without exceeding the material yield limits, suggesting a low risk of plastic deformation or mechanical failure under the simulated loading conditions.

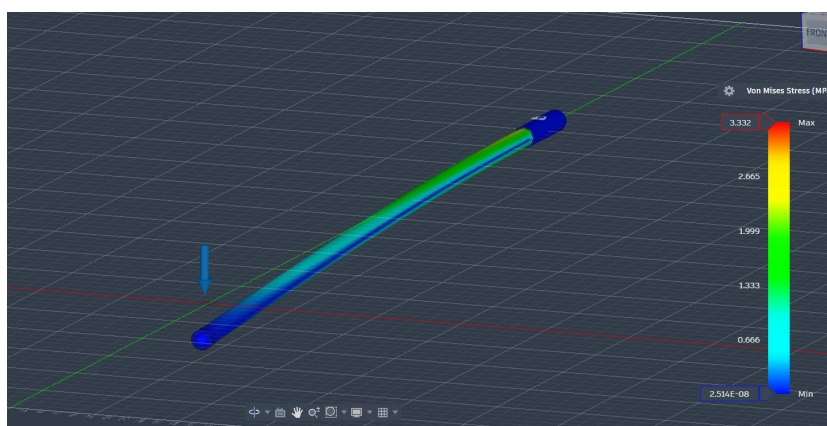


Fig. 13. Von Mises stress distribution on the BUZZ-TOMATO pole assembly with a maximum stress of 3.332 MPa

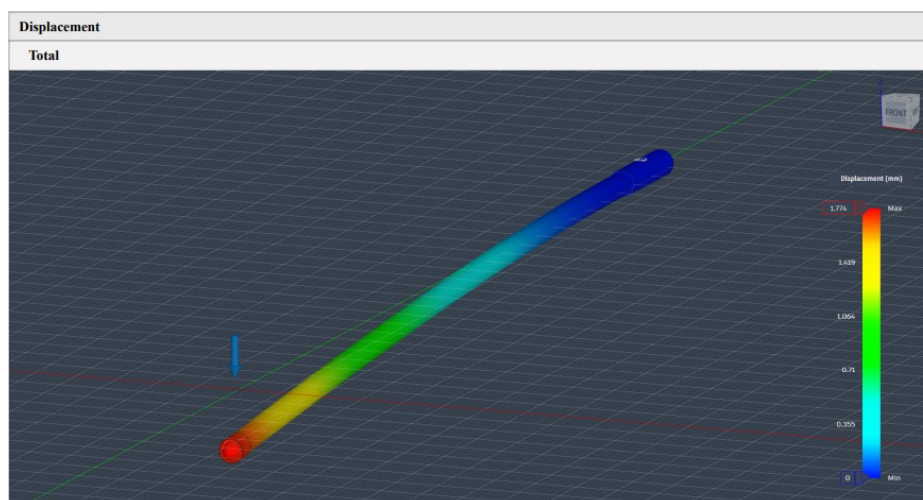


Fig. 14. Total displacement contour of the pole structure showing a maximum deflection of 1.774 mm at the free end

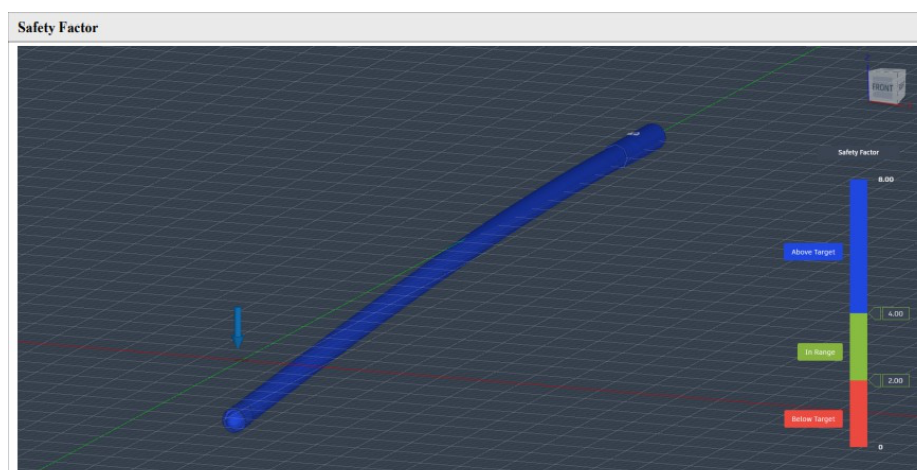


Fig. 15. Safety factor distribution confirming structural integrity under operational static loading

3.5 Correlation Between Theoretical Calculations and Numerical FEA Results

The evaluation results demonstrate a correlation between the theoretical calculations based on cantilever beam theory and the numerical results obtained through Finite Element Analysis (FEA) using Autodesk Fusion 360. The differences between the theoretical and numerical results reflect variations in the analytical assumptions and modeling approaches. The maximum von Mises stress of 3.332 MPa indicates that the structural modifications introduced through component elimination and simplification during the Design for Assembly (DFA) analysis maintain the mechanical reliability of the BUZZ-TOMATO structure under the specified loading conditions.

