

## Design and Development of Electrical Multi-tool Carrier and its Compatible Equipment for Protected Cultivation

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The present paper describes the design and development of an electric multi-tool carrier and its compatible equipment (bed former, sprayer, and pollinator) for critical operations in protected cultivation. Design values were derived from protected structure dimensions and layout, soil properties, cropping parameters, and human factors with diverse cultivation needs. Field evaluations demonstrate the performance of the electric multi-tool carrier, navigating a 400 kg load at 20 km/h off-road and on-road with consistent track width and pneumatic tyre footprint. Maneuverability is highlighted by mean values for minimum turning diameter (6.9 m) and minimum clearance diameter (7.75 m). Traction parameters infer values of Travel Reduction Ratio (8.7%), Net Traction Ratio (0.84%), Tractive Efficiency (61.47%), Gross Traction Ratio (1.24%), Motion Resistance Ratio (0.40%), and Rolling Radius (1595.12 mm). Equipment-specific results show the bed former's efficiency of 52.08% at 2.0 km/h, 12% wheel slippage, and 1.53 kW power, sprayer's optimal uniformity at 3.0 km/h, 3.0 kg/cm<sup>2</sup> and maximum droplet density at 3.5 km/h, 2.5 kg/cm<sup>2</sup>. The pollinator, under optimal conditions (AFR 1.6-1.8 m<sup>3</sup>/min, PFA 18-21 Hz, ET 20 sec), yielded a mean pollination efficiency of 82.63% and a crop yield of 17.99 kg/5 m<sup>2</sup>. The entire system, had a total cost of Rs. 2,12,000.00 and an operational cost of Rs. 206 per hour, demonstrates economic viability, with a calculated payback period of 3.25 years. The developed machine has great potential for dissemination as it is powered by batteries, a source of green energy. The developed machine is one of its kind as it is versatile and can be used for haulage, bund formation, spraying and pollination.

**Keywords:** Bed former, Electric multitool carrier, Greenhouse cultivation, Pollinator, Vertical boom sprayer

### Introduction

The global population surge, coupled with the ever-growing challenges in ensuring food and water security, has necessitated a paradigm shift in agricultural practices. With over 15 percent of the world's population facing hunger daily and a projected global population of 10 billion by 2057, the need for innovative solutions in agriculture becomes imperative.<sup>1</sup> In this context, the efficient use of limited resources becomes paramount, and mechanization emerges as a key factor in optimizing agricultural operations.

Agricultural mechanization has proven instrumental in reducing production costs while increasing crop yield. This is particularly significant for countries like India, where small and marginal farmers, constituting 86% of the agricultural

community, play a pivotal role in overall production.<sup>2</sup> Protected cultivation has gained prominence due to its ability to provide off-season cultivation, higher productivity, and efficient space utilization. While greenhouse cultivation offers numerous benefits, including controlled climatic conditions and high-quality crop yields, it comes with its set of challenges – primarily, the high capital costs and the need for skilled labor and advanced technology.<sup>3</sup> In the Indian context, where small and marginal farmers dominate, the adoption of greenhouse technology becomes a critical aspect for future agricultural sustainability.

In India, the total area under protected cultivation is approximately 70,000 hectares; the technology has gained momentum, especially in regions like Ladakh, where it ensures year-round availability of fresh vegetables despite a limited growing season.<sup>4</sup> However, this growth is not uniform across the country, and there exists a considerable untapped

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potential for expanding protected cultivation practices. One of the key areas requiring immediate attention is the integration of technological advancements to address manual and time-consuming operations in protected cultivation. Presently, activities such as bed preparation, spraying and pollination are predominantly performed manually or with traditional tools and machinery, resulting in high production costs. Furthermore, the lack of specialized equipment compatible with multiple operations is not available.

The development of e-transport means is picking up now. The first electric vehicle was built by Frenchman Gustave Trouve in 1881. It was a tricycle vehicle, propelled by a 75 W DC electric prime mover placed on the rear axle and powered by the use of a lead acid battery pack. Researchers<sup>5,6</sup> explained the working of electric vehicles (EVs). The electric vehicle operates on an electric current principle. It is propelled by an electric prime mover, powered by rechargeable lead acid battery packs and controlled by regenerative controllers in place of a gasoline engine. The prime mover then uses the power (voltage) received from the batteries to rotate a transmission, and the transmission turns the wheels. Brushless direct current (BLDC) prime mover torque calculations for electric vehicles were studied.<sup>7</sup> The torque delivered by the prime mover plays a decisive role in its speed, acceleration and performance. An article on a preliminary study for building an autonomous vehicle for safe agricultural activities within the protected structure was published.<sup>8</sup> The maximum width of the boom should be 0.8 m, and the minimum speed should be 1.5 m/s, with skid steering for swift turning and rubber chain tyres for overcoming obstacles. The power source was derived from 12V 180Ah lead acid batteries, and the vehicle's overall weight was roughly 300 kg. It was also equipped with a 630-watt BLDC motor with 3000 rpm at no load conditions. A work on the design of a self-driving vehicle for greenhouses was done.<sup>9</sup> It was made up of a chassis, rail wheels, a pesticide tank that can be removed, a battery, and a pesticide spraying mechanism. Many musculoskeletal disorders have been recorded as a result of pruning and harvesting operations conducted in unusual postures and at heights above shoulder working height. A hydraulic system was used to raise a variable height platform using a scissor lift to a height of 5 feet. A design of an ergonomic variable height platform for training and

harvesting tomato crops in a greenhouse was done. It was determined that pruning with secateurs in conjunction with a variable height platform for above-shoulder work in a protected structure reduced drudgery in greenhouse operations.<sup>10</sup> Commercial ventures IDM Agrometal European developed three and four-wheel electric-charged battery power-operated trollies for protected cultivation.<sup>11</sup> The electric trolleys were provided with wide wheels and the chassis for greater stability even in the turning mode. The trolley power and the traction system through wheels allow steering on any ground, even very sandy and moist soil, in protected structures and open fields. The working platform where the operator stands was made of anti-slip aluminum material. Amate and Company developed four-wheel electric scaffolding for the internal work of the protected structure and necessary equipment for working inside the greenhouse.<sup>12</sup> However, there is scarce or almost no literature on multi-tool carriers for greenhouse operations. This is the rationale behind the current study on the design and development of an electrical multi-tool carrier and its compatible equipment for protected cultivation. With the existing research and technology gaps and the pressing need for efficient, cost-effective solutions, the study aims to bridge the divide between traditional practices and modern technological interventions by developing a versatile electrical multi-tool carrier and compatible equipment, addressing key challenges in protected cultivation.

### **Material and Methods**

The design values for the electrical multi-tool carrier and its compatible equipment (bed former, sprayer, and pollinator) for protected cultivation were determined from measured relevant parameters inside the protected structure, such as dimensions and layout of the greenhouse, agronomic parameters, crop parameters and human factors. Based on these design values, the system was developed in the Division of Agricultural Engineering, ICAR-IARI, New Delhi and the performance was evaluated in the Centre for Protected Cultivation Technology (CPCT)-IARI, New Delhi.

### **Critical Parameters Measurement**

In the pursuit of the development of an electric multi-tool carrier and its compatible equipment, a thorough investigation of crucial parameters has been undertaken. Four pivotal categories of parameters,

namely protected structure dimensions, soil characteristics, cropping parameters, and human factors, each contribute significantly to the design values of the electrical multi-tool carrier and its associated compatible equipment, were meticulously measured.

