Sonar sensing predicated automatic spraying technology for orchards

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Wastage of chemical inputs and environmental degradation have been a serious issues with conventional methods of pesticide application in agricultural and horticultural engenderment, resulting in fruit poisoning. A tractor-operated low-cost, ultrasonic sensor predicated selective pesticide sprayer was developed and tested for efficient spraying on the plant canopy and to abstain from spraying in canopy absentia. Sensing technology was interfaced with programmed Atmega328P for automatic spray control through pump, solenoid valves and nozzles. The sensing signals instigated the microcontroller system for desired spraying. The sprayer was evaluated with two different types of nozzles for optimal input resulting in best spray coverage and impact fruit infection. Water sensitive papers were used for estimation of spray characteristics. The turbo nozzle sprayer resulted in 47.41% of spray coverage, 171 drops/cm^2 with 26% of pesticide savings and considerably prevented fruit infection up to 95.64%. This proved to be much better than hollow cone nozzle spraying. The technology was provisioned for boom height and nozzle angle adjustment as per canopy geometry. The ultrasonic sensor sprayer was designed for low cost and precise pesticide spraying especially for marginal farmers, thereby reducing both costs and environmental pollution by plant protection products.

Keywords: Agricultural engenderment, efficient spraying, environment pollution, fruit infection, ultrasonic sensing technology.

CONTROL of insects and pests in agricultural production is a complex task because of their easy and quick multiplication to infest the agricultural plantations, especially the horticultural crops. Fruit flies have high reproduction capacity and can easily adapt to different environmental conditions[1]. Various types of sprayers are commercially available for infection and pest infestation control. Manually operated back pack sprayer, self-propelled units, tractor operated sprayer and air assisted power sprayer are common for orchard applications, but the large air assisted mist sprayers constantly generated large spray plume which was highly drifted and lost to the ground[2]. Plant protection products (PPPs) are often constantly applied in large volumes without any relation to canopy density of the plant or tree. Efficient chemical application on plant canopies is a challenge because of their complex structure and wide plant spacing. Tractor-operated power sprayers are popular to spray liquid chemicals in orchard crops with conventionally employed axial fan air-assisted sprayers. These conventional sprayers have a limited range of adjustments, especially in their spray profile or air flow rate[3]. Public opinion, environment degradation concerns and demands for healthy fruits, have stimulated researchers for more sustainable spraying techniques, by optimizing the spray treatments in orchards and preventing spray losses towards environment degradation[4–7]. A number of systems for adjusting the applied dose of plant protection products according to orchard structure have been developed in the past decades. Tree row volume (TRV) system[8], varied the spray dose by varying the spray volume at TRV proportional constant pesticide concentration; this system of volume adjustment was tested in European countries[9–11]. Contrary to TRV, Pergher *et al.*[12,13], introduced leaf area measurements to correlate spray deposits with different spraying equipment and hedgerow vineyards. However, the continuous calculation of TRV for different tree canopies, even in the same orchards, required continuous adjustments and interventions to optimize the spray application efficiency[7]. Hence a sensor-based target spraying approach is necessary as it saves chemicals and minimizes environmental risk. Environmentally safe spray techniques were developed to reduce the use of PPPs through target applications for reduced environment losses[14]. Many techniques as well as computational processing were employed to calculate a wide range of parameters based on light interception characteristics of the crop[15]. But these radar-based and infrared systems were very expensive for implementation. The use of ultrasonic sensors and proportional electrovalves with software and automation, allowed real time spray modification as per the orchard crop structure and