3.5.1 Dynamic and Modal Analysis

Dynamic and modal analyses were conducted to determine the natural vibration characteristics of the BUZZ-TOMATO structure and evaluate the potential occurrence of resonance during device operation. These analyses employed a computational approach based on modal frequency analysis as an alternative to physical vibration testing.

3.5.2 Determination of the Natural Frequency of the Structure

The natural frequency analysis was performed to determine the fundamental vibration characteristics of the mechanical assembly, consisting of the supporting pole and main casing, in the absence of external excitation. The resulting natural frequencies represent the inherent dynamic characteristics of the structure and provide a basis for evaluating its response to operational vibrations.

3.5.3 Validation of Operating Frequency Against the Literature

The target operating frequency for facilitating pollen release was established at 324 Hz based on the findings reported by Shi et al. (2025). The proposed operating frequency was compared with the natural frequencies of the BUZZ-TOMATO structure to evaluate the frequency separation between the motor excitation and the structural vibration modes.

Finite element simulations were conducted to determine the natural vibration modes of the structure. The results indicated that the highest natural frequency among the analyzed modes was 19.7 Hz. This value represents the upper limit of the natural frequencies identified within the simulated vibration modes. The frequency difference between the proposed operating frequency and the highest identified natural frequency was calculated as follows:

$$\Delta f = f_{\text{operation}} - f_{\text{natural}} = 324 \text{ Hz} - 19.7 \text{ Hz} = 304.3 \text{ Hz}$$

3.5.4 Evaluation of Dynamic Stability and Resonance

The substantial difference between the motor excitation frequency of 324 Hz and the highest identified natural frequency of 19.7 Hz indicates a considerable frequency separation of 304.3 Hz. This separation suggests that the proposed operating frequency does not coincide with any of the natural frequencies identified in the modal analysis, thereby reducing the likelihood of resonance within the analyzed vibration modes. These findings provide preliminary evidence of the dynamic stability of the BUZZ-TOMATO structure under the proposed operating conditions. However, further experimental validation is required to confirm its vibration response and long-term structural reliability during continuous operation.

3.6 Electrical and Off-Grid Energy System Modeling

3.6.1 Battery Power and Operating Life

Based on the electrical power calculations, the BUZZ-TOMATO system consumes approximately 1.25 W during active operation and 0.15 W under idle/standby conditions. The proposed energy storage system utilizes a 4S lithium iron phosphate (LiFePO₄) battery with a nominal voltage of 12.8 V and a rated capacity of 2 Ah, providing a total nominal energy capacity of 25.6 Wh. Based on this energy storage capacity, the theoretical operating duration of BUZZ-TOMATO is estimated to be approximately 20.5 hours under continuous active operation. Under idle/standby conditions, the estimated operating duration increases to approximately 170.7 hours, equivalent to 7.1 days. These estimates are based on the nominal battery capacity and calculated power consumption under the specified operating conditions.

Table 8
BUZZ-TOMATO Battery Power and Life

Parameter	Results
Total active power	1.25 W
Idle/standby power	0.15 W
Battery voltage	12.8 V
Battery capacity	2 Ah
Battery power	25.6 Wh
Estimated active operation time	20.5 Hours

Estimated idle/standby time	170.7 hours (7.1 days)
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The calculation results indicate that the 25.6 Wh battery can meet the power requirements of the BUZZ-TOMATO system for the estimated operating durations. These estimates were determined based on the calculated power consumption of the system components under active and idle/standby operating conditions, using the parameters established during the design stage. However, as these results were obtained through theoretical calculations, actual operating durations may vary depending on environmental conditions, battery performance, and operational demands.

3.6.2 Battery and Solar Panel Durability Simulation

Off-grid energy system modeling was conducted to evaluate the energy autonomy of BUZZ-TOMATO based on the combined performance of solar photovoltaic (PV) power generation and battery energy storage. The proposed configuration is intended to enable independent operation in agricultural plantation areas without requiring access to the conventional electrical grid.

The charging system incorporates a 5 W solar PV module mounted on the device body. Assuming an average of four effective sunlight hours per day and an overall energy conversion efficiency of 80%, the solar panel is estimated to generate approximately 16 Wh of electrical energy daily. This energy can be used to recharge the 25.6 Wh LiFePO₄ battery and support the device's operational requirements.

