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Design and Development of Solar PV based Power Sprayer for Agricultural Use

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Abstract: Spraying of agricultural chemicals (herbicides, pesticides etc.) is an important field activity to protect crops from different insect, pests and diseases. Conventionally, knapsack sprayers are most commonly used in agricultural crops. Recently, the hand operated knapsack sprayer has been upgraded to power operated sprayer by addition of diesel operated pumps. In this study, a solar PV based sprayer was designed and developed. The developed solar PV sprayer operates both on direct mode and indirect mode. In the direct mode, the sprayer was operated by using electricity generated by 100 W_P polycrystalline PV modules mounted on the sprayer and in the indirect mode it was operated on battery mode using stored electric energy in a deep cycle battery (12 V, 32 Ah). In both modes, a DC motor pump of 60 W was used to generate the required operating pressure to spray the liquid pesticide formulations. Among different types of nozzles available in the market, the best suited one for spraying is the brass nozzle, which requires an operating pressure of about 1.5-2 kg cm^{-2} to provide a discharge of 900 cm^3 min^{-1} was used in the study. The capacity of the liquid tank in the sprayer was designed with 50 litre capacity for an uninterrupted operation for 2 hours with two nozzles. Analysis of solar radiation data from Jodhpur station showed that the sprayer can be best operated during 9:00 AM to 3:00 PM. Performance of the developed solar PV sprayer on manually drawn vehicle has been tested in field and found satisfactory to spray pesticide in different arid crops. The developed sprayer may be a boon to farmers in Indian farming scenario especially in region where solar energy is available in plenty.

Key words: Renewable energy, photovoltaic, pesticide sprayer, diaphragm pump, portable.

Agriculture has been the back bone of Indian economy and culture and it will be continued to remain as such for a long time in future. Parallel to this, energy security of a country is also very important and efforts have been given on renewable energy utilization since the fossil fuel based energy is depleting at a very fast rate. In agricultural fields, considerable amount of energy is used to do different field activities e.g. ploughing, irrigation through pumps, intercultural operations, spraying of agricultural chemicals for plant protection, harvesting, post-harvest processing, etc. Therefore, there is also need to replace the conventional energy source with renewable sources to operate above mentioned agricultural activities.

Approximately, 35% of the crop production is damaged if pest and diseases are not controlled at right time. Uniform spraying of liquid formulations throughout the crop field is very important for effective control of pest and diseases. Using sprayer, liquid pesticide formulations are generally broken down to minute droplets of effective size for uniform distribution over a large surface area. Different types of sprayers are used in agricultural field based on different requirements.

Ultra-low volume spraying: <5 L ha^{-1}

Low volume spraying: 50-150 L ha^{-1}

High volume spraying: 250-500 L ha^{-1}

On the basis of energy employed to atomise and eject the spray fluid the sprayers are categorized as: (i) hydraulic energy sprayer, (ii) gaseous energy sprayer, (iii) centrifugal energy sprayer and (iv) kinetic energy sprayer. Dose of agricultural chemicals also plays a critical role since under dose may not give the desired coverage whereas overdose is expensive and may contaminate the food chain through residues. Therefore, design and development of spray equipment for uniform and effective

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application is essential for different type of field and crop conditions.

Considering the above requirements, several researchers have recently developed different types of sprayer e.g. high pressure sprayer, engine operated sprayer, tractor mounted sprayer etc. For example, Joshua *et al.* (2010) developed a power sprayer with two stroke petrol engine. Since the operating cost was found high they suggested a solar operated sprayer. Rao *et al*. (2013) reported the performance of a multiple power supplied fertilizer sprayer, which could be able to spray 580 litre of pesticide in about 5-6 acre land using a fully charged battery. Khan (2014) designed a spray jet which can be operated by a DC pump run by PV panels. Chavan *et al.* (2015) developed a prototype solar powered agricultural pesticide sprayer using a 20 Wp PV module and a brushless DC motor (12 V, 2.2 A). Apart from these, detailed reports on few different types of solar PV powered pesticide sprayer are available in literatures (Kulkarni *et al*., 2015, Lad *et al*., 2015; Patil *et al*., 2014; Sawalakhe *et al*., 2015). With an aim to reduce human drudgery while spraying in field carrying conventional sprayer on user's back, few researchers have also designed and developed vehicle for carrying the sprayer (Kshirsagar *et al*., 2016). In this study, it was aimed to design and develop a solar PV sprayer, which can be moved in field with the help of manually drawn vehicle.

