Air flow characteristics of an air-assisted sprayer through horizontal crop canopy

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Abstract: Artificially induced air currents or air-assistance to droplet spectrum produced by hydraulic nozzles not only facilitate in transporting and depositing the droplets in different parts of canopy but also reduce the application rate of chemicals. The air streams increase the velocity of smaller droplets so that extra momentum would increase impaction and improve penetration into the crop as well as mitigating the influence of wind on drift. It is necessary to quantify the airflow characteristics. But, control of climatic and other conditions in the field is very difficult. Thus, airflow characteristics study was done under controlled conditions on a horizontal simulated crop canopy. Based on this study, an airflow distribution model was developed and airflow characteristics for vegetable crops, namely, eggplant, chilli and bittergourd were predicted. The differences between predicted and actual field study values were not statistically significant. Kinetic energy of air stream dissipated with its movement from top to bottom of the canopy. The rate of kinetic energy dissipation was higher in denser canopies. Higher air velocity 15 m/s was the best as it produced maximum turbulence throughout the canopy.

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1 Introduction

Pesticide spraying generally provides effective crop protection, but very much depends on the correct type of equipment and its usage. Some wastage of pesticide to the surroundings either by missing or overdosing is inevitable. Under application of pesticides is not completely effective, while over application of pesticides increases the risk of environmental pollution and excessive residues on plant produce. To avoid economic losses and health hazards, it is necessary that the pesticide application should be efficient and precise. The magnitude and uniformity of spray deposition are mainly influenced by the target canopy characteristics, properties of chemical and design of spray equipment. Studies have suggested that air assistance to spray droplets is more effective for enhanced distribution and deposition of spray on target canopy compared to spray through hydraulic nozzles alone[1-3].

Incorporation of high speed air stream into droplet spectrum, produced by hydraulic nozzles, facilitates in transporting and depositing the droplets in different parts of canopy, especially on underside of the leaves, more effectively and uniformly[1,3,4]. The air stream causes fluttering of plant leaves and assists to push the droplets down inside the canopy, thus enhancing the spray deposition onto the crop canopy[2]. It also increases the velocity of smaller droplets so that extra momentum

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would increase impaction and improve penetration into the crop as well as mitigating the influence of wind on drift. Incorporation of air assistance in sprayer increases deposition uniformity throughout the plant or tree[5] and deposition on underside of the leaf increases where most of the pests reside. The amount of spray volume with air-assistance can also be reduced substantially without compromising the effectiveness of the spray leading to economic benefits to the user[6]. A minimum threshold air velocity at canopy surface is required to penetrate the spray into the foliage[7]. The air assistance also contributes towards reduction in spray drift and losses on the ground[8,9].

Keeping in view the obvious advantages of air assistance to spray droplets, it is necessary to quantify the airflow characteristics for field crops as airflow patterns inside crop canopy determine the spread and deposition of spray droplets on plant leaves. But, quantification of air flow characteristics for different crops in field is very complex as control of climatic and other conditions in the field is difficult. Thus, a study was planned to observe the air flow characteristics under controlled conditions on a horizontal simulated crop canopy and to predict these for different crops with the help of a model developed so that an efficient air assisted sprayer could be developed.

2 Materials and methods

The study of air flow characteristics were done by conducting experiments under controlled conditions on uniform horizontal simulated crop canopy. Then, an airflow distribution model was developed based on the experiments to predict the air velocity in particular crop canopy. The predicted values of simulated canopy were compared with the observations obtained in different natural canopies.

