Design, Development and Evaluation of a Swinging Lance Sprayer

by

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Abstract

Application of pesticide in recommended dose not only reduces the input cost of chemical but also reduces the ill effects due to excess application. The spray swath of conventional tractor mounted gun type sprayer depends on the movement of the spray gun by the operator, resulted in uneven distribution. A tractor operated swinging lance sprayer was developed with automation of spray gun operation by eliminating manual operation of spray guns. The developed sprayer consists of piston type pump, power transmission system, chemical tank, crank-rocker type swinging mechanism, worm gear DC motors, power terminals. The developed swinging lance sprayer resulted in uniformity distribution of spray chemical over crop canopy. The theoretical field capacity, effective field capacity and field efficiency of developed sprayer was 3.6 ha/h, 2.56 ha/h, 71.1%, respectively at forward speed of 0.75 m/s. The bio-efficiency of sprayer was 68.5% and 91% at 3DAS and 5DAS, respectively. The operating cost per hectare was USD 3.32. The developed sprayer performed better in terms of spray deposition, low application cost, saving of manpower, elimination of chemical exposure to the spray gun operators over conventional tractor mounted gun-type sprayer.

Introduction

The world is facing challenges of food, water, energy and environmental pollution, leading to a serious climate change risk. Optimum use of resources to meet the food demand of the burgeoning population is a major issue before researchers. Food grain production in India increased from 52 million MT in 1951-52 to 303.34 million MT in 2020-21. The critical role played by plant protection practices is well recognized. Direct yield losses range between 20 and 40% of global agricultural productivity due to pathogens, animals, and weeds (Oerke, 2006). The production loss due to pests estimated in India is USD 42.66 million annually (Devi et al., 2017). The increased damage to crops due to pests and subsequent losses results in serious threat to food security. A 40-50% reduction in pesticide consumption reduces the protection cost from USD50/ha to less than USD30/ha (Kumar et al., 2020). Tractor mounted gun type sprayer with hose pipe length 60-300 m, was popular in many parts of India due to its high field capacity, low application cost and versatility for multi crop usage. However, a tractor mounted gun-type sprayer required four persons, out of which two are for operating spray guns, one for handling hose pipes and one for operating tractor (Narang et al., 2015). Though this method gives satisfactory pest control, it consumes a large volume of liquid per hectare. The spray swath depends on the movement of the spray gun by the operator. Uneven distribution was a significant drawback from conventional spraying due to varying swing speed and distance by the operator (Hermosilla et al., 2011). On the other hand, the operators were exposed to the chemical spraying in front of his way. The dermal exposure with a manually operated gun sprayer is very high; a human-driven vehicle with fixed boom and constant spray volume can reduce dermal exposure by 60-fold compared with manual gun spraying (Nuyttens et al., 2007). Automation of swinging of spray guns could improve spraying efficiency in terms of uniform application, and reduction in chemical losses. Hence, a tractor operated swinging lance sprayer was developed with automation of spray gun operation by eliminating manual operation of spray guns. The present study focused on objectives of (1). Design and fabrication of various components of swinging lance sprayer (2). Performance evaluation of developed swinging lance sprayer in green gram crop.

Material and Methods

Design of Components for Swinging Lance Sprayer

To design swinging lance sprayer, some of the components were selected based on the requirement from the commercially available products. The other components were designed analytically and fabricated based on the requirement. The critical components of swinging lance sprayer, their selection and design procedure explained in details in following sections.

Selection of Spray Guns for Swinging Lance Sprayer

In order to ensure the application of recommended chemical, it was essential to estimate the required discharge rate of spray guns. The maximum time required to cover one hectare of field was 27 min at forward speed of 0.75m/s, swath width of 8 m. The recommended application rate of field crops was 500 l/ha. The required discharge rate of sprayer was 18.5 l/min. In developed swinging lance sprayer, there were two spray guns. Hence, the required discharge rate of each spray gun was 9.25 l/min.

Selection of Pump for Swinging Lance Sprayer

The required discharge rate of spray guns was 18.5 l/min. A capacity of 25% higher than the requirement needs to consider for the design. Usually, 5-10% of pump discharge required for hydraulic agitation of sprayer (Sharma and Mukesh, 2019). The sprayer demands a continuous supply of chemical of 25 l/min. Piston type pumps were most suitable for high pressure applications up to 40 kg/cm^2 (Manian et al., 2002). A commercially available piston type pump was with maximum discharge rate of 36 l/min with operating rpm of 950, maximum pressure of 28 kg/cm^2 was selected.

