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Development of solar powered knapsack sprayer

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ABSTRACT

The small and marginal farmers in India are 83% with land holding of 46.1% and contribution of 51.2% in the production. On Indian farms, knapsack sprayers are very commonly used by small and marginal farmers for pest control because of affordability and ease of operation but with lower outputs. An attempt was made to develop a solar powered sprayer which had higher output (0.3 ha/hr) with lower physiological energy consumption and discomfort. An electronic control had been embedded for protection against deep discharge and over charging of battery for longer operational life. The system could be fully charged by solar energy within two hours of irradiation and can be operated continuously for six hours.This ensures quality spray with uniform droplet size in the swath. Anti-clogging filter had also been installed before the nozzle in nozzle head for trouble free operation as well as longer service life of nozzle.

Key words: Ergonomics, Knapsack sprayer, Small farmers, Solar power

Knapsack sprayers are indispensable agricultural equipment for small and marginal farmers for pest control because of affordability and ease of operation. Commercially available knapsack sprayers are manual, petrol engine operated or battery operated. Mittal *et al.* (1996) reported that among all the farm operations, power spraying (47%) was the most detrimental because of vibrations transmission to human body parts. It results in early fatigue and reduced work output of the workers. Bawa and Kaul (1974) found that the vibration levels transmitted to specific body parts of the operator besides causing discomfort could be a source of long-term health hazards. The increased heart rate with the vibration to the human body in power knapsacks sprayer operation is also reported in a study by Gupta (1979). In case of manual sprayers, the recommended lever strokes per minute are 20-30 and 10-25 by FAO (1994 and 1998) and RNAM (1995), respectively. The working pressure and maximum flow rate, variation in pressure at the nozzle should not exceed 10% of the recommended rate for optimum performance. Maintaining a constant pressure is very difficult with a manual knapsack sprayer because of lack of consistent efforts of operator due to fatigue. Without pressure regulation, pressure fluctuates between the down stroke of the pump and the upstroke, high on the down stroke and low on the upstroke (Miller and Bellinder 2001).The lever operation induces fatigue to workers along with greater variation in spray pressure results inconsistency of application which adversely affect pest control (Awulu and Sohotshan 2012, Nag and Nag 2004). The maximum discomfort in the body parts experienced in the lever-operated knapsack sprayer were in the left clavicle region, followed by lower back, neck, left thigh and right clavicle (Ghugare *et al.* 1991). Tamilselvi and Krishnan (2016) evaluated two commercially available sprayers namely knapsack sprayer and rocker sprayer with nine male subjects for the study. Heart rate and operating energy requirement for ergo refined knapsack and rocker arm sprayers were observed as 93-120 beats/min, 97-120 beats/min, and 18.86- 24.31 kJ/min, 19.27-25.54 kJ/min respectively. With ergo refinement knapsack sprayer and ergo refined rocker sprayer the energy expenditure reduced by 7% and 8%, oxygen consumption as percentage of VO_2 max by 19% and 23%, HR results gave a reduction of 22% and 23%, ODR results reduced by 4% and 5% and BPDS score indicated a reduction of 13% to 12% respectively from the conventional sprayers. Pravin *et al.* (2014) analyzed various postures of farm worker during the operation of knapsack sprayer with modules of CATIA; Human Builder, Human Activity Analysis and Rapid Upper Limb Assessment (RULA) analysis. In their study, with handle improvement the fatigue reduced.

In tropical countries like India, harsh weather also inhibits the efficient work of operator because of very high temperatures. In general, farmers are not able to execute the

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work as per technical requirements. Ultimately, the spray quality and pattern get affected and farmers are unable to harness the benefit of pesticide application even after investing cost and efforts. Commercially available battery operated sprayers have operational constraints namely choking of nozzle, poor quality of spray, high human effort, low field capacity, uncertainty of grid power availability and deep discharge of battery etc. It was estimated that about 50-80% of applied pesticide is wasted due to poor spray machinery and inappropriate application methods. During spraying, farmers swing the spray nozzle head. It results in uneven application of pesticides making the operation less efficient and uneconomical. The non-uniform pesticide distribution results in phyto-toxicity (due to over dosing) and resistance (due to under dosing) of pests. The man-machine interaction is of utmost importance for performance of manual operations. Furthermore there is need for pragmatic approach to understand safety and health issues of the farming community engaged in agriculture. In light of the facts mentioned above, a solar powered knapsack sprayer was designed and developed.

MATERIALS AND METHODS

The main functional parts of the machine include, backpack, tank, lead-acid battery, motor-pump set, pressure control, electronic control, sprayer handle with lance, nozzle head, boom, solar panel and charge controller (Fig 1).