The first set of parameters is associated with a protected structure, encompassing dimensions, layout, agronomical practices, and operational requirements within the enclosed environment. These were integrated with the dynamic requirements of diverse protected cultivation practices. Soil parameters, the second point, involved an in-depth examination of physical properties, type, structure, texture, moisture content, bulk density, strength, electrical conductivity, and pH. These ensured that the design values aligned with the diverse soil conditions. Crop parameters, the third dimension, were critical in determining the design values for equipment such as the bed former, sprayer, and pollinator. Cropping patterns, plantation bed structures, and crop characteristics, including height and canopy dimensions, influenced the adaptability and efficiency of the tools designed for enhanced agricultural productivity. Human factors, the anthropometric and strength parameters of agricultural workers were also considered for the design.<sup>13</sup>

Soil texture was determined using the hydrolysis method, while electric conductivity (EC) was measured with an EC bridge. pH levels were

measured using a soil pH meter, and moisture content was determined by oven drying method. Soil samples were collected using a core sampler, and crop canopy was measured using a digital leaf area index (LAI) meter. Droplet parameters were analyzed using *Deposit Scan software*.

#### Design Values for Electrical Multi-tool Carrier

With a measured area of 0.1 hectares of greenhouse and a specific bed cluster configuration comprising four beds with a staking height of 3000 mm, the carrier's chassis parameters were decided. The designed values include an 850 mm track width, 1300 mm wheelbase, and 2700 mm working height to optimize maneuverability within the protected structure. The center of gravity (C.G.) located at 1150 × 520 × 1130 mm ensures stability during operations, enhancing the carrier's overall performance (Table 1 and Fig. 1a).

Soil parameters are crucial, with measured values encompassing soil resistance, strength, type (sandy loam), structure (angular blocky), and key physical attributes like moisture content (21.31%) and bulk density (1.44 gm/cm<sup>3</sup>). The designed values for the power system were calibrated, with a power requirement and prime mover both set at 1500 W, coupled with a 72V, 42 Ah lead acid battery. The traction device, tires and a differential-type transmission system were used for efficient power utilization across diverse soil conditions.

Table 1 — Design values of multi-tool carrier and its compatible equipment

Parameters	Measured value	Parameters	Designed value
<i>Protected structure parameter</i>		<i>Chassis</i>	
Dimensions ( <i>l</i> × <i>b</i> ), m	25×40	—	—
Average area, ha	0.1 ha	Track width, mm	850
Bed cluster	4 beds	Wheelbase, mm	1300
Staking height, mm	3000	Working height, mm	2700
—	—	C.G. location ( <i>x</i> × <i>y</i> × <i>z</i> ) mm	1150 × 520 × 1130
<i>Soil Parameters</i>		<i>Power system</i>	
Soil resistance, kg/cm <sup>2</sup>	0.3 to 0.65	Power requirement, W	1500
Soil strength, kg/cm <sup>2</sup>	0.52	Prime mover, W	1500
Soil type	Sandy loam	Transmission system	Differential type
Soil structure	Angular blocky	Traction device:	5.00/12.00
Moisture content, %	21.31	Power source:	Pneumatic tyre
Bulk density, gm/cm <sup>3</sup>	1.44	Power capacity	Lead acid battery 72V and 42 Ah
<i>Human Parameters</i>		<i>Workplace</i>	
Vertical reach, mm	1829-2141	Max. working height, mm	2100
Olecranon height, mm	913 – 1085	Steering height, mm	1000
Grip diameter, mm	39 – 57	Steering ring diameter, mm	35
—	—	Operator work area size ( <i>l</i> × <i>b</i> × <i>t</i> ), mm	960 × 660 × 10

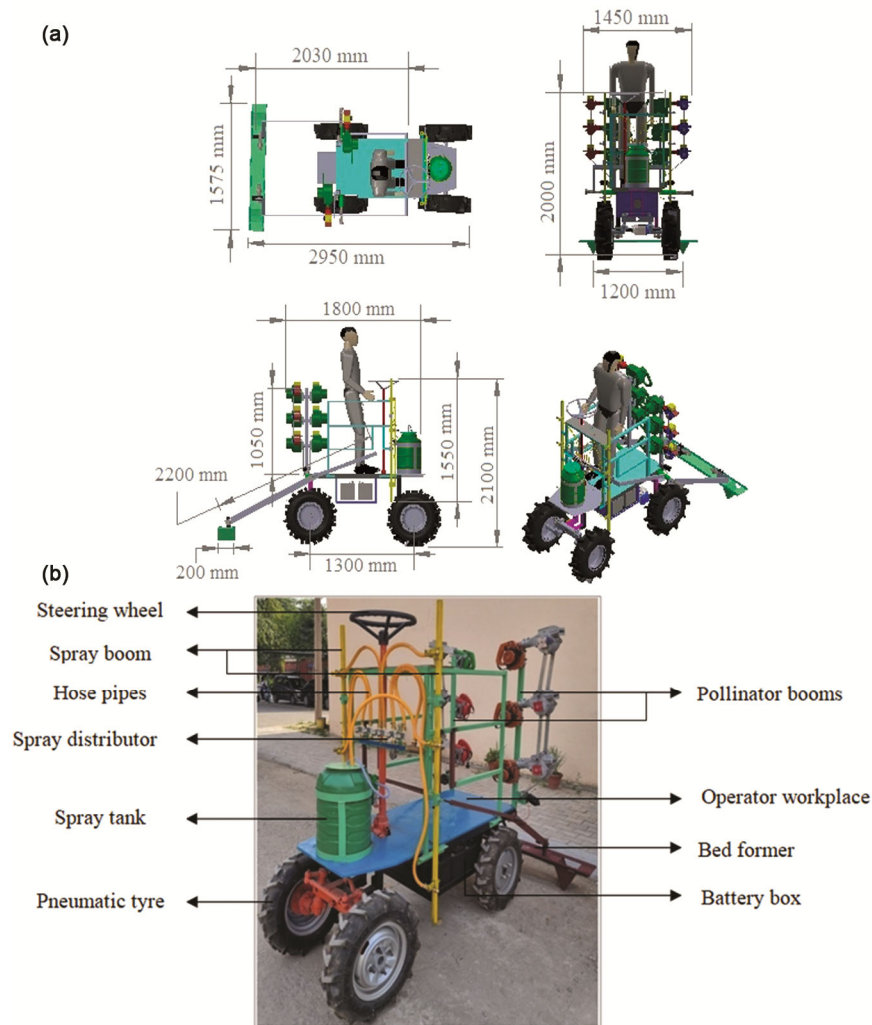


Fig. 1 — (a) CAD model, (b) Developed machine electric multi-tool carrier and its compatible equipment

Human factors, values of vertical reach (1829–2141 mm), olecranon height (913–1085 mm), and grip diameter (39–57 mm) were used for workplace dimensions. Designed values for the workplace, including a maximum working height of 2100 mm, a steering height of 1000 mm, and a steering ring diameter of 35 mm, tailored to enhance operator comfort and efficiency.<sup>13</sup> The operator work area was  $960 \times 660 \times 10$  mm, considering the ergonomic aspect to facilitate prolonged use without compromising productivity.

#### Design Values for Compatible Equipment

##### *Bed former*

Agronomic parameters with a trapezoidal bed profile, a working width of 1.0 m, and spacing between beds, the bed former's size and power requirement were 1000 mm and 1500 W, respectively. The incorporation of a designed mechanical hitch cum

position control lever enhances the bed former's efficiency in various cultivation scenarios (Table 2 and Fig. 1).