2.1 Uniform horizontal simulated crop canopy

Airflow characteristics of air stream penetrating into the natural canopy can be simulated on an artificial canopy. Nordbo[10] and Walklate et al.[11] had studied airflow patterns at different levels of leaf area index and density on a vertical artificial crop canopy. Based on similar concepts, a uniform horizontal simulated canopy structure was designed and constructed[12] (Figure 1). The values of leaf area density in simulated crop canopy were chosen in such a way that it might represent most of vegetable crops at different growth stages. The simulated crop canopy was made using a multi-layer grid of 3 mm diameter steel wires supported on track pillars underneath the carriage. Steel wires were stretched along the length of experimental setup and tied to 25 mm ×25 mm m.s. angle irons at the lateral spacing of 50 mm. Plastic leaves of size 50 mm×60 mm and 0.2 mm thickness were put in different configurations on the wire grid in such a way that they were not displaced by the air stream coming from the blower. Five such horizontal planes were formed at the vertical spacing of 200 mm (Figure 2). The leaf area density (LAD) was varied by making three different LAD at test bench. The

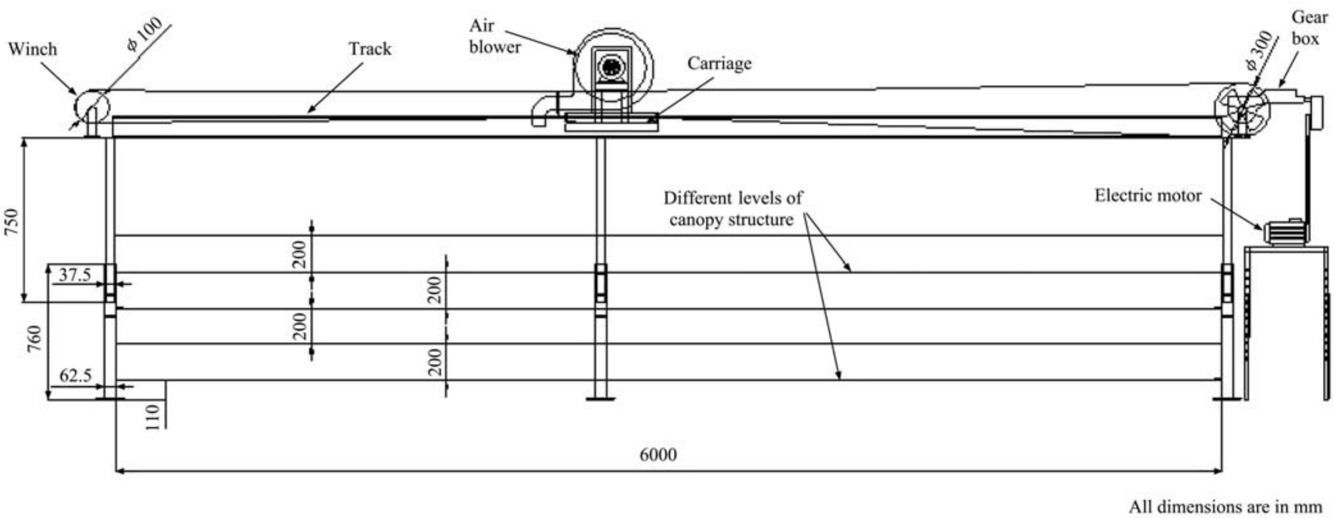

Figure 1 Schematic diagram of laboratory setup

dimensional parameters that defined the canopy are summarized in Table 1. Blockage in the Table 1 is referred to the percentage of simulated leaf area per plane. The numbers of plastic leaves arrangement on a plane were varied to create different levels of leaf area index and leaf area density. An electric motor operated blower, having maximum output capacity of 0.13 m^3/s, was used to deliver the required airflow rate. The airflow rate was varied by regulating the baffles at inlet of blower.

Figure 2 Uniform horizontal crop canopies

Table 1 Parameters of uniform horizontal simulated crop canopy

S. No.	Plane spacing/mm	Number of planes	Blockage/%	Leaf area index (LAI)/$m^2 \cdot m^{-2}$	Leaf area density (LAD)/$m^2 \cdot m^{-3}$
1	200	5	40	2.0	2.27
2	200	5	60	3.0	3.41
3	200	5	80	4.0	4.54