Based on the mathematical modeling results, the 25.6 Wh LiFePO₄ battery provides an estimated operating duration of approximately 20.5 hours in active mode and 170.7 hours in idle/standby mode. Meanwhile, the estimated daily solar energy generation of 16 Wh represents approximately 62.5% of the battery's nominal energy capacity. This suggests that the solar charging system has the potential to replenish a substantial proportion of the stored energy under the assumed sunlight conditions. However, the ability to sustain long-term off-grid operation depends on daily energy consumption, actual solar irradiance, charging efficiency, and the frequency and duration of device use. Therefore, further experimental validation is required to confirm the energy autonomy of the proposed system under practical field conditions.

4. Conclusions

This study successfully developed the conceptual design of BUZZ-TOMATO, a mechanical vibration-based tomato pollination device incorporating computer-aided design (CAD), finite element analysis (FEA), and an off-grid solar-powered energy system. Based on the structural analysis and computational modeling results, the cantilever mechanism constructed from 6061-T6 aluminum demonstrated satisfactory structural integrity under the specified loading conditions. The manual analytical calculations yielded a safety factor of approximately 32.74, whereas the three-dimensional FEA simulations conducted using Autodesk Fusion 360 produced a minimum safety factor of 8.00. Both values exceeded the predefined minimum safety requirement of 2.0, indicating that the proposed structure is unlikely to experience yielding under the simulated operational loads. These findings support the mechanical feasibility and structural reliability of the proposed device for horticultural applications.

To facilitate the development of BUZZ-TOMATO into a practical and accessible agricultural technology, a collaborative framework involving multiple stakeholders is proposed. This framework

includes partnerships with agricultural research institutions responsible for technology development, evaluation, and validation. To encourage adoption among farmers, technology transfer activities should be supported through the preparation of Standard Operating Procedures (SOPs), including digital pocket-sized visual guides and printed instruction manuals. Field implementation could be further strengthened through the involvement of agricultural extension officers, who could facilitate demonstration plots, practical training sessions, and periodic technical assistance.

Future research should focus on fabricating and experimentally evaluating physical prototypes under actual field conditions, determining the optimal vibration frequencies for effective pollen release in tomato flowers, and assessing pollination performance and fruit development. In addition, integrating Internet of Things (IoT)-based automation and monitoring systems could enhance operational efficiency, adaptability, and responsiveness, thereby supporting the further development and practical implementation of BUZZ-TOMATO as a sustainable agricultural technology.

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Conflict of Interest Statement

The authors declare that they have no conflicts of interest related to the publication of this manuscript. No financial support, grants, or other forms of compensation were received that could have influenced the research outcomes. Furthermore, the study was conducted without any commercial or financial relationships that could be perceived as potential conflicts of interest.

Author Contributions Statement

R.I.F. Nugraha conceptualized and designed the study. N.D.A. Faustino developed the three-dimensional design and prototype model using Autodesk Fusion 360. N.I.R. Yuwansyah conducted the structural and mechanical analyses using ANSYS simulation software. W.T. Rahayu and S.E. Rahono analyzed and interpreted the simulation results and prepared the initial draft of the manuscript. S.D. Prasetyo supervised the research, provided methodological and technical guidance, and critically reviewed the manuscript. All authors contributed to the revision of the manuscript, read the final version, and approved it for publication.

Data Availability Statement

The datasets and simulation models generated or analyzed during this study, including the CAD/FEA structural models, House of Quality (HoQ) matrices, and energy balance calculations, are presented within the article. Additional technical datasets are available from the corresponding author upon reasonable request. Publicly available datasets and relevant literature used in this study are appropriately cited in the reference section.

Ethics Statement

This study did not involve human participants, animal subjects, or the collection or processing of personal or sensitive data. The research was conducted entirely through computer-aided design using Autodesk Fusion 360 and simulation-based analyses using ANSYS as part of the KI-RBSET 2026 design competition. Therefore, ethical approval and informed consent were not required.