##### *Sprayer*

Crop parameters determine the design of the sprayer and pollinator components. Major crops such as Tomato, Capsicum, and Cucumber influence the maximum crop height (3 m) and canopy area of 1.57 m<sup>2</sup>. The sprayer with designed with a vertical spray boom length of 1.5 m, with six solid cone nozzles for precise and controlled application. Three spraying in the crop cycle, each with a tank capacity of 25 liters, sufficient for optimal application and coverage (Table 2 and Fig. 1).

##### *Pollinator*

The pollinator, with a vertical boom length of 1.05 m, has six blowers with angular movement of  $\pm 15$  degrees for efficient pollination (Table 2 and Fig. 1).

Table 2 — Design values of compatible equipment of multi-tool carrier

Parameters	Measured value	Parameters	Designed value
<i>Agronomic parameter- soil bed</i>		<i>Bed former</i>	
Bed profile	Trapezoidal	Bed former Profile	Trapezoidal
Bed working width, m	1	Bed former size, m	1500
Spacing between beds, cm	30	Bed former working width, mm	1000
Bed length, m	25	Power requirement, W	1500
Row-to-row spacing on the same bed, cm	60	Hitching system	Mechanical hitch cum position control lever
<i>Crop parameters</i>		<i>Sprayer and Pollination</i>	
Major crops and cropping pattern	Tomato, Capsicum, Cucumber	—	—
Max. crop height, m	3	Spray boom length, m	1.5
Max. crop canopy, m <sup>2</sup>	1.57	Pollinator boom length, m	1.05
No. of spraying in crop cycle	3	No. of spray nozzles and type	6 Solid cone
EAV, m/s	30-45	No. of pollination blowers	6
APF, Hz	10-25	Tank capacity, liters	25
Liquid spray and airflow direction	Horizontal and vertical	Blower size, Watt	500
No. of pollination in week	3	Spray and pollinator boom arrangement	Vertical
—	—	Blowers' angular movement, deg.	± 15
		Agitation system	Electrical type

The blower size of 500 W aligns with the required airflow for effective pollination. Parameters like Effective Air Velocity (i.e., 30–45 m/s)<sup>14</sup> and Pulsation Frequency of Air (i.e., 15 to 25 Hz)<sup>15</sup> were chosen for optimal operational conditions, ensuring precision.<sup>16</sup>

#### Development of electrical multi-tool carrier

The development of the electrical multi-tool carrier and its compatible equipment was executed by incorporating measured parameters, design values, and careful selection of functional components. The specifications of the developed electrical multi-tool carrier are detailed in Table 3 and presented in Fig. 1(b).

#### Electric Multi-tool Carrier

The rear axle of the electric loader was designed for optimal fitting space, accommodating the BLDC prime mover, differential unit, and mechanical speed reduction unit. The 1.5 kW BLDC prime mover, along with other electric accessories integrated into the electric multi-tool carrier chassis. This configuration ensures suitability, adequate payload capacity and seamless field operation. The front axle was customized to align with chassis dimensions, ensuring optimal steering geometry and reduced operator drudgery. The swinging-type front axle,

attached securely with robust nuts and bolts, fulfills the operational demands of traversing on uneven surfaces. It ensures its crucial role in enhancing steerability and operational efficiency.

The chassis designed to specifications was fabricated using MS square pipes (50×50×5 mm) chosen for their strength, load distribution, machining qualities, and cost-effectiveness. The tubular material serves dual purposes by acting as both chassis and compensating for the absence of a suspension system. The battery box for the electric multi-tool carrier, fastened to the chassis, accommodates lead acid batteries within its dimensions (560 × 500 × 300 mm). It was fabricated using MS angle sizes (25 × 25 × 5 mm) and a 3 mm thick MS plate; the box includes an acrylic sheet lower electronic shelf (560 × 500 × 10 mm) for electric accessories. It houses the regenerative controller, DC-DC converter, DC electric MCB, and connections for the prime mover, sprayer, pollinator, and charging socket.

The compatibility was ensured for different attached equipment with the electric multi-tool carrier, considering the highest power requirement in the bed former. However, the center of gravity was placed at the lowest point by arranging the batteries at the bottom. The attachment mechanism for the bed former was separately designed and integrated with the multi-tool carrier. At the same time, the

Table 3 — Specifications of the developed electrical multi-tool carrier and its compatible equipment (bed former, sprayer and pollinator)

Parameters	Specifications
<i>Electrical multi-tool Carrier</i>	
Overall carrier dimensions ( $l \times b \times h$ ), mm	2030 × 1575 × 2000
Rim-type and material	Disc type- Stainless steel
Rim diameter, mm	304.8
Chassis material and size	MS rectangular pipe of 50 mm with 3 mm thickness
BLDC prime mover capacity, W	1500
Rated speed of prime mover, rpm	3300
Torque output of the prime mover, Nm	3.8–4.5
Mechanical transmission system type integrated between rear axle and prime mover	Gear motor type, power train final drive gear ratio 25:1 and torque: 120 Nm
Prime mover controller type	Regenerative DC 1500W
Power source	Lead acid battery
Battery pack capacity	72 V 42 Ah
Loading capacity of rear axle, kg	2000
Braking system	Regenerative braking and drum braking system
Steering gearbox type	Worm gear and peg
Operator climb step dimension ( $b \times h$ ), mm	300 × 200
Operator's platform material	Wooden platform
Operator's platform dimensions ( $l \times b \times t$ ), mm	960 × 660 × 10
MS Safety guard's dimensions ( $l \times b \times h$ ), mm	860 × 735 × 880
Weight of the carrier, kg	280
<i>Electrical multi-tool carrier operated bed former</i>	
Mainframe dimensions ( $l \times b \times h$ ), mm	1500×200×320
Working width, mm	1000
Profile of bed former and shape of forming board	Trapezoidal and Cymboidal
Forming board dimensions ( $l \times b \times t$ ), mm	240 × 425 × 3
Hitch cum-position control lever dimensions ( $l \times b \times t$ ), mm	1780 × 1200 × 50
Bed former material	Mild steel
Bed former integration on the carrier	Manually attached at the rear of the carrier
<i>Electrical multi-tool carrier-operated sprayer</i>	
No. of nozzle its type	Six solid cone nozzle
Nozzle spacing, mm	300
Spray liquid control system	Water control valve
Hose pipe size and material, mm	12 mm flexible nylon
Spray boom length, mm	1500
Working spray boom length, mm	1000
No. of spray booms, Nos.	2
Boom and nozzle spacing adjustment	Manual
Water pump	DC 12 V
Spray tank capacity, litre	25
Spray tank material and shape	HDPE- cylindrical
Sprayer tank dimensions ( $D \times l$ ), mm	320 × 510
Agitation system	Electrically actuated 12 V DC motor
<i>Electrical multi-tool carrier operated pollinator</i>	
No. of Pollination booms, Nos.	2
No. of blowers, Nos.	6
Pollination boom dimensions ( $l \times b$ ), mm	1070 × 300
Pollination boom arrangement on the carrier	Both vertically on left and right side of rear portion of carrier
Pollination boom angular movement, degree	±15
Pollination blower power source	AC
Power consumption, W	500
Voltage, V	220
Blower Weight, gm	960
Pollination unit material	Aluminum sand casted
Pollination unit dimensions ( $l \times b \times h$ ), mm	235 × 80 × 140

attachment for the pollinator and sprayer was done with the attachment on the platform. The center of gravity was also analyzed with the help of *SolidWorks 2021 software* to ensure stability. Weight distribution was done in such a way that the weights and positions of the battery, chassis, operator and attached equipment were appropriate. The bed former was attached to the electric multi-tool carrier using a hitch-cum-position control lever, which controls the position and bed height. It consists of two levers: a hitching lever and a position control lever. It was attached to a fixed extension shaft of the multi-tool carrier's chassis rear end. The hitching lever carries the weight of the implement and controls the draft during operation is directly connected to the bed former. The position control lever is attached to the hitching lever and can be operated by push force by the left leg (Fig. 2a).