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considerably reduced the spray and pesticide application amount[4]. Wei *et al.*[16] developed and tested an automatic toward-target sprayer that employed infrared sensors and hall effect sensors for automatic spray of pesticides. But the infrared sensor had a limited range of operation; thus any orchard tree out of this range was undetectable and the spray remained inactivated. Zaman *et al.*[17] developed a prototype automated variable rate sprayer for real-time spot-application of agrochemicals in wild blueberry fields. This was intended for application of herbicides to kill weeds, and the systems consisted of an array of ultrasonic sensors, and 8-channel variable rate controller interfaced to a pocket computer using wireless bluetooth with windows mobile software. The system is ideal for well-managed farms, but the less maintained farms of the marginal orchard growers cannot afford such systems. Stajnko *et al.*[18] developed a programmable ultrasonic sensing system for targeted spraying in orchards. The system employed ultrasonic sensing processed in LPC1343 microcontroller and spray using electromagnetic valves. The sprayer reduced the spray amount up to 37.7% as it abstained from spraying within gaps. The system sprayed as per expectation, but electromagnetic valves, air blower add up considerable cost which seems unaffordable for marginal farmers. Sharma and Borse[19] developed an automatic agriculture spraying robot which monitors plant diseases and controls the fertilizer and pesticide application. The technology is robust for real time application, but the use of robots is very sensitive to unmanaged farms or ill-managed orchards. Also the sensing technology for disease assessment consumes a significant cost, which is still unaffordable by a majority of marginal farmers especially in countries like India. However, excluding the disease assessment, which is now normally assessed by various low-cost technologies, could make the technology more adaptable. Sheng[20] developed a robotic system for pesticide application, which has the potential to replace humans in agricultural farms, but the operation is restricted to well maintained and uniform farms due to robotic sensing and movement constraints. Londhe and Sujatha[21] studied a remotely operated pesticide sprayer under laboratory conditions which identified pest affected leaves through image analysis; however no field test has been provided to assess the operating efficiency of the system. Junxiong *et al.*[22] developed a mobile spray robotic system for greenhouse, which employs a mobile platform, manipulator, disease diagnosis system and variable nozzles based on image analysis and processing of cucumber leaves. The technology is significant in real-time modification of spray, but is limited to green houses which have a uniformly maintained environment, that could be ideal for image capturing and analysis. However, no evidence was provided by them for its successful application in open field orchards where conditions are non-uniform and unmanaged. Berenstein and Edan[23] developed an automatic pesticide spraying system for accurate spraying on canopy, assisted by complex assembly of colour cameras, distance sensors and adjustable nozzles. The technology holds potentiality for accurate spraying; however, evaluation has been carried on artificial plants, not in real field conditions.

This paper presents the recent development of a precise ultrasonic sensor-based orchard spraying system developed specially for marginal farmers and minimally managed farms so as to have profitable, comfortable and most importantly an affordable system.

Materials and methods

Sensor-based spraying system

A sensor-based, tractor mounted automatic spraying system for small orchard holders was developed for plant canopy detection and spraying of liquid chemical over the detected canopy. The system consists of ultrasonic sensors, microcontroller board, solenoid valves, one-way valves, fixed displacement pump, pressure gauge, relief valve, nozzles, storage tank of 200 litre capacity and 12 V battery. The pump was driven through the tractor PTO. The ultrasonic sensor could detect a set object with a sensing range of 0–3 m. Three turbojet nozzles on each boom divided the spray region into three parts which can be adjusted by their tilt and height according to the average canopy height and width. Figure 1 presents the functional block diagram of the sensing and spray controller unit. The system was mounted on a tractor for high field capacity spraying on two rows of the orchard canopy.

The operating software

Ultrasonic sensor works by interpreting the sound waves transmitted and received. As soon as the plant canopy is detected, a voltage signal is transmitted to the microcontroller which turns the relay switch to ON mode for actuation of the solenoid valve and allows the pressurized liquid spray precisely through the nozzle on the plant canopy. In case of no canopy, the sensor will not generate a voltage signal that withholds the system from spraying in the blank region. A code block and algorithm of system functioning was developed in the IDE of the Arduino (Atmega 328P) to switch relays based on sensing of sonic waves. The controller circuit was powered by a 12 V DC battery for system actuation. Figure 2 displays the control circuit of the sensor-based automatic orchard sprayer. The microcontroller was programmed so as to neglect the continuous ultrasonic pulses generated for single canopy for a particular pre-set period and again accepts the first ultrasonic pulse after the blank region has passed by.

Sprayer application rate

The sprayer components and control system were tested, cross checked and fine-tuned in the laboratory and on