Materials and Methods

Theories used for designing the PV sprayer

Theory of flow through a nozzle: Pressure required for a obtaining a particular discharge is another criteria for designing a sprayer. Therefore, the theory of flow through a nozzle is discussed here. By applying Bernoulli's theorem, the flow through a nozzle is shown in Fig. 1.

Bernoulli theorem:

$$1/2\rho v_1^2 + \rho g Z_1 + P_1 = 1/2\rho v_2^2 + \rho g Z_2 + P_2 \quad ....(1)$$

If we apply the following conditions in Eq (2),

v_1 is negligible in comparison to v_2;

$Z_1 = Z_2$ (Both are on same height from a reference level)

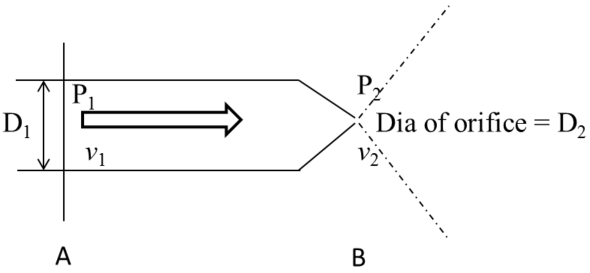

Fig. 1. Flow through a nozzle.

P_1 = Differential pressure in respect of atmospheric pressure (P_2 = atmospheric pressure)

We obtain following results

$$P_1 = ½ \rho v_2^2 \quad ....(2)$$

$$v_2 = 2\sqrt{((2\times P_1)/\rho)} \quad ....(3)$$

$$Q = A\times 2 \sqrt{((2\times P_1)/\rho)} \quad ....(4)$$

where, Q is the discharge of nozzle and A is the cross sectional area of the orifice ($pD^2/4$) and D is the diameter of the orifice. It has been found from the Eq (5) that discharge depends proportionally on the operating pressure P and the cross sectional area of the orifice A, whereas inversely proportional to density of the flowing liquid, r. From the theoretical data of the spray nozzle, it was noted that the nozzle perform optimally at an operating pressure of about 2 kg cm^{-2}. Therefore, this becomes an important criteria for designing the pump size for spraying purpose.

Pressure discharge relationship of pump: Hydraulic head and pressure of a pump can be calculated using the following formula:

$$\text{Pressure} = \rho\ g\ h \quad ....(5)$$

If we consider the metric unit, this relationship can be written as follows

Pressure (Pa) = ρ (1000 kg m^{-3}) × g (9.81 m s^{-2}) × h (m)

If we consider the fps unit, this relationship can be written as follows

Pressure (PSI) = ρ (62.42796 lb./ft3) × h (ft.)

Power requirement of a manually drawn vehicle: Another important design criterion of the sprayer is the calculation of power requirement for manually drawn vehicle on which the solar panel, battery, spraying tank, nozzles and other accessories will be kept. Therefore, the knowledge of forces acting upon a moving body on ground surface is very essential. We have discussed in previous sections that for designing a solar sprayer we need two solar PV panels, each of about 5 kg, 50 litre spraying tank having about 50 kg weight, two 12 V, 25 Ah batteries having 16 kg weight each, DC pump having 4 kg weight and other accessories with 2 kg weight. Therefore, a total weight of about 100 kg needs to be carried by the vehicle.

Total forces required to move an object is as follows:

$$FT = FR + FD + FG + FA \quad ....(6)$$

where, FT is the total force required, FR is the rolling resistance force, FD is the aerodynamic dragging force, FG is the gradient force, FA is the force required for acceleration

The power required to pull the spray vehicle may be calculated as follows:

$$P = FT \times v/\eta \quad ....(7)$$

where, p is the engine power (W) required to pull the spray vehicle, v is the velocity of the vehicle (m s^{-1}), h is the efficiency of the engine.

Rolling resistance force: The force that resists the motion when a body rolls on a surface is called the rolling resistance or the rolling friction. For example, a simple sketch diagram is presented below, where a wheeled vehicle is pulled against the rolling resistance on a plane surface.