The total weight of machine should be such that an operator can carry it comfortably for 6 hr without any discomfort affecting his performance and health. It should have DC power backup for six hours of operation. The setup should be sturdy with ease of operation and controls along with low repair and maintenance cost. It should meet the technical, functional, operational, and structural requirements for quality spraying of pesticides and economically viable.

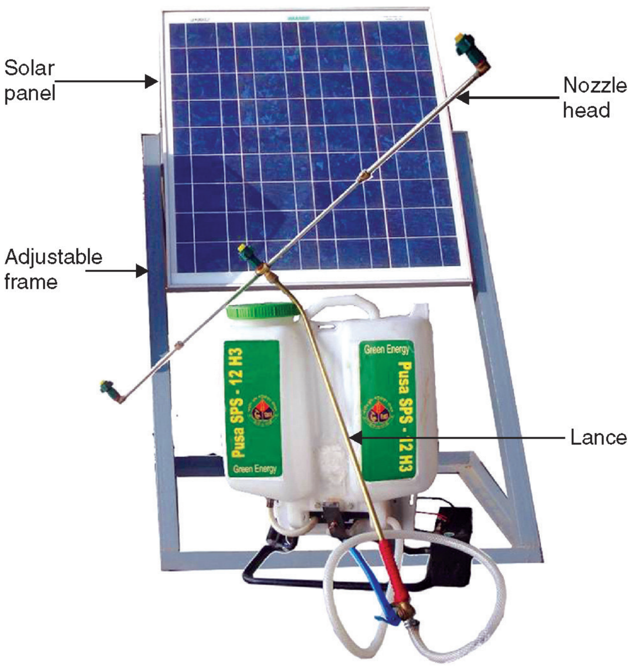

Fig 1 Solar powered sprayer.

The hydraulic spray nozzle used in the application to convert the spray solution into droplets for efficient target coverage. The target can be foliage, bark, stumps, soil or insects. In general, effective droplet size for herbicides is 250 microns; for fungicides 100 to 150 microns, and insecticides 100 microns. Spray pattern and quality are also function of operational parameters namely pressure, forward speed, nozzle spacing, spray height apart from nozzle type and its characteristics. In the present design, a nozzle head was selected in which nozzle could be replaced easily as per spray requirement without any specific tool. Clogging of nozzle is frequent due to finer impurity in water sources. General practice of farmers is to use pin or wire for removing clogging of nozzle or they blow air with mouth. In this process they may damage the nozzle characteristics or intake the harmful chemical. In order to avoid clogging, a 100 mesh filter was placed before the nozzle in the nozzle head to prevent clogging. It could be easily cleaned and maintained for enhanced service life of the nozzle.

The power requirement of motor was computed with the following equation:

$$P = \frac{q * dp}{\mu_m * \mu_p} \times 1.66 \quad (1)$$

where, P = Power (W), q=discharge (l/min), dp = discharge pressure (kg/cm^2), μ_m= motor efficiency, μ_p= pump efficiency.

Considering the safety factor of 25%, the design value of motor power was computed with the following equation:

$$P_d = P \times 1.25 \quad (2)$$

where, P_d = Design value power (W), P = Power (W).

An adjustable electro-mechanical pressure control switch was integrated in line with power supply of the motor. It facilitated constant pressure of discharge liquid. It isolated power supply of motor to protect it from overloading in case of excessive pressure. The operator could adjust the required pressure with the movement of adjustment screw in clockwise or anti clockwise.

The walking spray boom consisted of three nozzle head, stainless steel pipe (14 mm outer ϕ) and control valve. The interspacing of nozzles were kept at 50 cm to achieve overlap of 30%. The total length of boom was one meter. A 90 cm lance was connected with the boom through T connector to facilitate ease of operation. The other end of lance was fitted with on/off liquid control valve.

The rechargeable sealed lead acid battery 12 V; 7 Ah was selected for the sprayer considering weight, size, chargeability, energy requirement and cost.

Deep discharge of battery is a common problem encountered by farmers in commercially available battery sprayers. However, these are equipped with battery level indicators. In order to overcome this problem, an electronic module was designed to cut off power supply to motor whenever battery voltage reduced to 10 V with the help of

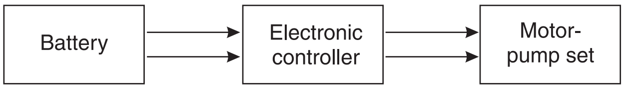

Fig 2 Block diagram of electronic controller.