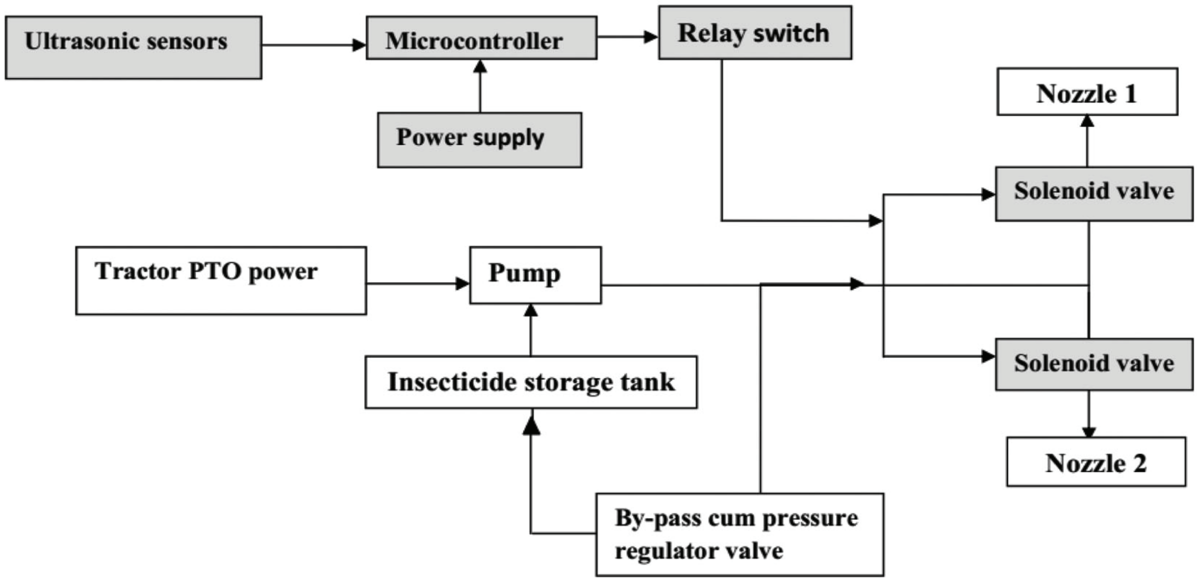

Figure 1. Block diagram of the functioning of the controller unit.