Air velocities were measured at three different locations (top, middle and bottom surface) in three simulated horizontal canopies (having LAD- 2.27, 3.41 and 5.54 m^2/m^3) to determine the effects of leaf area density and distance from air outlet on air velocity diminution. The experiments were done for three air penetrating velocities (5, 10 and 15 m/s) at canopy surface and repeated five times to minimize the experimental errors. Although, five planes of simulated crop canopy were constructed, but measurements were taken at only three planes. Because it was difficult to divide the natural canopy (height of different crops varying from 0.35 to 1.0 m) exactly into five different planes as the heights of leaves in different plants located at the same virtual plane were not equal. The distance between air outlet and the top of canopy surface was kept 0.55 m. Vane type anemometer was used to measure air velocity at the horizontal line passing through top, middle and bottom surface of canopy i.e. 0, 0.4 and 0.8 m from top surface of canopy at the center of air outlet as shown in Figure 3. The velocity of air coming from outlet was varied by regulating the air coming into blower.

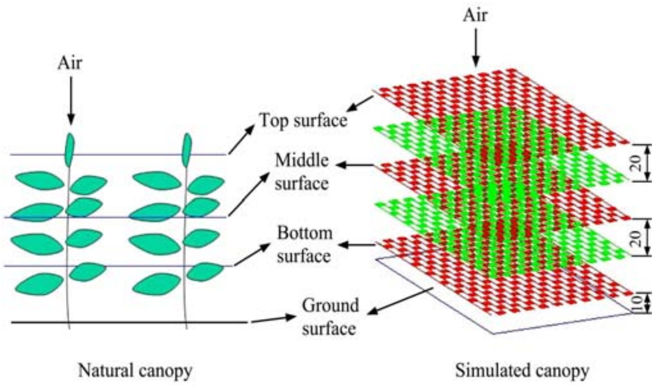

Figure 3 Different planes in natural and simulated crop canopy

2.2 Natural canopy

The air velocity profile in natural canopy was predicted based on results obtained from simulated canopy. The predicted values were compared with the air velocities in three vegetable crops, namely, eggplant, chilli and bittergourd having different crop canopy characteristics (Table 2).

Table 2 Characteristics of natural crop canopy

S. No.	Crop	Average length of a plant/m	Average width of a plant/m	Average height of a plant/m	Total leaf area /m^2	Leaf area index (LAI) /$m^2 \cdot m^{-2}$	Leaf area density (LAD)/$m^2 \cdot m^{-3}$
1	Chilli	0.30	0.35	0.45	0.1719	1.64	3.64
2	Eggplant	0.40	1.00	0.72	1.2748	3.19	4.43
3	Bittergourd	0.50	0.50	0.20	0.6731	2.69	13.46

The leaf area density was calculated assuming uniform density of leaves in crop canopy. The width and height of the crop was measured and volume of one-meter length was calculated. Total number of leaves in that volume was counted and 20 leaves were collected from three different locations in crop canopy. The leaf area was measured by passing each leaf through a leaf area meter. The cumulative area was divided by number of leaves passed through the leaf area meter to determine the average leaf area. Total numbers of leaves were multiplied by average leaf area to calculate the total leaf area. Then, leaf area density and leaf area index were calculated using Equations (1) and (2) given below, respectively.

$$LAD = \frac{\text{Total leaf area}}{\text{Canopy volume}} \quad (1)$$

$$LAI = \frac{\text{Total leaf area}}{\text{Projected area}} \quad (2)$$

The field observations were taken on air stream produced by an air assisted sprayer developed by Sirohi et al.[13]. It had an air duct of 0.25 m diameter and 6 m length and a standard axial flow fan of diameter 0.85 m, having air output 4.5 m^3/s at 2 500 r/min without attachment of duct, to produce the required airflow rate. The air velocities in vegetable crops were measured in the same way as measured in simulated crop canopy by virtually dividing the natural canopy in three different planes (Figure 3). Observations were taken in the center of air stream coming out of air duct at the horizontal line passing through top, middle and bottom surface of canopy. The experiments were conducted at 5, 10 and 15 m/s air stream penetration velocity at top surface of natural canopy. Air velocities were measured at top, middle and bottom surface of three different crops (eggplant, chilli and bittergourd). The experiments were repeated five times to minimize experimental errors.