Table 1 Specifications of solar voltaic panel

Specification	Value
Open circuit voltage, Voc (V)	21.57
Short circuit current, Isc (A)	3.71
Voltage at maximum power, Vmp (V)	17.26
Current at maximum power, Imp (A)	3.48
Module efficiency (%)	12
Maximum series fuse rating (A)	10
Limiting reverse current (A)	10
Length × Width × Thickness (mm)	740 × 675 × 35
Weight (kg)	6

voltage comparator circuit and magnetic relay. The module was connected in series with power supply and motor (Fig 2).

A solar photo voltaic (SPV) panel of 60 Wp was selected for charging the power pack of sprayer system. The specification at (25 degree C cell temperature; 100 m W/cm^2 irradiance) are given in Table 1.

The maximum performance of SPV can be harnessed when the irradiation falls perpendicular to the panel surface. Hence, adjustable frame was designed to alter the angle of SPV as per latitude of the site.

An electronic charging module was designed for charging the lead acid battery from solar photovoltaic panel of 60 Wp (Fig 1). The charging current was taken as 2.5 A so as the battery should be charged fully in 3 hr. The module was imbedded overcharging cutoff feature to protect the battery from detrimental effect on service life due to overcharging (Fig 3). The voltage-current comparator circuit with magnetic relay was designed for cutoff from charging source to battery as and when the current drops below 70mA (Hou *et al*. 2005).The charging voltage was at a float voltage of 2.35 volts/cell set for14.4 volts.

The particle size distributions was measured by laser diffraction technique using Malvern SPRAYTEC instrument. It uses Mie theory of light scattering to calculate the particle size distribution, assuming a volume equivalent sphere model. The scattered light intensity is measured using a series of semicircular photo-diodes housed in the receiver unit. A curve-fitting program is used in inbuilt software to convert the light intensity distribution into any of the empirical drop size distribution functions ($D_{V0.9}$, $D_{V0.5}$ and $D_{V0.1}$). $D_{V0.9}$, a value where 90% of the total volume of liquid sprayed is made up of drops with diameters smaller or equal to the value. $D_{V0.5}$: Volume Median Diameter (VMD). A means

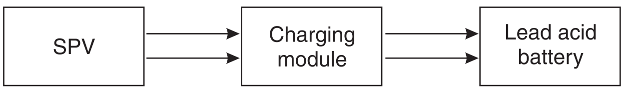

Fig 3 Block diagram of charging module.

of expressing droplet size in terms of the volume of liquid sprayed. The VMD is a value where 50% of the total volume of liquid sprayed is made up of drops with diameters larger than the median value and 50% smaller than the median value. $D_{V0.1}$:a value where 10% of the total volume of liquid sprayed is made up of drops with diameters smaller or equal to this value. A dimensionless parameter; Relative Span Factor (RSF) indicate the uniformity of the drop size distribution and was computed by following equation:

$$RSF = \frac{D_{V0.9} - D_{V0.1}}{D_{V0.5}} \quad (3)$$

The developed solar powered knapsack sprayer was evaluated in the field and compared with commercially available manual knapsack sprayer and air assisted power operated knapsack sprayer.

Each machine was operated for 30 min. After every 10 min swath width and coverage length, time and volume of liquid sprayed were recorded (Garg 1990). The experiment was conducted in three replications for all the machines and subjects. Field capacity and volume of liquid sprayed per unit area was computed as:

$$F_C = \frac{W*L*O}{t} \quad (4)$$

$$D_C = \frac{V}{W*L*O} \quad (5)$$

where, F_c = Field capacity (m^2/min), W = Swath width (m), L= *L*ength (m), t = Time (min.), O = Overlap (decimal), D_c = Specific volume (l/m^2), V = Volume (l).

For conducting experiments for ergonomic study, the selection of subjects plays a vital role. The selected subject should be physically and medically fit for carrying the experiments (Seidel *et al*. 1980). It was ensured that subjects were from particular age group, physically fit, not suffering from any illness and had willingness to participate in undertaking experiments.

The maximum aerobic capacity, heart rate and muscle strength decreases with increase in age (Astrand *et al.* 1965, Astrand and Rodahl 1986). For this study, six subjects were selected, from the available workforce. Two age groups were considered and three subjects of each age group were chosen. BMI,the ratio of weight of the subject to the square of height of the subject was computed for all the subjects. The details of subjects selected for the study are furnished in Table 2.

All the major dimensions in standing and sitting postures of the selected subjects were measured by means of an anthropometer. The details of anthropometric data are furnished in Table 3.

The selected subjects for conducting experiments should be physically fit. There should not be any chronic disease or illness and handicaps. The selected subjects were physically fit and engaged in physical work regularly, not having any illness, handicap or chronic problem.