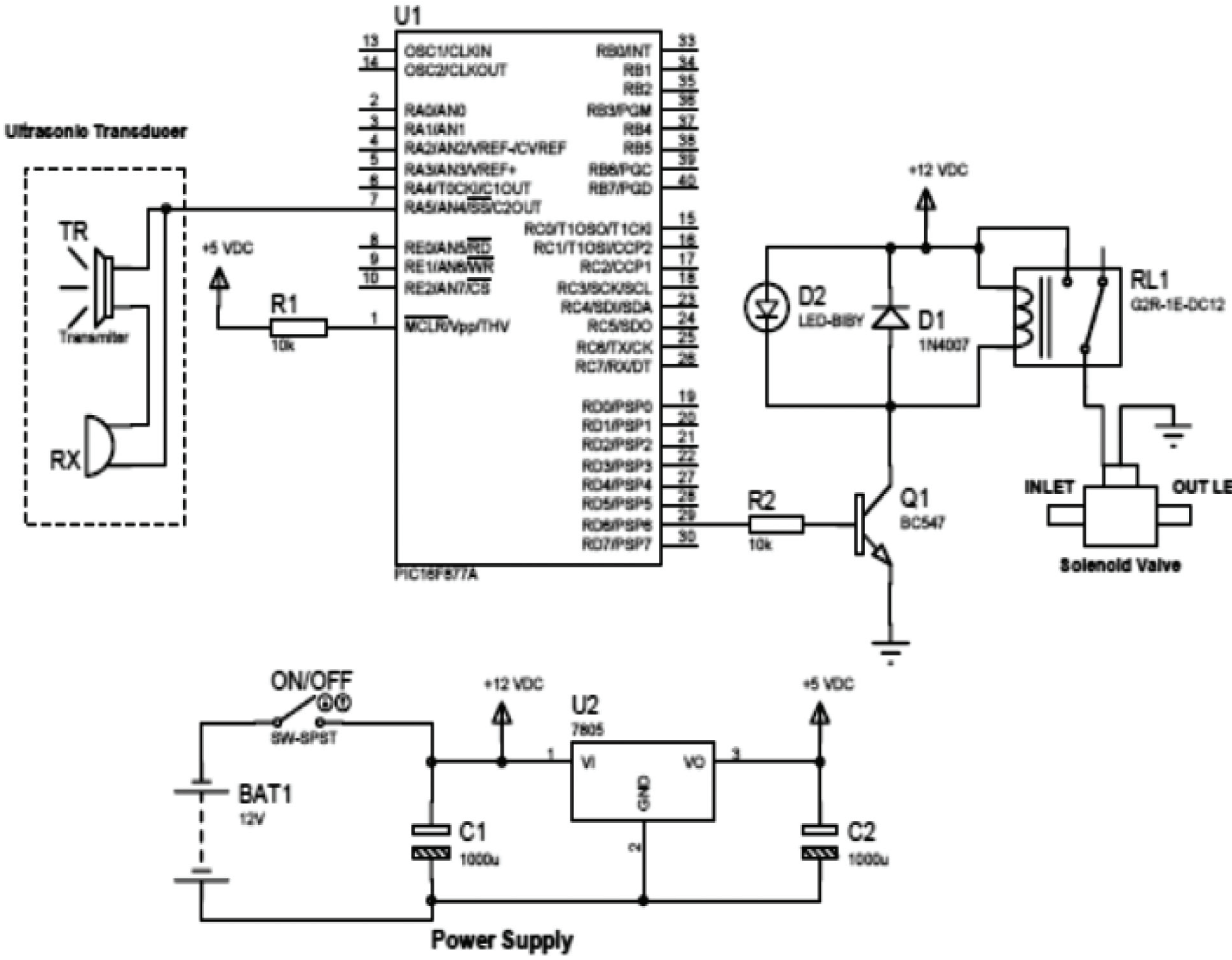

Figure 2. Control circuit of the sensor based orchard sprayer.

artificial trees. This process resulted in a real-time robust system for automated opening and shutting of all three nozzles as per canopy presence. The real-time pesticide application rate (A_r) was computed as given in eq. (1)

$$A_r(l/ha) = \frac{qN600}{ws}, \tag{1}$$

where q is the flow rate per nozzle in l/min, w the one-sided working width (m), s the operating speed (km/h) and N is the number of nozzles on one side. To analyse and quantify the spray coverage and spray deposit, 75 × 26 mm water sensitive papers (WSPs), were used to calculate the number of spray droplets (No./cm^2) and the percent of spray coverage. As shown in Figures 3–6, WSPs were placed using pins at six locations on a canopy and at three locations in the inter-canopy region for 24 trees just before the spraying[2]. The WSP were collected back soon after they dried following spraying. The WSPs were scanned separately in PC and analysed in Image J software for spray droplet analysis. The results presented are the average percentage of WSPs covered by spray and average number of droplets (S_n/cm^2) at every location.

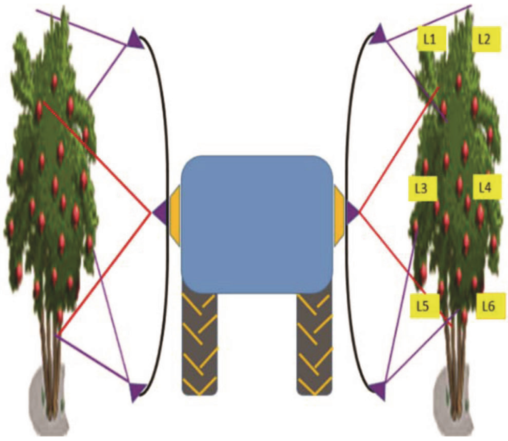

Figure 3. WSP within tree canopy.

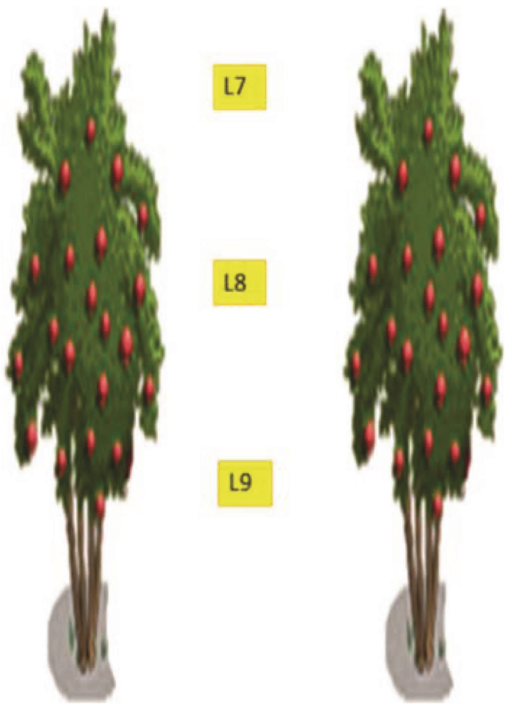

Figure 4. WSP in the inter-canopy region.

Field evaluation

The tractor-mounted ultrasonic sensor-based orchard sprayer was tested at a pomegranate orchard research farm at MPKV Rahuri (Maharashtra, India; Figure 7). The trees were spaced at 2.4 × 4 m intervals with a density of 1248 plants/ha. They had an average canopy size of 2.52 × 2.36 × 2.24 m (height × width × length). The sprayer

Figure 5. WSP placement in pomegranate orchard.

Figure 6. WSP on a pomegranate tree canopy.