Design of Chemical Tank for Swinging Lance Sprayer

The tank acts as a reservoir for the supply of chemical solution during the spray. The application rate for field crops was 500 l/ha. The majority of farmers in the selected area were marginal and small group with the average field size of one acre. Hence, a capacity of 400 liters was selected to avoid frequent refilling. The material of tank was polyvinyl chloride chosen due to its low expensive and highly resistant to most of the agrochemicals used.

Design of Power Transmission System for Swinging Lance Sprayer

The sprayer pumps, driven by tractor PTO shaft were widely acceptable due to its mounting versatility and ease of operation and maintenance (Wolf et al., 2004). The rotary power to drive the hydraulic pump of the sprayer was taken from the tractor PTO shaft. Adjustable telescopic universal propeller shaft was used to transmit the tractor P.T.O shaft power. The rotary power of tractor PTO transmitted to piston type pump through pulley and V-belt drive. The design criteria to determine size of the pulley and V-belt was given below

Design of pulley

The selected pump was fitted with pulley of 101 mm size (D_1). The size of the pulley for universal propeller shaft was calculated based on following criteria.

Available speed at tractor P.T.O shaft = 540 ± 10 rpm

Required speed at pump shaft = 950 rpm

Velocity ratio = Speed of the pump, rpm / Speed of PTO, rpm [1]

Velocity ratio = 950 / 540 = 1.76

Size of universal PTO shaft pulley (D_2) = Velocity ratio × D_1 = 1.76 × 101 = 177.76 ≈ 178 mm

Hence, a pulley of 178 mm size was selected for universal PTO shaft.

Selection of V-belt

Velocity of belt is calculated by using Formula 2.

$$V = (\pi \times D \times N) / 60 \quad [2]$$

$$V = (3.14 \times 0.178 \times 540) / 60$$

$$V = 5.03 \text{ m/s}$$

When the belt continuously runs over the pulley, centrifugal forces were caused to increase the tension on both the tight side as well as slack sides. At lower belt speed (< 10 m/s), centrifugal tension is very small. The designed speed of the belt is 5.03 m/s; hence its centrifugal tensions was neglected.

The distance between pump pulley and PTO pulley was 830 mm. The length of V-belt was calculated by using Formula 3 (Sharma and Mukesh, 2019).

$$L = (\pi/2) \times (d_2 + d_1) + (2x) + [(d_2 - d_1)^2 / 4x] \quad [3]$$

$$L = (3.14/2) \times (178 + 101) + (2 \times 830) + [(178 - 101)^2 / 4 \times 830]$$

$$L = 2057 \text{ mm}$$

The total length of belt was 2057 mm, hence A81 inch V-belt was selected for the power transmission system of developed swinging lance sprayer.

Design of Frame for Swinging Lance Sprayer

The rectangular frame was fabricated using a hallow square MS pipe of with 50 × 50 × 5 mm. The MS flat of size 50 × 10 mm was fabricated on the sides of the rectangular frame with of size 3200 × 920 × 1550 mm (L × W × H). The inner section of the frame accommodate 400 liters chemical tank. The front of the frame fixed with a three-point linkage. The rear end of the frame has provision to adjust the spacing between spray guns, height of the spray gun and swing angle of the spray gun. The boom has telescopic extension. The spacing between spray guns was 2 m; there was provision to 30 cm and 60 cm either sides of the boom. If extension was 30 cm in both the sides, the spacing between spray guns was 2.6 m; if the extension was 60 cm in both the sides, the spacing between spray guns was 3.2 m.

Design of Swinging Mechanism of Spray Guns

The mechanism considered for the design of swinging of spray guns was four-bar linkage mechanism. A four-bar linkage mechanism consists of four rigid links connected end to end and forms a closed loop. The fours links were: fixed link, crank, coupler and rocker. The fixed link was a stationary link, the crank was input link, and rocker was output link. The rotary motion of crank was converted to oscillating motion of rocker by means of coupler link (**Fig. 1**).

(a) Degree of freedom

The degree of freedom can be defined as the number of actuators needed to operate the mechanism. The degree of freedom of a mechanism can be calculated by using the Formula 4 (Esmail et al., 2018).

$$DOF = 3L - 2J - 3 \quad [4]$$

Where,

L = number of links

J = number of joints

There are four links and four joints in selected linkage mechanism.

$$DOF = 3(4) - 2(4) - 3 = 1$$

The degree of freedom of selected four bar linkage was one, hence it can be operated by a single motor.

(b) Grashof's Criteria

Let the length of links of four-bar mechanism be as following:

a = shortest link,

b = longest link,

c = one of the intermediate links,

d = other intermediate link.