References

- [1] Anwar, Sidra, Happy Happy, Angus Dingley, et al. "Sonic-Induced Cellular Vibrations Unzip Intertwined Anther Cone Trichomes to Trigger Floral Self-Pollination and Boost Tomato Fruit Size." *Horticulture Research* (February 19, 2025): uhaf053. <https://doi.org/10.1093/hr/uhaf053>.
- [2] Cazonelli, Christopher, Sidra Anwar, Angus Dingley, et al. "Sonic-Induced Cellular Vibrations Disrupt Poricidal Cone Trichomes to Boost Tomato Floral Pollination." Preprint, In Review, August 3, 2023. <https://doi.org/10.21203/rs.3.rs-3198339/v1>.
- [3] Chung, Hsien-Ching. "Charge and Discharge Profiles of Repurposed LiFePO₄ Batteries Based on the UL 1974 Standard." *Scientific Data* 8, no. 1 (2021): 165. <https://doi.org/10.1038/s41597-021-00954-3>.
- [4] Cooley, Hazel, and Mario Vallejo-Marín. "Buzz-Pollinated Crops: A Global Review and Meta-Analysis of the Effects of Supplemental Bee Pollination in Tomato." *Journal of Economic Entomology* 114, no. 2 (2021): 505–19. <https://doi.org/10.1093/jee/toab009>.
- [5] Hiraguri, Takefumi, Tomotaka Kimura, Keita Endo, Takeshi Ohya, Takuma Takanashi, and Hiroyuki Shimizu. "Shape Classification Technology of Pollinated Tomato Flowers for Robotic Implementation." *Scientific Reports* 13, no. 1 (2023): 2159. <https://doi.org/10.1038/s41598-023-27971-z>.
- [6] Li, Mingyong, Xiaowu Zhu, Qianwen Li, et al. "Design and Performance Verification of an Intelligent Pollination Robot for Facility Tomatoes." *Computers and Electronics in Agriculture* 240 (January 2026): 111139. <https://doi.org/10.1016/j.compag.2025.111139>.
- [7] Liu, Siyao, Subo Tian, Zhen Zhang, Lingfei Liu, and Tianlai Li. "Design and Experimental Investigation of a Non-Contact Tomato Pollination Device Based on Pulse Airflow." *Agriculture* 15, no. 13 (2025): 1436. <https://doi.org/10.3390/agriculture15131436>.
- [8] Liu, Siyao, Xuemin Zhang, Xiaoyan Wang, et al. "Vibration Inducing and Airflow Guiding Coupled Tomato Pollination Method Research Based on Gas–Solid Two-Phase Flow Model." *Computers and Electronics in Agriculture* 216 (January 2024): 108472. <https://doi.org/10.1016/j.compag.2023.108472>.
- [9] Ngoy, Kitalu Ricin, Valantine Takwa Lukong, Kelvin O. Yoro, et al. "Lithium-Ion Batteries and the Future of Sustainable Energy: A Comprehensive Review." *Renewable and Sustainable Energy Reviews* 223 (November 2025): 115971. <https://doi.org/10.1016/j.rser.2025.115971>.
- [10] Shi, Qiang, Yong Liu, Bin Wang, et al. "Discrete Element Simulation of Buzz Pollination in Tomato." *Scientific Reports* 15, no. 1 (2025): 6710. <https://doi.org/10.1038/s41598-025-91490-2>.
- [11] Singh, Rajmeet, Manveen Kaur, Appaso M. Gadade, and Irfan Hussain. "YOLOv8-PnP Fusion Architecture for Non-Contact Robotic Pollination: A 6D Pose Estimation Approach for Autonomous Greenhouse Operations." *Frontiers in Plant Science* 17 (March 2026): 1771732. <https://doi.org/10.3389/fpls.2026.1771732>.
- [12] Singh, Rajmeet, Lakmal Seneviratne, and Irfan Hussain. "A Comprehensive Review of Current Robot-Based Pollinators in Greenhouse Farming." *arXiv preprint arXiv:2410.23747*, October 31, 2024. <https://doi.org/10.48550/arXiv.2410.23747>.
- [13] Singh, Rajmeet, Lakmal Seneviratne, and Irfan Hussain. "A Comprehensive Review of Current Robot-Based Pollinators for Crop Pollination." *Artificial Intelligence Review* 59, no. 1 (2025): 26. <https://doi.org/10.1007/s10462-025-11409-1>.
- [14] Urairi, Chihiro, Takuma Takanashi, and Takuji Koike. "Determination of Frequencies and Amplitudes in Flowers of Tomato Varieties for Vibrational Pollination." *Environment Control in Biology* 64, no. 1 (2026): 41–49. <https://doi.org/10.2525/ecb.64.41>.
- [15] Vallejo-Marín, Mario, and Avery L. Russell. "Harvesting Pollen with Vibrations: Towards an Integrative Understanding of the Proximate and Ultimate Reasons for Buzz Pollination." *Annals of Botany* 133, no. 3 (2024): 379–98. <https://doi.org/10.1093/aob/mcad189>.
- [16] Wongsu, Kanyanat, Orawan Duangphakdee, and Atsarek Rattanawanee. "Pollination Efficacy of Stingless Bees, *Tetragonula pagdeni* Schwarz (Apidae: Meliponini), on Greenhouse Tomatoes (*Solanum lycopersicum* Linnaeus)." *PeerJ* 11 (May 2023): e15367. <https://doi.org/10.7717/peerj.15367>.
- [17] Xu, Jing, Xuemin Zhang, Bo Deng, Hao Song, and Xiaoyan Wang. "Mechanized Pollination in Greenhouse Tomato Production: Applications, Challenges, and Future Perspectives." *Revista Brasileira de Engenharia Agrícola e Ambiental* 30, no. 6 (2026): e291023. <https://doi.org/10.1590/1807-1929/agriambi.v30n6e291023>