The rolling resistance can be expressed as

$$FR = CR \times W \quad ....(8)$$

where, FR is rolling resistance or rolling friction (N or lbf), CR = rolling resistance coefficient, which is dimensionless and also called as coefficient of rolling friction (CRF). Weight of any substances is realized due to gravitational force, mg, where m is the mass of the substances and g is the acceleration due to gravity.

Aerodynamic dragging force: To overcome forces while moving, aerodynamic drag force is required to move the object as per the following drag equation

$$FD = \tfrac{1}{2}\, \rho\, u2\, CD\, A \quad ....(9)$$

FD is the drag force, which is the force component in the direction of the flow velocity, ρ is the mass density of the fluid, which is air density here because the substances is to be moved in atmosphere, u is the flow velocity relative to the object, A is the cross sectional frontal area, and CD is the drag coefficient.

Gradient force: The component forces acting upon a body while it has to be pulled over an inclined surface is presented in Fig. 7. Total gradient forces required to pull the object up the slope is,

$$FG = mg\, \mathrm{Sin}\theta + \mu s\, mg\, \mathrm{Cos}\theta \quad ....(10)$$

where, Fg is the gradient force, m is the mass of the object, g is the acceleration due to gravity, q is the tilting angle or slope of the surface, µs is the static friction coefficient. From literature, it has been found that for earth surface µs varies from 0.57 to 1 and for sandy soil it is higher than clay soil. In general, µs depends on the angle of repose (a) with relationship of µs = tana. For earth surface angle of repose varies from 30° to 45° and for dry sandy soil, it is about 45°.

Forces required for acceleration: Forces required to pull an object with an accelerated speed can be calculated as follows and is presented in Fig 2.

$$FA = m \times a \quad ....(11)$$

where, FA is the forces required for acceleration, m is the mass of the object and a is the acceleration.

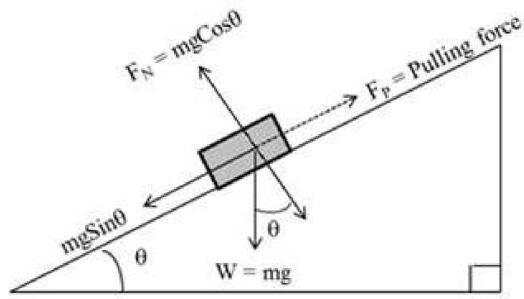

Fig. 2. Component forces acting on an object while pulling up on a tilted surface.

Results and Discussion

Specifications of the PV sprayer

To provide energy to the system, 100 W (50W each) solar panels and 60W DC motor was selected, so that the produced energy may be directly used by DC motor. To provide continuous supply of power to the system

Table 1. Technical specifications of different components of the sprayer

Components	Specification
DC pump (Diaphragm pump)	Diaphragm pump power: 60W Volts: 24V Amps: 2.5A Suction height: 2 m Working pressure: 82 PSI Open flow: 5.0 LPM
Solar PV modules of 100 W_p capacity (2×100 W_p)	Power, W_p: 50W, Open circuit voltage, V_{oc}: 21.9V Short circuit current, I_{sc}: 3.18A Maximum voltage, V_{max}: 17.4V Maximum current, I_{max} : 2.89A Dimension of panel = 790 mm × 500 mm × 30 mm Weight of panel: 4.989 kg Module efficiency: 13.1 %
Battery	Operating voltage: 12V Current: 25Ah Output power: 300Wh Dimensions of the battery: 258 mm × 177 mm × 238 mm Weight of the battery: 16 kg
Charge controller	24V, 10A
Nozzle (Hollow cone brass nozzle)	Discharge rate: 900 cm^3 min^{-1} Spray angle: 60°

and its other uses, a provision of battery bank (two batteries 12V, 25Ah each) was made. The PV sprayer was designed with following units: (i) energy conversion unit for generating electricity from solar irradiation using solar PV panel, (ii) energy storage unit in the form of battery, (iii) DC motor with pumping system and (iv) sprayer unit. The specification of the components selected for the system is listed in Table 1.