Table 1. Specifications of the tractor mounted ultrasonic sensor based sprayer

Type of nozzles	Hollow cone	Turbo
Number of nozzles per side	3	3
Operating pressure (kpa)	700	800
Per nozzle discharge (l/min)	0–0.98	0–1.22
Total one side nozzle discharge (l/min)	0–2.94	0–3.66
Forward speed of operation (km/h)	2.04	2.04
PTO speed (rev/min)	750	750
Field area covered (ha)	0.2	0.2
Estimated application rate (l/ha) without sensor	400.64	500.80
Estimated application rate (l/ha) with sensor	200.32	370.59

Table 2. Hollow cone nozzle spray coverage (%) for constant and sonic sensor-based spraying

WSP	Mode	Mean	SD	RD	*F*	*P* value	*F* Crit.	Inf.	*t* Stat	*P* value	*t* Crit.	Inf.
L1	CA	25.14	2.67	10.62	1.75	0.09	2.01	NS	0.73	0.23	1.68	NS
	SA	25.91	3.62	13.96								
L2	CA	23.53	7.52	31.95	1.40	0.21	2.01	NS	1.40	0.08	1.68	NS
	SA	25.18	5.50	21.84								
L3	CA	34.20	6.81	19.91	1.12	0.39	2.01	NS	1.36	0.09	1.68	NS
	SA	31.23	7.16	22.93								
L4	CA	28.28	7.47	26.42	1.48	0.17	2.01	NS	0.77	0.22	1.68	NS
	SA	30.83	9.28	30.10								
L5	CA	41.23	9.96	24.16	1.45	0.19	2.01	NS	0.26	0.40	1.68	NS
	SA	43.28	8.22	18.99								
L6	CA	28.68	6.11	21.30	1.48	0.18	2.01	NS	0.68	0.25	1.68	NS
	SA	30.16	7.42	24.59								
L7	CA	33.83	7.56	22.34	4.26	<0.01	2.01	S	13.52	<0.01	1.69	S
	SA	10.08	3.71	36.83								
L8	CA	31.06	7.60	24.48	3.14	<0.01	2.01	S	12.16	<0.01	1.68	S
	SA	8.85	4.30	48.55								
L9	CA	31.43	6.59	20.98	3.47	<0.01	2.01	S	13.06	<0.01	1.69	S
	SA	11.20	3.65	32.58								

was tested once with constant spraying mode and once with sensor-based spraying mode with hollow cone nozzle and turbo nozzle for 24 trees separately. Nozzles on the boom were set at 65, 160 and 255 cm above the ground. WSPs, L1, L3 and L5 were placed at 10 cm from the canopy exterior and L2, L4 and L6 were placed 50 cm behind the central trunk axis. WSPs L7, L8 and L9 were placed in the blank region between two canopies in a row, to figure out the amount of spray reduced while operating with the ultrasonic technology. The automatic sprayer unit was mounted and operated by a MT 180 D (Mitsubishi Shakti) tractor. Table 1 presents the operating specifications including discharge and application outputs. Based on the sensor-nozzle spacing of 50 cm and speed of operation, the nozzles were actuated with set operating lag of 0.8824 sec for 4.166 sec to cover the entire canopy. Percentage of infected fruits was calculated after one week of spraying in every mode. Twenty-four trees were kept unsprayed as control and infected fruit fraction was calculated and compared with all spray modes. The spray area coverage and spray impact on WSPs were statistically analysed along with pesticide reduction and fruit infection in every mode of spraying.

Results and discussion

Spray coverage and impact

The ultrasonic sensor-based sprayer was tested in every mode for spray coverage, impact, pesticide savings and fruit infection, followed by statistical analysis for significant difference ($\alpha = 0.05$) in variance and in mean output parameters. Table 2 presents statistical comparison of spray coverage (%) with hollow cone nozzle during constant spraying (CA) and during sensor-based spraying (SA). Average spray coverage of 30.18% and maximum of 41.23% on WSP L5 was observed within canopy with

Table 3. Hollow cone nozzle impact (drops/cm^2) for constant and sonic sensor based spraying