The workplace for the electrical multi-tool carrier was fabricated using lightweight, sturdy MS rectangular pipes ( $25 \times 25 \times 5$  mm). The platform for operators ( $960 \times 660 \times 10$  mm) incorporated with controlling units like the brake and accelerator pedals, while an acrylic dashboard panel ( $225 \times 660 \times 10$  mm) beneath the steering wheel housed essential controls including the ignition key, forward/reverse switch, digital meter, pollinator movement switch, water solenoid valve, and sprayer pump switch.

The electric multi-tool carrier's traction devices were pneumatic lug-type tires (5-5/12 – 4PR), selected for optimal weight distribution and traction parameters. The disc-type rim, a hub-type cast iron rim (5/12 inch), ensures machine compactness and equal dead load distribution. Rim size and pitch size (Pitch Circle Diameter: PCD) align with front and rear axle dimensions, enhancing overall efficiency.

The speed of 20 km/h was considered only for the extreme working conditions on an experimental purpose. However, the operations inside the greenhouse were conducted at a very low speed. The efficient two braking mechanisms were provided. The braking distance was measured according to IS 12061:1994.<sup>(17)</sup> Mechanical braking, with a distance of 1.75 m, was found to be more efficient than the regenerative braking system, which had a distance of 3.5 m. For operator safety, safety grills were provided on the platform, and safeguards on the chassis were included to support the operator while driving. Additionally, step climbers were installed for safe entry to the vehicle's platform, along with holding

rails, and a buzzer sound was equipped to alert when the vehicle was reversing.

The control system governs the electric multi-tool carrier, regulating speed in relation to load. An electrical braking system halts the carrier by disrupting the circuit. For precise stoppage, a mechanical pedal-operated braking system was also provided. An electric accelerating pedal, linked to the regenerative controller, ensures automatic speed control. Power is sourced from the carrier's main 5 V DC electric supply (Table 3).

#### ***Bed Former***

The primary frame of the electric multi-tool carrier, i.e., the mainframe, vital for protected cultivation, was fabricated using MS angle ( $25 \times 25 \times 10$  mm) and MS hardened plate ( $200 \times 150 \times 7$  mm), welded into a  $1500 \times 200 \times 180$  mm size. This robust design ensures hitching strength and stability, preventing deformation in the bed former. The frame withstands a pull of 9.8 N/mm without altering the bed profile. Bed former was fabricated with a 4 mm MS-hardened sheet featuring a  $25^\circ$  curvature to turn the soil effectively (Table 3 and Figs. 1b and 2a). Attached to the front side of the bed former, these boards lift and turn the soil, achieving the desired bed height. A single mould board per furrow opener ensures efficient bed formation, considering available power.

The hitching lever, developed from a 5 mm MS plate, was drilled to fit into the main frame of the bed former and the electric multi-tool carrier's rear end extension point on its chassis. Fastened with two 12 mm nut bolts, they stabilize the bed former during operation. Cotter pins secure the four hitching points. The position control lever, situated at the operator's knee height, aids bed former positioning and depth control. Connected to the bed former's mainframe, it features a locking system for bed former adjustment during turning and on-road transportation.

#### ***Sprayer***

A 25-liter HDPE sprayer tank was securely mounted on the electric multi-tool carrier using a cylindrical tank holder made of MS plate ( $25 \times 25 \times 3$  mm) at the front, ensuring weight transfer and carrier stability. An electronic agitation system, driven by a Nema 17 motor and propelling fan, maintained a uniform mixture aided by water jet streams generated from spray lance overflow. The 12 V DC electric water pump, connected to the lead acid battery (12 V

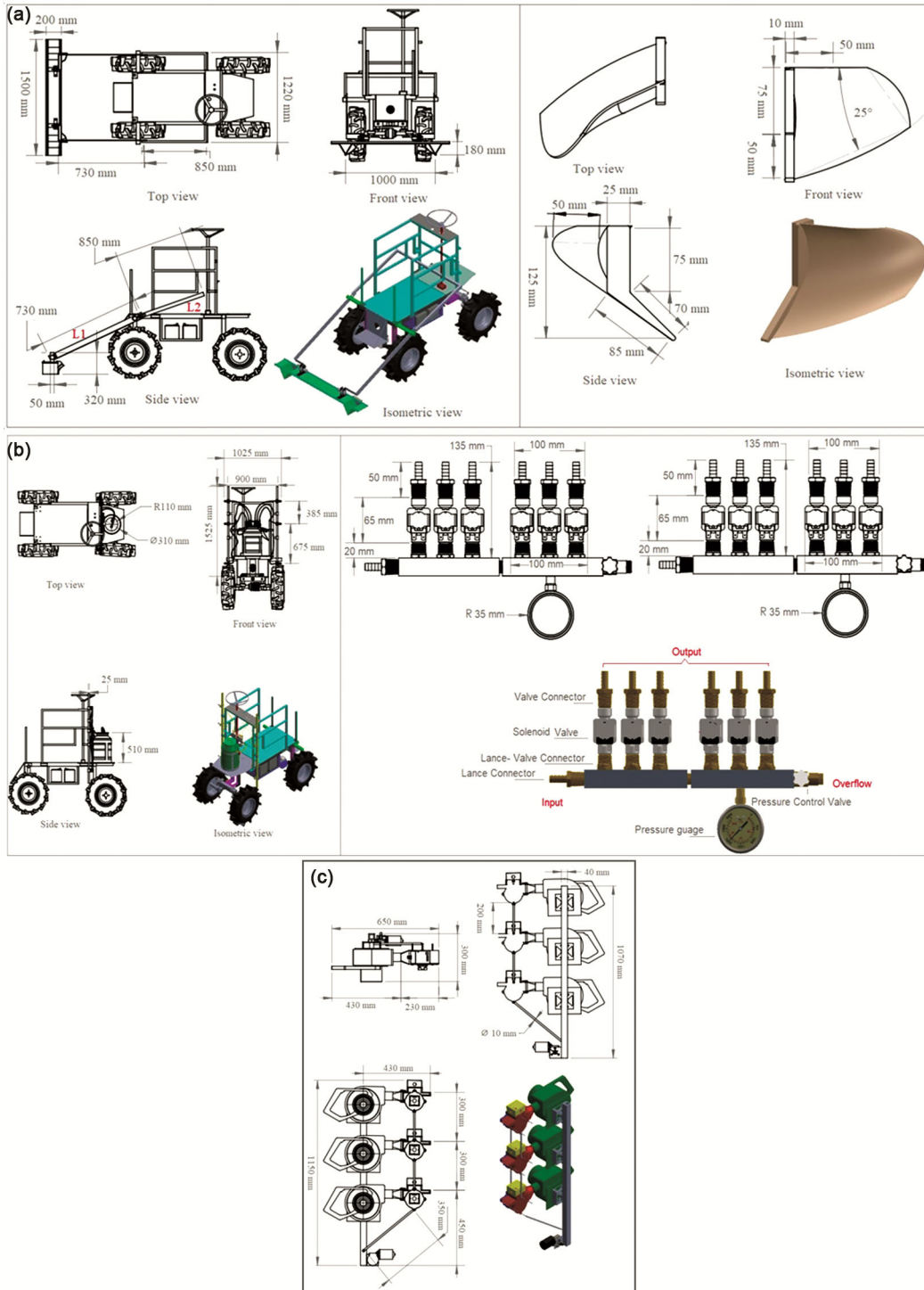


Fig. 2 — Details of (a) Bed former and Forming board frontal plane, (b) Sprayer and distributor, and (c) Pollinator boom

DC) on the carrier chassis, pressurized chemical effluents from the tank.