Spray angle and spray distance

The specification of the nozzles such as spray angle, discharge rate, coverage area, distance from the nozzle orifice, pressure requirement and material used of the nozzle etc. were considered as parameters of selection of the nozzle. Generally, actual ground coverage of spraying depends on two factors, (i) spray angle and (ii) spray distance, which are illustrated in Fig. 3. Again, the actual coverage is lesser than the theoretical coverage for a particular spray angle and spray distance because of interaction of several forces acting upon on the sprayed liquid droplets e.g. kinetic force of the droplets, gravity force, drifting force due to wind action etc.

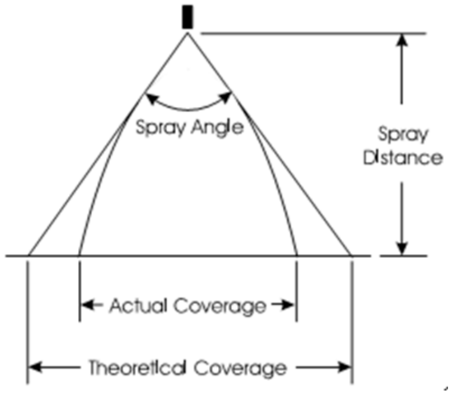

Fig. 3. Actual vs. theoretical coverage of a nozzle

Theoretical coverage of spray nozzle can be calculated using the following equation:

Theoretical coverage = 2×D tan (θ/2)…….. (12)

where, D is the spray distance and q is the spray angle. For example, if the spray angle is 60° and the spray distance is maintained at 1 m height, then the theoretical coverage will

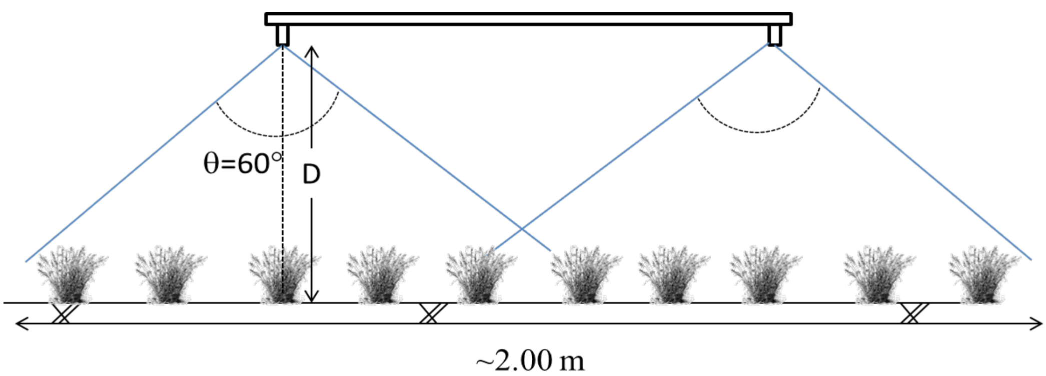

Fig. 4. Actual coverage of the nozzles considering a spray angle of 60° and spray distance of 1 m.

Table 2. Conversion of PSI to head of water in feet

Pressure (PSI)	Head (ft.)									
	0	1	2	3	4	5	6	7	8	9
00	0.0	2.3	4.6	6.9	9.2	11.6	13.9	16.2	18.5	20.8
10	23.1	25.4	27.7	30.0	32.3	34.7	37.0	39.3	41.6	43.9
20	46.2	48.5	50.8	53.1	55.5	57.8	60.1	62.4	64.7	67.0
30	69.3	71.6	73.9	76.2	78.6	80.9	83.2	85.5	87.8	90.1
40	92.4	94.7	97.0	99.4	102	104	106	109	111	113
50	116	118	120	122	125	127	129	132	134	136
60	139	141	143	146	148	150	152	155	157	159
70	162	164	166	169	171	173	176	178	180	183
80	185	187	189	192	194	196	199	201	203	206
90	208	210	213	215	217	220	222	224	226	229

be 1.114 m (tan 30° = 0.557). If we consider the actual coverage as the 90% of the theoretical coverage, then the ground coverage by a single nozzle will be about 1 m. therefore, if we adjust two nozzles 1 m apart at the end of a single rod frame as shown in Fig. 4, we can obtain ground coverage of 2 m. This is one critical criteria based on which the design of sprayer was finalized. For example, if the spray distance is adjusted to 0.75 m above ground surface, the actual coverage area will be reduced to 1.56 m.