For swinging operation of spray guns, oscillating motion was required, hence crank- rocker type four bar linkage considered. For the crank-rocker type mechanism, the shortest link should be at side as per four-bar linkage classification (**Table 1**). Hence, the crank was considered as shortest link and fixed as side link, the rocker was longest link, the other two links were coupler and frame.

The dimension of shortest link (crank) was 8.5 cm, longest link (rocker) was 42 cm, coupler was (38-42 cm), fixed link was 40 cm.

Grashof's criteria: $(a + b) < (c + d)$

$(8.5 + 42) < (40 + 42)$

$50.5 < 82$

The positions of the mechanism when the rocker is at a limit position are called the dead-center positions of the four-bar mechanism. The oscillation angle of the rocker between the dead-center positions and measured from the extended dead-center to the folded dead-center position was called the swing angle (Θ), (**Fig. 2**). The swing angle was always corresponding with crank angle. The maximum swing angle between dead center positions was 120°, (**Fig. 3**).

The swinging mechanism of developed sprayer required one rotary motion. There were two such swinging mechanisms in the developed sprayer; hence two motors are required. The torque required by the motor was calculated, Formula 5.

$$T = F \times \mu \times f_s \times f_l \times l \times (\omega a/\omega m) \times (1/e) \quad [5]$$

Where,

T = Torque of wiper motor, N-m;

F = Force required by swinging rocker, N;

μ = maximum dry coefficient of friction, 2.5;

f_s = multiplier for joint friction, 1.15;

f_l = tolerance factor, 1.12;

l = length of swinging rocker, m;

ωa = max. angular velocity of rocker, rad/s;

ωm = mean angular velocity of motor, rad/s;

e = efficiency of motor gear unit, 0.8.

Table 1 Classifications of four bar linkage (Esmail et al., 2018)

Classification	Conditions	
	Criteria	Smallest link
Double Crank	(a + b) < (c + d)	Frame
Crank-Rocker	(a + b) < (c + d)	Side
Double -Rocker	(a + b) < (c + d)	Coupler
Change Point	(a + b) = (c + d)	Any link

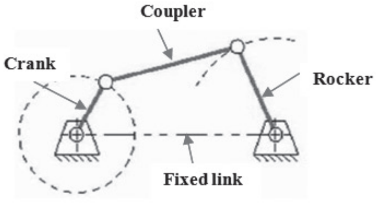


Fig. 1 Line diagram showing various links of four-bar linkage

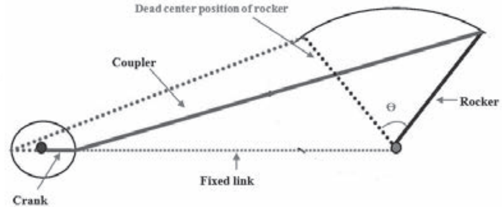


Fig. 2 Line diagram of crank-rocker mechanism

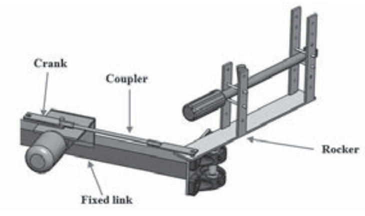
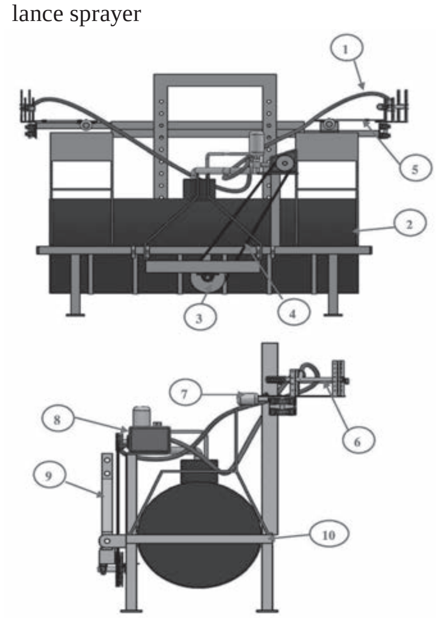


Fig. 3 Schematic diagram of swinging mechanism of developed sprayer

The force required to operate swinging mechanism was 17.95 N, maximum angular velocity of rocker was 4.68 rad/s, mean angular velocity of motor was 4.68 rad/s. By substituting the values in the equation 3.6, the torque required for swinging operation was 26 N-m, hence commercially available worm gear DC motor of 30 N-m torque, 12 V DC, 50 W was selected for design.