A nylon fabric hose of 16 mm diameter, corrosion-resistant and burst-proof, connected nozzles and water-sensitive valves, controlling safe chemical

effluent application and overflow discharge. The spray boom, made from lightweight hollow MS square pipes (25×25×5 mm), was manually adjustable to accommodate foliage beds of Tomato, Capsicum, and Cucumber (Table 3 and Figs. 1b and 2b).

Integrated into the carrier's front side ensured operator safety, preventing spray drift or foliar contact.

#### **Pollinator**

The pollination unit components were developed with sand-casted lightweight and durable Aluminum. MS box-type structures were designed and fabricated using hollow square pipes (100 mm, 5 mm thickness) for blower-pollination unit attachment. A lever mechanism for angular movement utilized 6 mm thick MS flat plates, while the pollination boom, made of 5 mm thick MS square pipes (25 mm), was attached to the chassis. A 12 V DC electric prime motor controlled angular movement, powered by the electric multi-tool carrier's battery, regulated by the operator's dashboard switch (Figs. 1b and 2c).

The detailed developed electrical multi-tool carrier and its compatible equipment (bed former, sprayer, and pollinator) integrated on the carrier are shown in Fig. 1b, and its specifications are given in Table 3.

#### **Performance Evaluation**

The developed electric multi-tool carrier and its compatible equipment (bed former, sprayer, and pollinator) were field evaluated in protected structures at IARI-CPCT, Delhi (Fig. 3).

#### **Electric Multi-tool Carrier**

The evaluation was done by varying the load and speed. The performance characteristics were evaluated in terms of tyre footprint, track width, wheel slippage, and battery loading (current and voltage). The pulling capacity, haulage capacity, brake testing, and turning ability of the electric multi-tool carrier were also evaluated in the field.

The developed electric multi-tool carrier was evaluated in both off-road and on-road conditions. Varied parameters, including load (200, 300, 400 kg) and speed (10, 15, 20 km/h), were used to assess performance metrics such as tyre footprint depth,

wheel slippage percentage, and battery loading. The experiment was replicated thrice, resulting in 27 observations. As such, there were no challenges encountered while achieving consistent track width and pneumatic tyre footprint of the electric multi-tool carrier, as most of the operations are performed on leveled soil surfaces inside the greenhouse.

The electric multi-tool carrier's power consumption was assessed using Current (A) and Voltage (V), determined by readings from a digital multi-meter during field operations. Pulling capacity was measured with a spring dynamometer and haulage capacity was tested on an 80% tarmacadam and 20% earthen surface with a slope below 8%, covering a minimum distance of 30 km. The turning ability tests followed IS 12222:2011<sup>(18)</sup> standards. The electric multi-tool carrier was tested unballasted and moving slowly at a speed of 1.5 to 2.0 km/h. The test shall be made by turning the multi-tool carrier to the right and left (clockwise and anti-clockwise directions) and with and without a full steering lock after each turn. Minimum turning diameter and Minimum clearance diameter were recorded. Brake tests were conducted at the maximum forward speed of 30 km/h, per IS 12061:1994<sup>(17)</sup>, measuring stopping distance for mechanical and electric braking systems. The stopping distance is the distance traveled by a multi-tool carrier between the point when the braking device control was pushed for the first time and the point where the multi-tool carrier comes to a halt. The electric multi-tool carrier's stopping distance after the application of the brake was measured using measuring tape and analyzed. This test was conducted in two categories, mechanical braking system and electric braking system, and the results were compared between them. The experimental data from the electric multi-tool carrier field evaluation was analyzed to assess mean-variance and variable interactions.

Traction device performance parameters of an electric multi-tool carrier were rigorously assessed. The methodology for traction parameters was done as per the various ISO standards.<sup>13</sup> Travel Reduction Ratio (TRR), representing wheel slip, was calculated using  $TRR = 1 - V_a/V_t$ , where  $V_a$  is actual velocity and  $V_t$  is theoretical velocity. Net Traction Ratio (NTR), expressing force in the direction of travel, was determined by  $NTR = 1 - NT/W_d$ , where NT is net traction and  $W_d$  is the dynamic reaction force. Additional parameters, including Tractive Efficiency (TE), were derived from the ratio of net tractive ratio

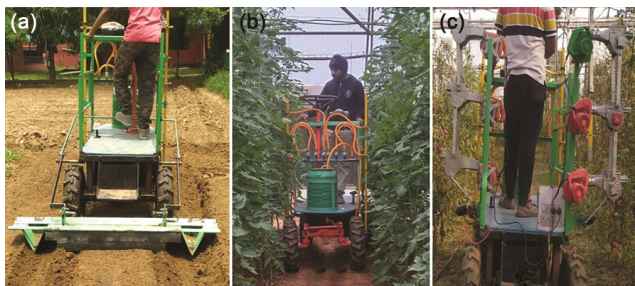


Fig. 3 — Evaluation of electric carrier: (a) Bed former, (b) Sprayer, and (c) Pollinator

to gross tractive ratio (GTR). Gross Traction Ratio (GTR) was determined as  $GTR = NTR/[TE(1-TRR)]$ . Motion Resistance Ratio (MRR) was obtained by subtracting NTR from GTR. Rolling Radius was measured as the distance travelled per revolution divided by  $2\pi$ . These parameters offer comprehensive insights into traction device performance. The data was taken at 400 kg load and 20 km/h speed. The observed parameter for the Travel Reduction Ratio was (8.7%), Net Traction Ratio (0.84%), Tractive Efficiency (61%), Gross Traction Ratio (1.24%), and Motion Resistance Ratio (0.40%).

#### ***Electric Multi-tool Carrier Operated Bed Former***

The performance of bed former was evaluated in terms of bed profile (width, raised bed height, and bed shape), power consumption, field capacity, effective field capacity, and field efficiency. The performance parameters, including draft requirement, bed profile (raised height and width), wheel slippage, and electrical characteristics (current and voltage), were measured and recorded. The independent variables were speed of operation (1.8, 2.0, 2.2 km/h) and bed height (10, 15, 20 cm). The experiment was replicated thrice, with a total of 27 observations.

The electric multi-tool carrier-operated bed former was field evaluated over a 50 m row length in manipulated soil. Bed dimensions (bed width, raised height and profile) were measured at 3 m intervals for various speeds (1.8, 2.0, 2.2 km/h). Power requirement was calculated using Current (A) and Voltage (V) product, and draft requirement was determined using calculated power and operating speed of bed former. Effective field capacity (E.F.C.), theoretical field capacity (T.F.C.), and field efficiency (%) were calculated using established formulas. Wheel slippage (%) was assessed through the travel reduction ratio formula.<sup>19</sup> A CRD model was employed for statistical analysis, assessing mean-variance and interactions for multiple variables.

#### ***Electric Multi-tool Carrier Operated Sprayer***

The sprayer was evaluated using droplet size, Volume Median Diameter (VMD), Number Median Diameter (NMD), Uniformity Coefficient (UC), Droplet Density (DD), and Discharge Rate (DR) using water-sensitive papers placed at different locations on the foliage. The lower pressure and higher speed give a coarser droplet spectrum. The performance parameters, including droplet size (VMD and NMD), uniformity coefficient (UC), droplet

density, and discharge rate, were measured and recorded at operating three pressures (2.5, 3.0, 3.5 kg/cm<sup>2</sup>) and speed (2.0, 2.5, 3.0 km/h). A total of 81 observations were made. The spray deposits on crop leaves were assessed using water-sensitive paper and the *DepositScan software* for droplet parameter analysis. The CRD model is employed for statistical analysis, examining mean-variance and interactions for the specified variables, providing valuable insights for scientific literature publication.