WSP	Mode	Mean	SD	RD	*F*	*P* value	*F* Crit.	Inf.	*t* Stat	*P* value	*t* Crit.	Inf.
L1	CA	82.66	11.53	13.95	1.21	0.33	2.01	NS	1.05	0.15	1.68	NS
	SA	86.33	12.67	14.68								
L2	CA	124.91	14.47	11.59	1.30	0.26	2.01	NS	0.19	0.42	1.68	NS
	SA	124.04	16.53	13.32								
L3	CA	93.79	16.52	17.62	1.02	0.48	2.01	NS	0.32	0.37	1.68	NS
	SA	92.25	16.35	17.72								
L4	CA	95.37	15.63	16.39	1.89	0.07	2.01	NS	0.62	0.27	1.68	NS
	SA	92.91	11.37	12.24								
L5	CA	47.12	6.80	14.45	1.70	0.11	2.01	NS	1.53	0.07	1.68	NS
	SA	43.62	8.87	20.34								
L6	CA	103.50	11.99	11.59	1.14	0.38	2.01	NS	0.78	0.22	1.68	NS
	SA	100.87	11.24	11.14								
L7	CA	126.41	16.09	12.73	12.71	<0.01	2.01	S	30.86	<0.01	1.70	S
	SA	21.12	4.51	21.36								
L8	CA	141.58	13.60	9.61	15.66	<0.01	2.01	S	41.20	<0.01	1.70	S
	SA	23.54	3.43	14.60								
L9	CA	119.75	12.97	10.83	2.41	0.02	2.01	S	29.82	<0.01	1.68	S
	SA	25.83	8.35	32.33								

Figure 7. Field tests of the ultrasonic sensor based sprayer in pomegranate orchard.

maximum relative deviation (RD) of 32% under constant spray application. This was significantly (NS) similar to the spray coverage within canopy under sensor-based spraying with average and maximum values of 31.1% and 43.28% on WSP L5 respectively and maximum RD of 30%. Table 3 presents the statistical analysis of spray impact (S_n/cm^2) on WSP under CA and SA modes with hollow cone nozzles. An average impact of 91 drops/cm^2 and maximum of 125 drops/cm^2 on WSP L2 was observed within canopy with maximum RD of 17.62% and under CA mode. This was significantly similar to the impact within canopy under SA mode with average and maximum values of 90 drops/cm^2 and 124 drops/cm^2 on WSP L2 with maximum RD of 17.73%. However, significantly contradictory results were obtained in the blank region without canopy under SA mode (10% and 23.5 drops/cm^2) as compared to CA mode (32% and 129 drops/cm^2).

Table 4 presents similar statistical analysis of performance parameters of spray modes with turbo nozzles. An average spray coverage of 47.42% and maximum of 58.98% on WSP L3 was observed within canopy, with maximum RD of 24% under constant spray application. This was significantly (NS) similar to the spray coverage within canopy under sensor-based spraying with average and maximum values of 47.11% and 59% on WSP L5 respectively and maximum RD of 21.10%. Table 5 presents the statistical analysis of spray impact (*Sn*/cm^2) on WSP under CA and SA modes with turbo nozzles. An average impact of 174 drops/cm^2 and maximum of 194 drops/cm^2 on WSP L3 was observed within canopy with maximum RD of 9.8% and under CA mode. This was significantly similar to the impact within canopy under SA mode with average and maximum values of 171 drops/cm^2 and 189 drops/cm^2 on WSP L3 with maximum RD of 16.44%. However, significantly contradictory results were obtained in the blank region without canopy under SA mode (6.67% and 22 drops/cm^2) as compared to CA mode (57% and 195 drops/cm^2). From all tables, it is statistically evident that sensor-based spraying is effective in pesticide savings.

The turbo nozzles and hollow cone nozzles were compared as in Figures 8 and 9, for their spray coverage and impact. The average spray coverage and impact on WSPs within canopy with the hollow cone nozzle was 30.18% and 91 drops/cm^2 respectively and were significantly ($\alpha = 0.05$) less than that of 47.41% and 171 drops/cm^2

Table 4. Turbo nozzle spray coverage (%) for constant and sonic sensor based spraying

WSP	Mode	Mean	SD	RD	F-stat	P value	F Crit.	Inf.	t Stat	P value	t-Crit.	Inf.
L1	CA	60.85	9.57	15.73	1.18	0.35	2.01	NS	1.53	0.07	1.68	NS
	SA	64.93	8.81	13.58								
L2	CA	42.05	6.17	14.67	1.88	0.07	2.01	NS	0.91	0.18	1.68	NS
	SA	40.10	8.46	21.11								
L3	CA	58.97	9.29	15.75	1.60	0.13	2.01	NS	0.67	0.25	1.68	NS
	SA	57.35	7.35	12.82								
L4	CA	39.64	3.87	9.76	1.81	0.08	2.01	NS	1.17	0.12	1.68	NS
	SA	38.08	5.20	13.67								
L5	CA	60.13	5.09	8.47	1.31	0.26	2.01	NS	0.73	0.23	1.68	NS
	SA	58.97	5.82	9.87								
L6	CA	22.84	5.48	24.01	1.37	0.23	2.01	NS	0.28	0.39	1.68	NS
	SA	23.25	4.69	20.16								
L7	CA	63.73	9.54	14.97	28.16	<0.01	2.01	S	29.51	<0.01	1.71	S
	SA	5.21	1.79	34.48								
L8	CA	44.72	6.78	15.16	13.24	<0.01	2.01	S	26.26	<0.01	1.71	S
	SA	7.01	1.86	26.56								
L9	CA	62.86	6.42	10.22	12.44	<0.01	2.01	S	40.40	<0.01	1.70	S
	SA	7.77	1.82	23.43								