Pump size of the sprayer

Following the relationship of pressure and discharge as given in Eq (6), a chart between PSI and column of water head in feet was prepared, which is presented below (Table 3). This chart helps in identifying the suitable pump. From the Table 2, it is calculated that 30 PSI corresponds to 206843 Pa, which is equivalent to 21.12 m or 69.3 feet water head and 2.1 kg cm^{-2} pressure.

The pump is selected according to the hydraulic head or pressure because it governs the hydraulic power required to produce a particular discharge. Hydraulic power of a pump is defined as follows:

$$\text{Hydraulic power (W)} = \rho\, g\, h \times Q \qquad \text{.......(13)}$$

ρ = water density (1000 kg m^{-3})

g = acceleration due to gravity (9.81 m s^{-2})

h = hydraulic head (m)

Q = Flow rate ($m^3\, s^{-1}$)

Pump capacity = Hydralic power/Efficiency of pump ....(14)

Considering the requirement of the pumping head in the system, a motor of 60W is sufficient to maintain the required pressure for spraying purpose. In the test, motor runs with 60W direct current at 2-3 kg cm^{-2} pressure which was selected.

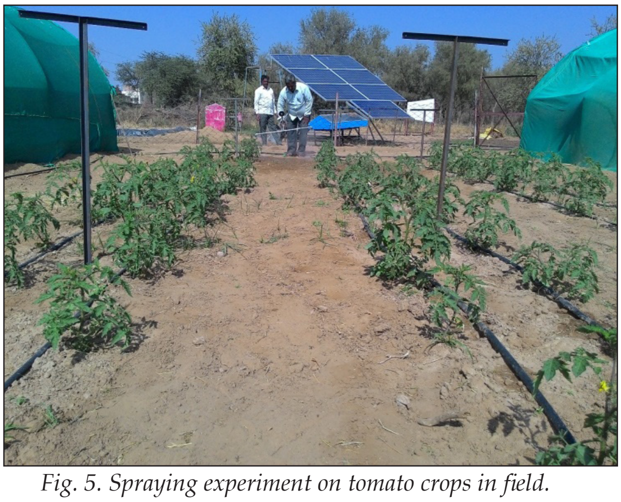

Fig. 5. Spraying experiment on tomato crops in field.

Table 3. Theoretical and actual coverage of spray nozzle at different spray distances and spray angles

Spray angle	Coverage (cm)	Distance of nozzle from surface (cm)				
		30	45	60	75	100
30°	Theoretical	16.1	24.1	32.2	40.2	53.6
	Actual	14.5	21.7	29.0	36.2	48.4
45°	Theoretical	24.9	37.3	49.7	62.2	82.8
	Actual	22.4	33.6	44.7	56.0	74.5
60°	Theoretical	34.6	51.9	69.3	86.6	115
	Actual	31.1	46.7	62.4	77.9	104

Performance of the sprayer in field

Three different types of nozzles were experimentally tested at field with solar PV pumping system at an operating pressure of 2 kg cm^{-2} (Fig. 5).

In markets, most of the spray nozzles are available with three spray angles i.e. 30°, 45° and 60°. Therefore, the actual coverage for these three angles are also calculated and presented in Table 3.

Design of manually drawn vehicle of the sprayer

The portability of the PV sprayer is one of the objectives of this study. A trolley was designed in a way that its top covers with two solar PV panels of 100W (50W each). Considering the height of arid legume and spice crops e.g. mung beans, moth beans, cumin, coriander, etc., the clearance of the sprayer from ground surface was given 60 cm. There is a scope to make this solar sprayer semi-automatic by