3 Results and discussion

In an air-assisted sprayer, airflow patterns inside the crop canopy determine the spread and deposition of spray droplets on plant leaves. Experiments were conducted to determine airflow characteristics in two types of canopy structures, namely, artificial and natural. The artificial canopy was constructed to simulate the natural canopy incorporating different levels of leaf area density, which determined resistance to airflow and consequently airflow patterns. The results of airflow characteristics through simulated canopy structures were validated in natural canopy of eggplant, chilli and bittergourd crops.

3.1 Simulated canopy

The air velocity was measured at different horizontal planes of the canopy structure for three levels of leaf area density, namely, 2.27, 3.41 and 4.54 m^2/m^3. The air velocities obtained for different combinations of leaf area density at various locations in the canopy are shown in Figure 4.

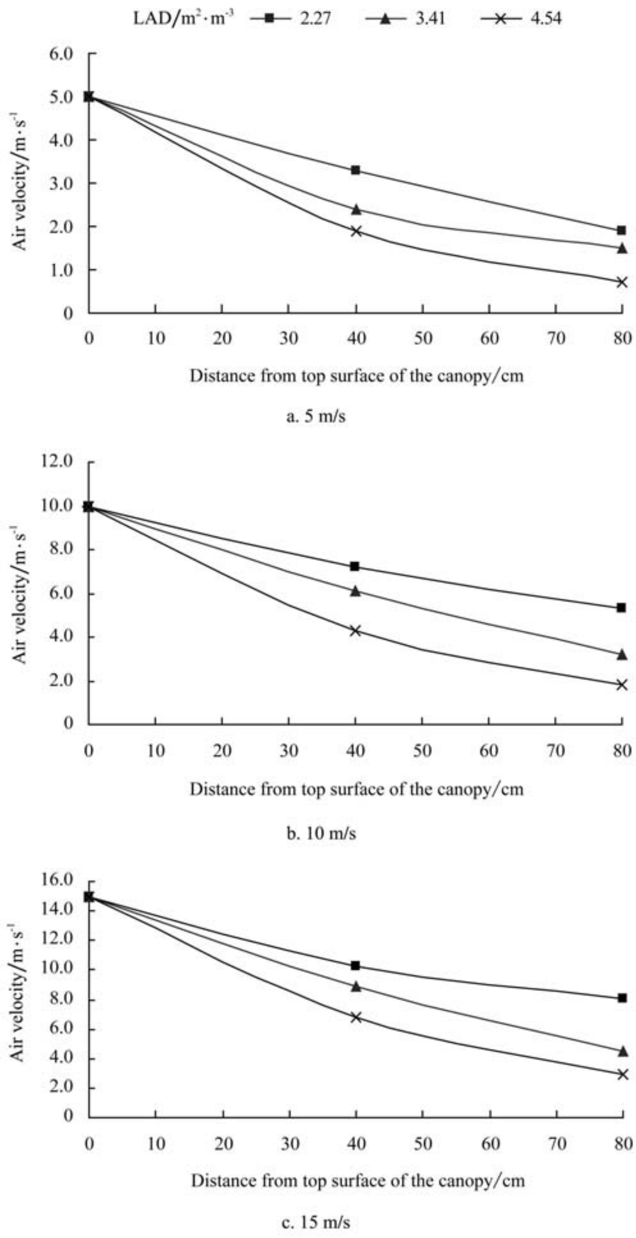

Figure 4 Effect of leaf area density (LAD) on air velocity of air stream penetrating simulated crop canopy at different speeds

Air velocity in all cases decreased towards the bottom of canopy as air stream moved from top to bottom. Resistance offered by the leaves to air stream resulted in loss of kinetic energy of air. Denser the canopy, higher was the dissipation rate of air's kinetic energy. Air velocity of 15 m/s at the top surface of the canopy decreased by 46% to a level of 8.1 m/s at the bottom of canopy having LAD of 2.27 m^2/m^3. It decreased to 2.9 m/s at the bottom of canopy when LAD increased to 4.54 m^2/m^3. The lower level of air velocity (5 m/s) at the top of canopy was highly insufficient to penetrate the dense canopy and to create turbulence for effective spread and deposition of spray droplets. It was reduced by 62% and 86% at middle and bottom points of canopy with LAD of 4.54 m^2/m^3.