Fig. 4 Schematic diagram of swinging lance sprayer



1. Hose pipe, 2. Chemical tank, 3. PTO-pulley, 4. V-belt, 5. Swinging mechanism. 6. Spray gun, 7. Worm gear DC-motor, 8. Pump, 9.3-point linkage, 10. Frame

Performance Evaluation of Developed Precision Swinging Lance Sprayer

Measurement of Application Rate

A distance of 100 m length was marked in the field. The sprayer was operated and covered 100 m distance at three forward speeds, i.e., 0.75 m/s, 1.0 m/s, 1.25 m/s. The waster consumed to spray 100 m was measured with top-up method. The actual discharge rate of sprayer was calculated from volume of water consumed and time taken to cover 100 m distance. The application rate was calculated by using following Formula 6.

Application rate (l/ha) = (D × 600) / (S × W) [6]

Where,

D = discharge rate, l/min;

S = speed of tractor, km/h;

W = swath width, m.

Measurement of Spray Droplet Deposition

Five plants were randomly selected in each run, and kromekote papers (5 × 2 cm) were placed on the upper side of the top and bottom portion of the plants (**Fig. 6b**). Methylene blue MS dye mixed @5 g/l was mixed with spray solution. After spraying kromekote papers were allowed to try and collected for droplet analysis. In first step, the deposit collected paper was scanned by using scanner. In second step, convert the image type from RGB to 8-bit gray image. Select the portion of image that need to analyze by using tool bar. Finally, gets the results window showing droplet size at DV0.1, DV0.5 and DV0.9, density, percent cover, volume of spray. The time required to process and get the results is less than 30 seconds (Zhu et al., 2011) (**Fig. 5**).

Measurement of Field Performance Parameters

The field performance parameters such as theoretical filed capacity (ha/h), effective field capacity (ha/h) and field efficiency (%) were measured with standard procedure. The theoretical field capacity was calculated by considering speed and swath width. The actual field capacity was calculated by measuring actual time taken to cover one-hectare area. The field efficiency was the ration of effective field capacity to theoretical field capacity.

Measurement of Bio-efficiency

The field experiment conducted in green gram field after 60DAS to control pod bug (Riptortus Pedestris). Thiamethoxam 25% WG @100g/ha, spray liquid volume of 500 l/ha sprayed on the crop. Before spraying activity, number of pod bugs in m^2 area counted randomly. After spraying activity, the number of pod bugs at 3DAS (days after spraying) and 5DAS (days after spraying) also counted and compared with control. The bio-efficiency was calculated using Formula 7 (Ordaz et al., 2016).

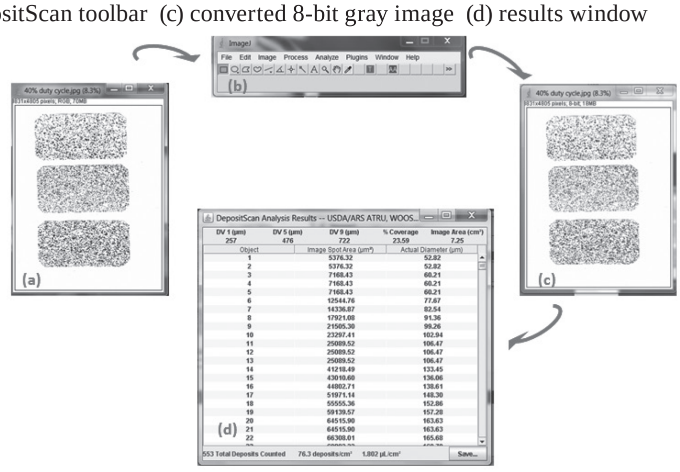
Percent pod bug reduction = 1 − (number of pod bugs after treatment / number of pod bugs in control) × 100 [7]

Results and Discussion

Application Rate (l/ha)

The application rate of the developed swinging lance sprayer was calculated at forwarding speeds of 0.75m/s, 1.0 m/s and 1.25 m/s. The application rate of 773 l/ha,580l/ha and 464l/ha observed for forward-

Fig. 5 Droplet analysis steps using DepositScan (a) original scanned color image (b) DepositScan toolbar (c) converted 8-bit gray image (d) results window



ing speeds of 0.75m/s, 1.0m/s and 1.25 m/s, respectively.