The information about energy consumption in activities

Table 2 Details of selected subjects

Age group (Years)	Age (Years)	Weight (kg)	Height (cm)	BMI (kg m^2)
20–30	24	52	163	19.57
	27	45	165	16.53
	28	63	161	24.30
30–40	38	76	162	28.96
	39	58	169	20.31
	40	70	167	25.10

Table 3 Anthropometric data of subjects

Anthropometric dimension (cm)	Subjects					
	A	B	C	D	E	F
Stature	163.0	165.0	161.3	162.0	168.9	167.0
Arm length	77.3	69.0	75.1	80.0	80.0	81.0
Arm span	164.0	165.5	164.5	158.0	173.0	165.0
Standing eye height	153.5	152.8	151.2	149.3	157.2	157.5
Sitting height	128.5	127.3	128.3	130.5	129.4	124.5
Sitting eye height	117.4	114.1	117.8	118.0	118.9	113.5
Popletal height	43.9	42.5	39.7	40.6	44.2	46.0
Knee height	48.9	49.1	46.7	50.4	49.8	54.0
Pelvic height	99.0	96.8	95.4	95.5	99.7	101.0
Elbow height	102.2	98.7	100.9	101.0	103.6	110.0
Shoulder height	132.4	131.8	133.2	133.0	134.4	141.5

can offer a rational basis for methods and equipment design for agricultural operation. These measurements of energy requirements are important from the safety and occupational health point of view. As the workload on the worker exceeds the limit, it is bound to cause excessive fatigue and results in unsafe operation. A simple method to assess physiological demand is heart rate measurement. If the load remains same, the heart rate stabilizes after 6 min. The same concept was used to measure heart rate with a help of wearable heart rate monitoring system. Astrand and Rodahl (1986) specified a classification of work load. According to which the physical work load categorized the work severity on the basis of energy expenditure level, oxygen consumption and heart rate of physical work.

The overall discomfort rating (ODR) and body part discomfort score (BPDS) was computed by Corlett and Bishop (1976) technique on a 10 point psycho physiological rating scale. After each trial with the selected spraying operation, the subject was asked to indicate their ODR and BPDS level on the 10 point rating scale.

RESULTS AND DISCUSSION

Solar powered sprayer- Evaluation

The tank capacity: 14 litre was selected to minimize discomfort of operator and maximize operational efficiency. The developed sprayer also compliant the FAO (1994), BIS-3906 Part I (1982). Matthews and Thornhill suggested that the capacity of the tank should be about 15 litres. Garg (1989) has suggested tank capacities as 10 l for low volume and 12 to 16 l for medium volume sprayers. Considering total discharge: 1.83 l/min, required pressure: 3 kg/cm^2, motor efficiency: 0.80 and pump efficiency: 0.70 required power for motor-pump set calculated was 16.7 W. The net power required for motor-pump set was computed with 25% safety factor as 19.5 W. As 20 W motor pump set commercially available, 20 W motor was selected for the development. The developed electronic controller was evaluated for its performance and reliability at different cutoff voltage values for 6 h of load conditions. The controller was also integrated with mobile charging module, which enables the system to be used as mobile charging and enhances its application. It was efficient in preventing the battery from deep discharging state (i.e. below 10.5 V). Lead sulfation occurs when power is being taken off from the battery after achieving battery voltage 10.5 V. It forms hard crystals of lead sulfate, which cannot be recovered by standard charging process. The developed charging module was also tested for charging of Lead acid battery through SPV panel (Fig 7).The charging module was effective in delinking the solar power to battery after complete charging to prevent over charging. The overcharging of lead acid battery reactions begin when the majority of lead sulphate has been converted, typically resulting in the generation of hydrogen and oxygen gases and in turn drastically affecting the battery life. The current for charging is ominously related with irradiation. It was found that even with 65% of irradiation (650 W/m^2), the selected battery could be charged fully within 2.5 to 3 hr (Fig 4).