The analysis of data was further done using air penetration model developed by Walklate et al.[11]. The model describes small-scale volume and time averaged momentum and turbulent kinetic energy equations for a two-dimensional air-jet penetrating a uniform crop canopy from a moving sprayer. The decay in air velocity was exponential as it traveled through the canopy and depended upon its leaf area density. A simplified equation describing the velocity decay could be written as follows:

$$V_x = V_0 \exp(-b\ x) \tag{3}$$

where, V_x = air velocity at vertical distance x from top surface of the canopy; V_0 = air velocity at top surface of the canopy; b = velocity decay coefficient; x = vertical distance along centerline of the canopy.

Assuming linear relationship between b and canopy structure factor (CSF), b could be expressed as

$$b = a_1 + a_2\ CSF \tag{4}$$

where, CSF = Leaf Area Density (LAD)* D, D = height of the plant; a_1 and a_2 are constants.

Thus, Equation (5) could be written in the following form

$$V_x = V_0 \exp(-(a_1 + a_2\ LAD{*}D)\ x) \tag{5}$$

The air velocity data obtained for simulated crop canopy were normalized and fitted into Equation (5) to determine the parameter a_1 and a_2. Based on the experimental data, the airflow distribution model obtained with R^2 value of 0.88 was

$$V_x = V_0 \exp(-(0.8194\ LAD{*}D - 0.425)\ x) \tag{6}$$

3.2 Natural canopy

The canopies of all three crops were virtually divided into three different planes. The air velocities at these planes were predicted based on airflow distribution model obtained from laboratory study on uniform horizontal simulated crop canopy. These values were compared with the actual values obtained in natural canopies.

Figure 5 shows the predicted and measured values of the air velocities in different crops at different planes. The air velocities measured in canopies of different LAD in field were found to be in close agreement with predicted values from developed model. The air velocities at the middle and bottom surfaces of natural canopy were lower compared to simulated canopy at corresponding levels. The variation between predicted and measured values ranged from 1.72 m/s to 0.49 m/s, but these were not significant. The variations could be attributed to the difference in the manner the leaves of simulated and natural canopies fluttered due to airflow. In simulated canopy, the leaves were held at four corners while natural leaves were supported on one end only. In the latter case, the leaves had more free movement causing air velocity to dissipate more than in the simulated canopy.

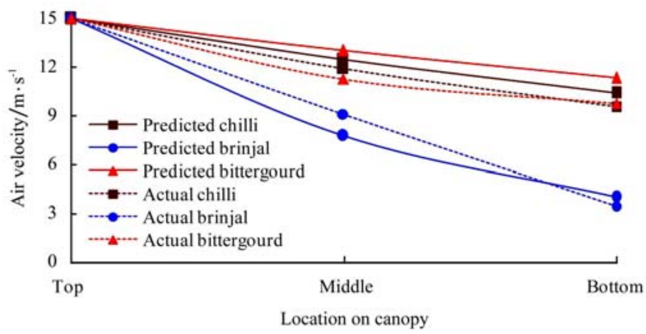

Figure 5 Comparison of air velocity in natural canopy with the predicted values

4 Conclusions

Based on the results of airflow characteristics study of air assisted sprayer on simulated crop canopy and subsequent experiments in natural canopy it was concluded that the airflow distribution model obtained from the laboratory study can be used for the prediction of airflow characteristics for different crops in field experiments to save time as well as efforts. Assistance of air to spray droplets may be beneficial in better and deeper penetration into crop canopy as higher air velocity at the top surface of crop canopy created more penetration and turbulence inside the canopy. A critical level of air velocity at the top of crop canopy of higher LAD was found to be 15 m/s.

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