Spray Droplet Deposition

The CV in droplet size was 3.9 and 5.78 for top leaves and bottom leaves, respectively. The mean droplet size of 427.5 m and 342. m for the top leaves and bottom leaves, respectively. The droplet size was not significantly influenced by the forward speed of the tractor (Pankaj et al., 2011). The CV in droplet density was 9.91 and 8.41 for top leaves and bottom leaves, respectively. The mean droplet density of 114.8 drops/cm^2 and 110.13 drops/cm^2 for the top leaves and bottom leaves, respectively. In comparison, the droplet density was more on top leaves than bottom leaves. The top leaves invariably receive more droplet density due to direct exposure (Narang et al., 2015; Sirohi et al., 2008) crop canopy influence the spray deposition on bottom leaves. At the same time, droplet density decreased with an increase in speed for top and bottom leaves. The forward speed of sprayer determines the exposure time of target to the spray. Lower operating speeds resulted in more spray per unit area of plant canopy, thereby, increase in droplet density (Jassowal et al., 2016; Pankaj et al., 2011). The CV in percent cover was 6.21 and 9.35 for top leaves and bottom leaves, respectively. The mean percent cover of 21.47% and 19.36% for top leaves and bottom leaves, respectively. The same time, the percentage cover decreased with an increase in speed for top and bottom leaves .The CV in volume of spray was 3.7 and 3.44 for top leaves and bottom leaves, respectively. The mean volume of spray of 1.47 L/cm^2 and 1.21 L/cm^2 for the top leaves and bottom leaves, respectively. The volume of spray increased with increase in speed for both the systems for top and bottom leaves. The CV in uniformity coefficient was 5.15 and 4.04 for top leaves and bottom leaves, respectively. The mean uniformity coefficient of 1.66 and 1.52 for the top leaves and bottom leaves, respectively. The Uniformity coefficient increased with an increase in speed for top leaves, whereas the uniformity coefficient decreased for bottom leaves. The uniformity coefficient nearer to one is desirable; the forward speed should be such that the canopy receives adequate spray.

Fig. 6 (a) Field evaluation of swinging lance sprayer (b) Placement of kromekote papers on crop canopy

(a)

(b)

Field Parameters

The theoretical field capacity of the developed swinging lance sprayer at forward speeds of 0.75 m/s, 1.0 m/s and 1.25 m/s, were 3.6 ha/h, 4.8 ha/h and 6.0 ha/h, respectively. The effective field capacity of the developed swinging lance sprayer, at forward speeds of 0.75 m/s, 1.0 m/s and 1.25 m/s, was 2.56 ha/h, 3.33 ha/h and 4.16 ha/h, respectively. The field efficiency capacity of the developed swinging lance sprayer, at forward speeds of 0.75 m/s, 1.0 m/s and 1.25 m/s, was 71.1%, 69.3% and 71.7%, respectively.

Bio-efficiency (%)

The percentage reduction in pod bugs was considered to identify bio-efficiency of developed swinging lance sprayer. The bio-efficiency of developed sprayer in control of pod bug at 3DAS and 5DAS was 68.5% and 91.0% , respectively.

Cost Economics

The operating cost of the tractor was USD 7.10 /h, the operating cost of swinging lance sprayer was USD 1.41 /h. Total operating cost of swinging lance sprayer was INR. 641 /h. The operating cost per hectare was USD 3.32. The break-even point was 127 h/year or 325 ha/year.

Conclusions

The developed swinging lance sprayer with automation of spray gun operations resulted in uniformity distribution of spray chemical over crop canopy. The theoretical field capacity, effective field capacity and field efficiency of developed

Table 2 Spray droplet deposition parameters

Parameter	Top leaves				Bottom leaves			
	Range	Mean	SD	CV	Range	Mean	SD	CV
Droplet size (µm)	405.1-465	427.52	16.7	3.9	310.1-378.7	342.9	19.82	5.78
Droplet density (drops/cm^2)	103.4-137	114.87	11.39	9.91	96.8-124.2	109.98	9.25	8.41
Percent cover (%)	19.07-23.73	21.42	1.33	6.21	17.67-21.8	19.36	1.22	9.35
Volume of spray (µl/cm^2)	1.4-1.59	1.49	0.05	3.7	1.13-1.27	1.21	0.04	3.44
UC	1.53-1.81	1.66	0.08	5.15	1.43-1.62	1.52	0.06	4.04

sprayer was 3.6 ha/h, 2.56 ha/h, 71.1%, respectively at forward speed of 0.75 m/s. The bio-efficiency of sprayer was 68.5% and 91% at 3DAS and 5DAS, respectively. The operating cost per hectare was USD 3.32. The developed swinging lance sprayer can be used for multiple crops like green gram, black gram, soya bean, chilli, cotton, tobacco. The developed sprayer performed better in terms of spray deposition, low application cost, saving of labor, elimination of chemical exposure to the spray gun operators over conventional tractor mounted gun-type sprayer.

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