#### ***Electric Multi-tool Carrier Operated Pollinator***

Pollination efficiency was calculated from no. of fruit set formed from the total no. of flowers after pollination. Crop yield was measured as the weight of fruit harvested from a 5×5 meter plot. The pollinator field experiments involved 10 Tomato crop beds, each 25×1 m. Beds were divided into 5 m<sup>2</sup> test plots for pollination by the electric pollinator. Pollination efficiency was calculated as the ratio of fruits to flowers. Yield was measured using a weighing balance. In the experimental plan, pulse frequency (Hz), airflow rate, m<sup>3</sup>/min (AFR), and exposure time, sec (ET) were used in a Box Behnken Design (BBD) with 27 combinations and 3 replications. So, the total number of observations was 81; however, in BBD model selected 17 observations with 3 replications, which gave 51 observations for statistical analysis, including assessing the effects of these variables on pollination efficiency and yield.

## **Results**

### ***Electric Multi-tool Carrier***

The experimental results of the electrical multi-tool carrier's performance under various load-speed combinations resulted in significant trends. As load and speed increase, battery loading also rises, impacting key parameters. Notably, Tyre footprint depth and slippage exhibit substantial variations across treatments. For instance, Treatment T-9 (400 kg, 20 km/h) achieves the highest values in Tyre footprint depth (10.33 cm) and slippage (10.46%), which was within the recommended values, i.e., 15%. The current and power consumption increased with an increase in load and speed. The Coefficient of Variation (C.V.) indicates the reliability of the results, with values ranging from 7.51% to 21.46% (Table 4).

The power consumption analysis of the electric multi-tool carrier revealed a mean power consumption of 1579.55 W, with a range of 2664 to 816 W under

Table 4 — Comparison of treatment means with CD (0.05) for Electrical Multi-tool carrier and its bed former

Electrical Multi-tool carrier					Electrical Multi-tool carrier operated bed former				
Independent parameters		Dependent parameters			Independent parameters		Dependent parameters		
Treatments: Load, kg; Speed, km/h	Battery loading Current, A	Power, W	Tyre footprint depth, cm	Slippage, %	Treatments: Speed, km/h; Depth, cm	Battery loading Current, A	Power, W	Raised bed height, cm	Draft, N
T1: (200, 10)	19.00 <sup>d</sup>	912 <sup>e</sup>	4.66 <sup>e</sup>	5.267 <sup>f</sup>	T1: (1.8, 10)	20.00 <sup>d</sup>	960 <sup>e</sup>	11.33 <sup>de</sup>	525 <sup>e</sup>
T2: (200, 15)	19.66 <sup>d</sup>	944 <sup>e</sup>	5.66 <sup>de</sup>	8.833 <sup>cd</sup>	T2: (1.8, 15)	25.66 <sup>c</sup>	1232 <sup>d</sup>	14.00 <sup>cd</sup>	667 <sup>d</sup>
T3: (200, 20)	20.66 <sup>d</sup>	922 <sup>e</sup>	9.33 <sup>abc</sup>	10.06 <sup>ab</sup>	T3: (1.8, 20)	26.00 <sup>c</sup>	1248 <sup>d</sup>	19.33 <sup>b</sup>	683 <sup>d</sup>
T4: (300, 10)	22.66 <sup>cd</sup>	1360 <sup>d</sup>	5.66 <sup>de</sup>	7.83 <sup>d</sup>	T4: (2.0, 10)	21.50 <sup>d</sup>	1290 <sup>d</sup>	10.66 <sup>7e</sup>	635 <sup>d</sup>
T5: (300, 15)	24.66 <sup>bc</sup>	1480 <sup>cd</sup>	7.33 <sup>bcde</sup>	9.63 <sup>abc</sup>	T5: (2.0, 15)	26.50 <sup>bc</sup>	1590 <sup>d</sup>	16.33 <sup>c</sup>	783 <sup>bc</sup>
T6: (300, 20)	28.33 <sup>b</sup>	1700 <sup>c</sup>	10.00 <sup>ab</sup>	10.36 <sup>a</sup>	T6: (2.0, 20)	29.167 <sup>ab</sup>	1750 <sup>bc</sup>	22.33 <sup>a</sup>	862 <sup>b</sup>
T7: (400, 10)	27.00 <sup>b</sup>	1944 <sup>b</sup>	6.66 <sup>cde</sup>	6.53 <sup>e</sup>	T7: (2.2, 10)	22.167 <sup>d</sup>	1596 <sup>c</sup>	11.667 <sup>de</sup>	715 <sup>cd</sup>
T8: (400, 15)	32.83 <sup>a</sup>	2364 <sup>a</sup>	8.33 <sup>abcd</sup>	9.20 <sup>bc</sup>	T8: (2.2, 15)	26.33 <sup>bc</sup>	1896 <sup>b</sup>	15.00 <sup>c</sup>	849 <sup>b</sup>
T9: (400, 20)	35.00 <sup>a</sup>	2520 <sup>a</sup>	10.33 <sup>a</sup>	10.46 <sup>a</sup>	T9: (2.2, 20)	30.33 <sup>a</sup>	2184 <sup>a</sup>	20.00 <sup>ab</sup>	978 <sup>a</sup>
C.V. (%)	8.972	8.567	21.46	7.515	C.V. (%)	6.741	6.872	10.228	6.776

different operational conditions. In pulling capacity tests, the carrier demonstrated the ability to tow a dead weight of 400 kg at a speed of 20 km/h, indicating robust performance. The mean values obtained for the minimum turning diameter and minimum clearance diameter were recorded at 6.9 and 7.75 m, respectively. During the haulage test, the carrier exhibited energy-efficient operation, recording mean values of 31.5 A, 60 V, and 2.01 hours for current, voltage, and battery discharging time, respectively. The power consumption, especially in soil manipulation, may vary with the type of soil can be a constraint in the operation of the electrical multi-tool carrier. Being versatile with a provision for attachment of different equipment makes it a very useful device for greenhouse cultivation. Integration of variability in the platform with a hydraulic lifting-lowering mechanism will facilitate workers for different heights of operation.

In the brake test, the mechanical braking system outperformed the regenerative system, showcasing superior braking efficiency. Traction device performance parameters, including Travel Reduction Ratio (8.7%), Net Traction Ratio (0.84), Tractive Efficiency (61.47%), Gross Traction Ratio (1.24), Motion Resistance Ratio (0.40), and Rolling Radius (1595.12 mm), provided comprehensive insights into the carrier's operational dynamics. These findings contribute valuable data addressing the performance and efficiency of the electric multi-tool carrier in diverse agricultural applications.

The developed electrical multi-tool carrier gives better performance in terms of battery discharging time,

load carrying capacity, turning ability, braking system and integration of various equipment for different kinds of operation in the protected cultivation as compared to the commercially available similar kind of electric scaffoldings used in the protected structure.<sup>20</sup>

#### Electric Multi-Tool Carrier-Operated Bed Former

The performance evaluation of the electrical multi-tool carrier-operated bed former shows trends influenced by varying speed and depth combinations. As the speed increases, battery loading, raised bed height, and draft exhibit noteworthy increments. At operational treatment of 2.2 km/h, 20 cm depth) attains the highest values in battery loading (2184 A) and draft (977 N), emphasizing the impact of operating parameters on machine capabilities. The current and power consumption also follow this pattern, with Treatment T-9 recording the highest values. The Coefficient of Variation (C.V.), ranging from 6.741% to 10.228%, highlights the reliability of the results in Table 4.