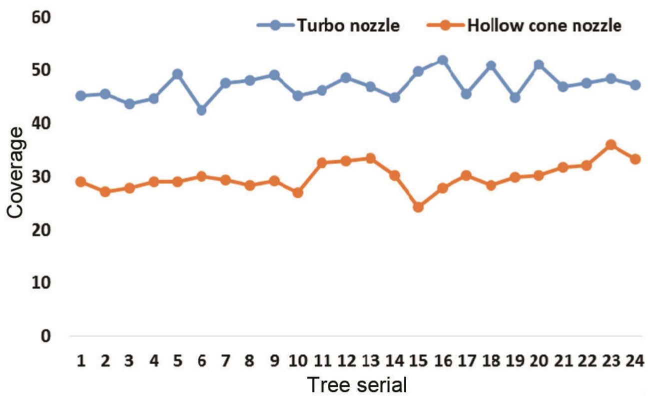

Figure 8. Spray coverage (%) with two nozzle types.

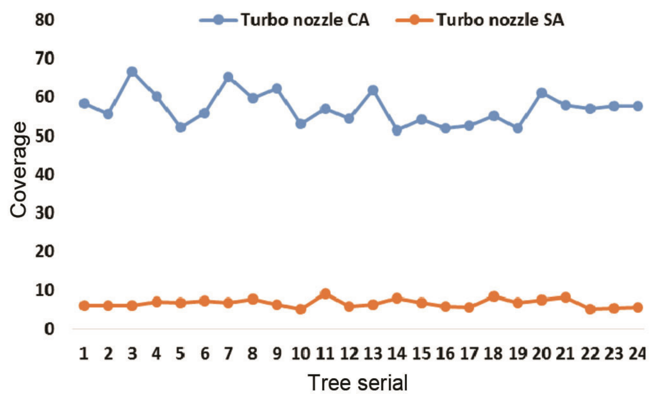

Figure 10. Spray coverage with turbo nozzles in two modes on WSP at L7, L8 and L9.

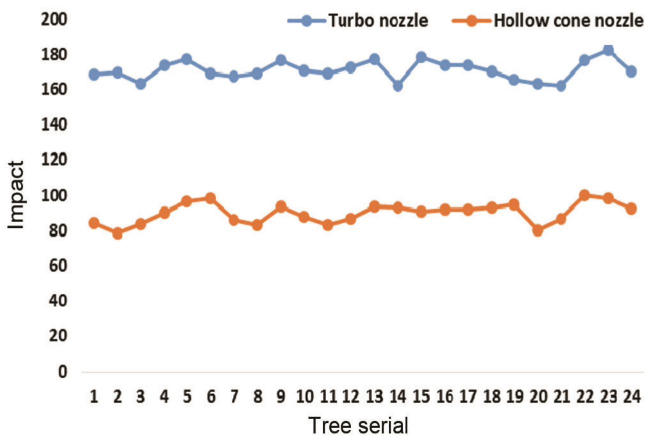

Figure 9. Spray impact with two types of nozzles.

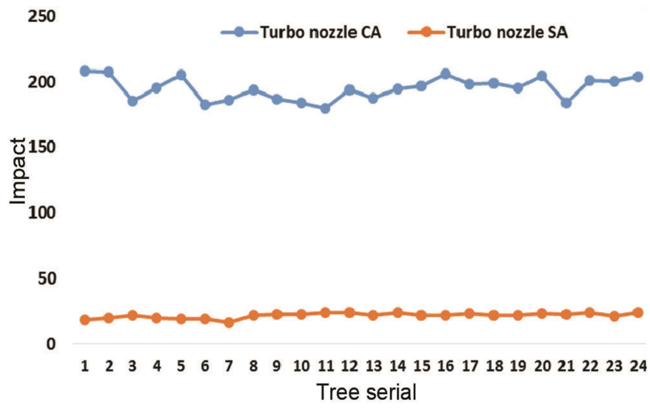

Figure 11. Spray impact with turbo nozzles in two modes on WSP at L7, L8 and L9.