Laser diffraction test of both the selected nozzles were suitable for pesticides spraying (Table 4). The value of D_{V90} for XR11002VP (Y) and XR11002VP (B) nozzle was 258.10 and 350.9 at 2.8 kg/cm^2 (40 psi), respectively. The XR11002VP (Y) nozzle falls under medium droplet size spray application. However, the XR11002VP (B) nozzle may be classified as coarse application. The relative span of both the nozzles was found minimum (1.28 and 1.32) at 2.8 kg/cm^2 (40 psi). It indicated that the distribution of droplet size in the spray spectrum was uniform. It signifies

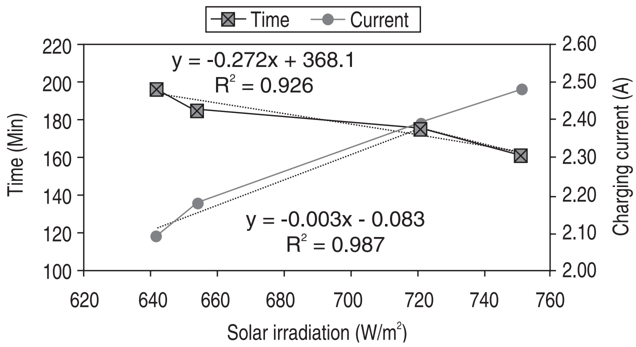

Fig 4 Relationship of solar irradiation, charging current and time for 7 Ah lead acid battery.

Table 4 Nozzle characteristics at different hydraulic pressure

Pressure kg/cm^2 (psi)	Empirical drop size distribution functions			RSF
	D10	D50	D90	
	XR11002VP (Y)			
1.4 (20)	92.46	173.20	316.00	1.29
2.1 (30)	76.87	130.30	264.80	1.44
2.5 (35)	61.20	136.80	295.00	1.71
2.8 (40)	73.02	145.10	258.10	1.28
3.1 (45)	72.10	141.40	251.40	1.27
	XR11002VP (B)			
1.4 (20)	110.60	328.60	740.60	1.92
2.1 (30)	100.90	237.90	502.20	1.69
2.5 (35)	85.66	184.30	304.60	1.44
2.8 (40)	87.30	165.20	350.90	1.32
3.1 (45)	77.39	161.40	321.50	1.51

that the selected nozzles require to be operated at 2.8 kg/cm^2 (40 psi) for maximum efficiency of nozzles as well as spray quality.

Ergonomic evaluation of developed sprayer

All the six subjects selected for the study operated the manual, solar and air assisted sprayer for half an hour duration. The physiological parameter (heart rate) along with postural parameter of Overall Discomfort (ODS) and Body Part Discomfort score (BDPS) were observed for all the experiments (Table 5). The mean heart rate (light work category) and BPDS was lowest for solar sprayer compared to manual and air assisted sprayer indicating lower physiological demand and discomfort to the body parts. Overall discomfort was similar for solar and air assisted sprayer but lower than the manual sprayer. Lower energy demand and postural comfort was because of non-requirement of "rocking the pump lever" as it was powered with battery. In case of air assisted sprayer, the engine operates at high speed results in vibration and also the higher weight which resulting in higher physiological energy demand. So, in solar sprayer with lower heart rate and postural discomfort, the output obtained was more than twice (approximately 3000 m^2/hour) compared to the other two sprayers.

The developed solar powered sprayer with 14 l capacity is equipped with efficient system for preventing the battery from deep discharging as well as overcharging and performed efficiently at 2.8 kg/cm^2 (40 psi) operating pressure for application of pesticides. The spray spectrum was also found uniform with the selected nozzle and operating pressure. It would be considerably enhance quality of spray and ultimately chemical efficacy as well as efficient pest control. This battery can be fully charged in three hours and the sprayer can be operated for six hours with this battery. The mean heart rate and BPDS were lowest for solar sprayer and covered area more than twice (3000 m^2) compared to the manual and air assisted sprayers indicating lower physiological demand and discomfort to body parts.

Table 5 Ergonomic evaluation of different sprayers

Sprayer type	Subject	Avg HR (beats/ min)	BPDS	ODS	Area covered (m^2)
Manual	S1	106	21	2	1010
Manual	S2	107	21	3	1162
Manual	S3	106	21	2	997
Manual	S4	103	21	4	991
Manual	S5	92	21	3	1142
Manual	S6	99	21	3	992
Mean		102	21	3	1049
Solar Sprayer	S1	107	12	1	2733
Solar Sprayer	S2	95	15	2	2468
Solar Sprayer	S3	102	18	2	2719
Solar Sprayer	S4	98	21	3	3641
Solar Sprayer	S5	95	6	3	3223
Solar Sprayer	S6	99	21	3	3071
Mean		99	16	2	2976
Air assisted-engine sprayer	S1	131	18	2	1401
Air assisted-engine sprayer	S2	100	15	2	1036
Air assisted-engine sprayer	S3	108	21	3	1035
Air Assisted-engine sprayer	S4	123	21	2	1162
Air Assisted-engine sprayer	S5	110	15	1	1054
Air Assisted-engine sprayer	S6	91	21	2	1410
Mean		111	19	2	1183

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