The efficiency of the bed former was calculated as mean theoretical field capacity (0.2 ha/h) and mean effective field capacity (0.102 ha/h), giving a field efficiency of 50.52%. However, the field efficiency of the bed former at optimized conditions was calculated as 52.08%. The results showed that the battery loading, current and voltage, depth, power, draft, and raised bed height were all affected by the speed and depth of the electric multi-tool carrier bed former. The battery loading increased with increasing speed, while the depth, power, draft, and raised bed height decreased with increasing speed.

The bed profile of the electric multi-tool carrier-operated bed former exhibited a trapezoidal shape, with a mean bed width of 1 m and a raised height of 15.62 cm. Power consumption during field tests at 2.0 km/h ranged from 864 to 2232W, with a mean power of 1527.33 W. The calculated draft requirement at 2.2 km/h ranged from 472 to 999 N, with a mean force of 745N. Field efficiency increased with speed, reaching a peak of 56.81% at 2.2 kmph. Wheel slippage increased from 9% at 1.8 km/h to 17% at 2.2 km/h, with a mean slippage of 12.66%.

**Electric Multi-tool Carrier-Operated Sprayer**

The evaluation of the electric multi-tool carrier-operated sprayer revealed significant variations in droplet parameters under different pressure-speed treatments. Uniformity of the sprayer is dependent on the uniformity coefficient and maximum droplet density. It is represented in the manuscript. Operation at the pressure of 3 kg/cm<sup>2</sup> and 2 km/h was favorable for fine droplets and uniform distribution for Tomato, Capsicum, and Cucumber, indicating the effectiveness of these conditions. The Uniformity Coefficient (UC) values indicate well-distributed droplet sizes. The VMD decreased with increasing pressure and speed. NMD decreased with increasing pressure. The uniformity coefficient increased with pressure but decreased with speed. Droplet density and discharge rate increased with pressure. The low Coefficient of Variation (C.V.) (ranging from 0.156% to 9.312%) affirms the reliability and consistency of the sprayer's performance across diverse operating conditions (Table 5).

The Uniformity Coefficient (UC) found for upper, middle and lower nozzles were 1.499, 1.46, and 1.361, with an operating pressure of 2.5 kg /cm<sup>2</sup>. In previous studies, the UC for mini-tractor operated sprayer cum weeder ranges from 0.99 to 1.23.<sup>(21)</sup> Also, the performance of the developed multi-tool carrier was better than the existing commercialized electric scaffolding-operated sprayers used in the protected structures in terms of field efficiency, droplet density and uniformity coefficient.<sup>22</sup>

**Electric Multi-tool Carrier-Operated Pollinator**

The Response Surface Method (RSM) analysis using *Python Software* (Fig. 4) revealed non-linear relationships between variables in pollination efficiency. Optimal ranges for ET and PFA were indicated at 10 sec and 21.20 Hz, respectively. Similarly, AFR and ET depicted optimal performance at 1.76 m<sup>3</sup>/min and 10 sec, and AFR with PFA at 1.6–1.8 m<sup>3</sup>/min and 18–21 Hz. The proposed model was accurately aligned with experimental data, providing an understanding of maximizing pollination efficiency in protected cultivation. Highest efficiency reached 92.5%, with the lowest at 77.5%. The RSM analysis (Fig. 4) revealed an inverse relationship between ET and PFA on crop yield. Optimal performance was observed at ET of 10 sec and PFA of 18 Hz, with decreasing scores as both parameters increased, reaching a minimum at ET of 20 sec and PFA of 24 Hz. The effect of AFR and PFA on crop yield had shown high values at low AFR and high PFA, and vice versa. The stable crop yield across a broad range of AFR and ET, peaking at lower AFR and higher ET

Table 5 — Comparison of treatment means with CD (0.05) for electrical multi-tool carrier-operated sprayer

Independent parameter Treatments (Pressure, kg/cm <sup>2</sup> , Speed kmph)	Dependent parameter												
	VMD, μm			NMD, μm			UC			Droplet density (Droplets/cm <sup>2</sup> )			Discharge rate, ml/min
	Upper	Middle	Lower	Upper	Middle	Lower	Upper	Middle	Lower	Upper	Middle	Lower	
T1: (2.5, 2)	144.267 <sup>cd</sup>	141.467 <sup>cde</sup>	138.340 <sup>b</sup>	125.070 <sup>b</sup>	122.320 <sup>b</sup>	119.400 <sup>b</sup>	1.154 <sup>f</sup>	1.157 <sup>c</sup>	1.159 <sup>d</sup>	30.493 <sup>b</sup>	29.227 <sup>abc</sup>	28.600 <sup>a</sup>	4482.333 <sup>c</sup>
T2: (2.5, 2.5)	145.593 <sup>bc</sup>	141.550 <sup>cd</sup>	128.453 <sup>d</sup>	97.157 <sup>f</sup>	96.990 <sup>e</sup>	94.390 <sup>de</sup>	1.499 <sup>a</sup>	1.460 <sup>a</sup>	1.361 <sup>ab</sup>	18.583 <sup>e</sup>	18.227 <sup>f</sup>	19.227 <sup>de</sup>	4445.333 <sup>f</sup>
T3: (2.5, 3)	141.990 <sup>c</sup>	138.930 <sup>def</sup>	132.460 <sup>c</sup>	119.847 <sup>c</sup>	119.307 <sup>bc</sup>	117.903 <sup>b</sup>	1.185 <sup>ef</sup>	1.165 <sup>e</sup>	1.124 <sup>d</sup>	27.227 <sup>c</sup>	27.350 <sup>bcd</sup>	28.127 <sup>ab</sup>	4483.000 <sup>e</sup>
T4: (3.0, 2)	111.947 <sup>g</sup>	111.603 <sup>g</sup>	113.913 <sup>e</sup>	90.093 <sup>g</sup>	89.100 <sup>f</sup>	87.853 <sup>e</sup>	1.243 <sup>cd</sup>	1.254 <sup>cd</sup>	1.299 <sup>bc</sup>	22.000 <sup>d</sup>	23.413 <sup>e</sup>	24.580 <sup>bc</sup>	4782.333 <sup>c</sup>
T5: (3.0, 2.5)	164.910 <sup>a</sup>	164.703 <sup>a</sup>	154.497 <sup>a</sup>	131.607 <sup>a</sup>	131.223 <sup>a</sup>	128.987 <sup>a</sup>	1.254 <sup>cd</sup>	1.259 <sup>bc</sup>	1.204 <sup>d</sup>	18.010 <sup>e</sup>	16.797 <sup>f</sup>	16.367 <sup>c</sup>	4724.000 <sup>d</sup>
T6: (3.0, 3)	142.957 <sup>de</sup>	137.357 <sup>f</sup>	126.297 <sup>d</sup>	116.623 <sup>c</sup>	114.480 <sup>c</sup>	104.493 <sup>c</sup>	1.226 <sup>de</sup>	1.200 <sup>de</sup>	1.209 <sup>cd</sup>	22.260 <sup>d</sup>	23.937 <sup>de</sup>	22.717 <sup>cd</sup>	4731.667 <sup>d</sup>
T7: (3.5, 2)	137.083 <sup>f</sup>	138.053 <sup>ef</sup>	129.307 <sup>cd</sup>	108.127 <sup>d</sup>	104.970 <sup>d</sup>	97.747 <sup>cd</sup>	1.268 <sup>c</sup>	1.316 <sup>b</sup>	1.323 <sup>ab</sup>	28.590 <sup>c</sup>	25.723 <sup>cde</sup>	24.217 <sup>bc</sup>	4991.333 <sup>a</sup>
T8: (3.5, 2.5)	146.660 <sup>b</sup>	145.177 <sup>b</sup>	126.790 <sup>d</sup>	102.690 <sup>e</sup>	102.363 <sup>de</sup>	96.297 <sup>d</sup>	1.428 <sup>b</sup>	1.418 <sup>a</sup>	1.317 <sup>b</sup>	31.947 <sup>b</sup>	32.120 <sup>a</sup>	30.920 <sup>a</sup>	4974.667 <sup>b</sup>
T9: (3.5, 3)	147.107 <sup>b</sup>	143.123 <sup>bc</sup>	132.920 <sup>c</sup>	103.273 <sup>c</sup>	98.040 <sup>de</sup>	94.013 <sup>de</sup>	1.425 <sup>b</sup>	1.460 <sup>a</sup>	1.414 <sup>a</sup>	33.903 <sup>a</sup>	30.533 <sup>ab</sup>	29.970 <sup>a</sup>	4982.667 <sup>ab</sup>
C.V. (%)	0.821	1.421	1.661	1.962	3.999	4.422	1.874	2.582	4.299	3.410	8.309	9.312	0.156