Table 5. Turbo nozzle impact (drops/cm^2) for constant and sonic sensor based spraying

WSP	Mode	Mean	SD	RD	*F* stat	*P* value	*F* Crit.	Inf.	*t* Stat	*P* value	*t* Crit.	Inf.
L1	CA	183.75	12.40	6.74	1.16	0.36	2.01	NS	1.52	0.07	1.68	NS
	SA	178.50	11.51	6.45								
L2	CA	180.17	14.57	8.09	1.75	0.09	2.01	NS	1.03	0.15	1.68	NS
	SA	176.33	11.020	6.25								
L3	CA	193.37	9.91	5.12	1.45	0.19	2.01	NS	1.47	0.07	1.68	NS
	SA	189.50	8.23	4.34								
L4	CA	173.00	12.66	7.32	1.27	0.29	2.01	NS	0.87	0.19	1.68	NS
	SA	170.00	11.26	6.62								
L5	CA	165.12	14.13	8.56	1.46	0.18	2.01	NS	0.94	0.18	1.68	NS
	SA	161.62	11.69	7.23								
L6	CA	148.58	14.51	9.76	1.28	0.27	2.01	NS	0.32	0.38	1.68	NS
	SA	150.00	16.43	10.95								
L7	CA	170.87	15.29	8.95	8.90	<0.01	2.01	S	45.68	<0.01	1.70	S
	SA	20.50	5.12	24.99								
L8	CA	208.75	17.94	8.59	26.17	<0.01	2.01	S	50.03	<0.01	1.71	S
	SA	22.04	3.50	15.91								
L9	CA	204.75	16.62	8.11	16.23	<0.01	2.01	S	52.17	<0.01	1.71	S
	SA	22.375	4.12	18.44								

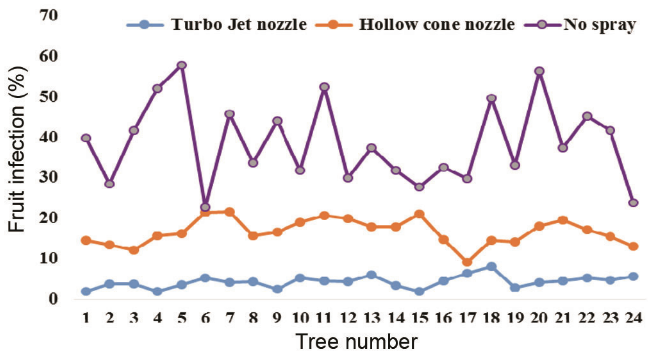

Figure 12. Fruit infection in two modes of spraying including no spray mode.

respectively with turbo nozzle amounting to a better penetration, canopy coverage and efficacy in spraying for minimum fruit infection. Figures 10 and 11 present that the average spray coverage and impact on WSP L7, L8 and L9 in the blank region was significantly higher than the sensor-based spraying with turbo nozzle, which saved a significant amount of pesticide upto about 26%. Hence from all above figures, the turbo nozzle-spraying forms the best combination for sensor-based efficient spraying.

Fruit infection

Average fruit infection (Figure 12) with sensor-based turbo nozzle spraying was only 4.37% which was significantly less than that of 17% and 39% in case of sensor-based hollow cone nozzle spraying and no spraying mode respectively. All the results were analysed with the two-stage statistical tests for significant difference of variances and means for 24 trees under each mode of spraying, and results revealed that turbo nozzle fit the best for sensor-based efficient spraying. The results were also analysed using the Duncan multiple range test[24] at 5% level of significance along with a statistical term, relative standard deviation (RD) as in Tables 2–5 calculated as

$$\mathrm{RD} = \frac{\mathrm{SD}}{\mathrm{Mean}} \times 100. \quad (2)$$

Conclusion

The designed sensor-based sprayer was rigorously tested in orchards and compared in different modes with two types of nozzles. The easily adjustable boom for adjusting height and tilt of nozzle improved the efficacy of spraying. The sprayer was observed for its best impact, spray coverage, penetration, minimum fruit infection and savings. Turbo nozzle spraying was observed to be better compared to hollow cone nozzle spraying and no spraying modes. The ultrasonic spraying technology was evidently able to abstain from spraying in blank region without canopy. Minimal spray coverage and impact was observed with sensor based spraying in the blank region and any amount was due to an acceptable impact of wind. Turbo nozzle was minimally affected by wind resulting in the desired efficient spraying. Turbo nozzle prevented the fruit infection by 95.64%, maximum than any other mode of spraying, thereby justifying the need, design and development of sensor-based spraying technology. The developed technology thus proves to be of assistance in pesticide saving (26%) and better fruit production especially in small orchards.

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