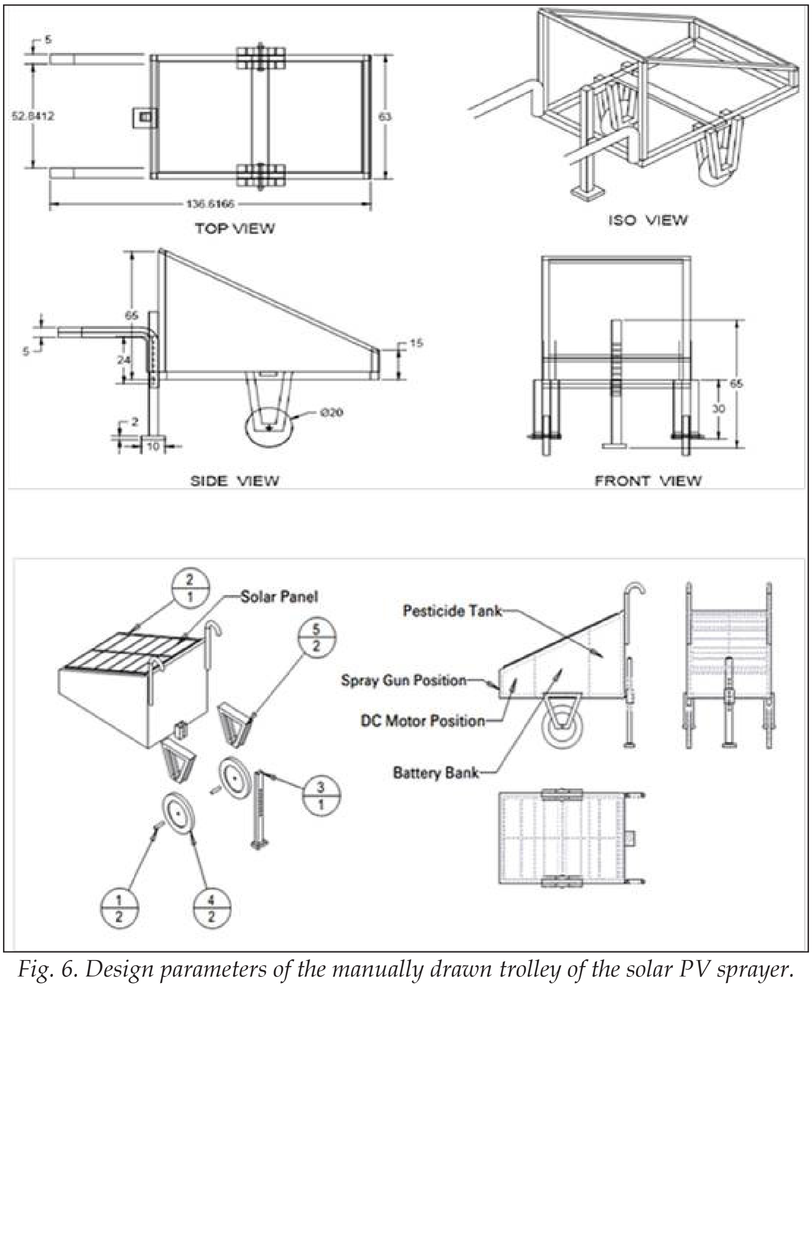

Fig. 6. Design parameters of the manually drawn trolley of the solar PV sprayer.

Table 4. Economics of developed solar PV sprayer

Component	Cost (₹)
Solar panels	5600
DC motor	5500
Batteries	7000
Charge controller	700
Trolley	4000
Pesticide tank	350
Accessories (nozzle, pipe, etc.)	1500
Total	24650

using gear mechanism. It is a light weight trolley which can be used for various other domestic purposes. Detailed drawing of the manually drawn trolley with different parts and assembly are shown in Fig. 6.

Techno economic analysis

The detailed cost of different components of the developed sprayer is presented in Table 4. The system is designed in such a way that its use will be multi-purpose. It provides additional facility to farmers for fulfilment of domestic use of energy.

Conclusion

The main emphasis of the project was to design and develop of solar based power sprayer for agricultural use. For this purpose, the sprayer was developed with following main components: (i) solar PV modules, (ii) DC motor and sprayer nozzle, (ii) a manually drawn trolley of 94 × 63 cm. The main frame of the sprayer was made up of light weight hollow rectangular angle iron. Considering the height of arid legumes and spice crops e.g. mung beans, moth beans, cumin, coriander etc. the clearance of the sprayer from ground surface was given 60 cm. The overall design of the sprayer provides spraying operation facilities even during off-sunshine hours. The sprayer was also tested in field and was found successful to spray agricultural chemicals. Although, initial cost of the proposed system is little more as compared to conventional sprayer but the running cost is very less. Further, the system is eco-friendly. The system can be further modified specially for transporting facility by adding gear mechanism. In future, multi nozzle sprayer may be designed by adopting high power motor in the system so that the area coverage will be increased and time and labour requirement may be saved.

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