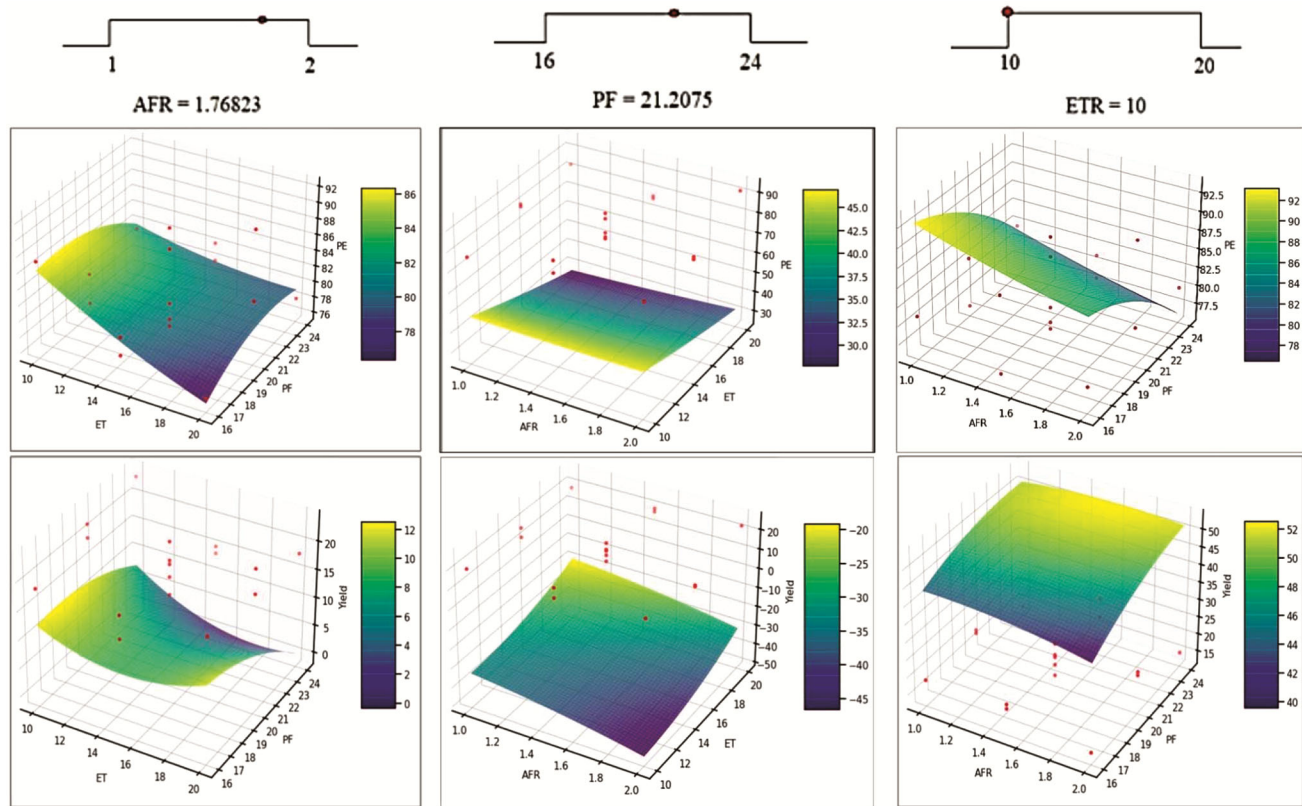


Fig. 4 — Optimized AFR, PF, ET and their effect on the Pollination efficiency and Yield

values. The maximum pollination efficiency and crop yield with pollination were achieved at an Air Flow Rate (AFR) of  $1.5 \text{ m}^3/\text{min}$ , Exposure Time (ET) of 20 sec and Pulsation Frequency of Air (PFA) of 20 Hz. The pollination efficiency and crop yield are correlated to each other.

The highest pollination efficiency and yield were found at 83.66% and 19.52 kg by using a pulsating air pollinator for the greenhouse in the previous study<sup>14</sup>, which is lower than the developed pollinator. In addition to this, the average yield was also higher with the developed multi-tool carrier operator pollinator ( $17.95 \text{ kg}/5\text{m}^2$ ) compared to pollination by a blower (36.6%) and controlled plot (95.7%).<sup>15</sup>

#### Cost Economics

The life of the developed electrical multi-tool carrier with its compatible equipment was considered 8 years with usage of 720 hours per year. Assumptions: the salvage value is 40% of the initial cost, the rate of interest is 5%, housing cost is 1.5% of the initial cost, and repair and maintenance are 15% of the initial cost. The electric multi-tool carrier, including compatible equipment, offers a holistic solution for protected cultivation, with a total cost of

Rs. 2,12,000.00 and an operational cost of Rs. 206 per hour, which covers a  $1000 \text{ m}^2$  area for bed formation and approx.  $4000 \text{ m}^2$  foliage bed area covered for spraying and pollination. The cost analysis revealed the economic aspects comprising fixed and variable components. This electro-mechanical intervention ensures operational efficiency, emphasizing its cost-effectiveness at Rs. 206 per hour, making it a financially viable choice for sustainable greenhouse farming practices. Labor costs for traditional tomato farming methods costs bed forming Rs. 3000 for  $1000 \text{ m}^2$  area and Rs. 500 for spraying and pollination for  $4000 \text{ m}^2$  foliage bed area each.

#### Conclusions

The developed multi-tool carrier not only enhances operational efficiency but also mitigates labour shortages, nurturing sustainable small-scale farming with a substantial impact on crop yields and economic outcomes. The research identifies a critical research gap concerning battery-operated agricultural electric vehicles, particularly in the context of protected cultivation. The study strives to offer an efficient and cost-effective solution for diverse agricultural operations. The machine has the versatility of

different operations on the same platform. It is enhancing the use of green energy on farm operations reducing the dependency on fossil fuels. It has the potential to be integrated with other systems like hydraulic lift, etc., which will facilitate working at varying heights for above-shoulder activities in protected and open fields and make it more useful and effective. In the future, the developed system can be made autonomous and equipped with sensors for foliage identification for the protection of workers and the environment by reducing harmful exposure with judicious application.

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