Characteristics of a nozzle spray in relation to its application to aeroponics

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Abstract

Aeroponics or Soil-less agriculture is a relatively new and recent type of practice, where plants are grown without soil while nutrient-rich water is provided via an atomized spray system to the suspended roots. Spray nozzles are easy-to-use in supplying water (and fertilizers) to (mainly) the roots and root hairs of the desired crop (or plant) for production. We characterize a spray nozzle delivering water vertically above against the gravity by measuring, experimentally, its (a) spray drift, (b) spray height, (c) maximum spray angle, (d) spray width, and (e) droplets sizes. Experiments were carried out at different inlet pressures and a majority of the above mentioned parameters were obtained by processing the images captured using digital (or high speed) camera, sometimes along a plane lighted by a high-power laser source. We also studied the spray (or jet) behaviour at different vertical heights and different horizontal planes using a unique polythene sponge method. We studied the mass flow rate, the mass of water absorbed, and droplet size dynamics (as a function of time and pressure) using this method. A mathematical model is proposed to understand such flows, whose results matched reasonably well with the experimental values. We believe that this study can be extrapolated to other nozzles (or sprays) to obtain similar characteristic parameters. A study was conducted on the characterization of "Plant-water uptake". This study hence is critical in selecting the desired spray system for a given canopy. The research conducted here would be crucial in designing an Aeroponic system in a controlled agricultural environment.

Introduction

Agriculture is at the root of our economic development. Open field agricultural system has been commonly followed since ancient times which have proven to be inefficient over the course of advancement. The traditional way of agriculture is more dependent on the mercy of nature, climate, weather and seasons rather than the technology. Still, we heavily depend on open field agriculture for our survival.

The world's population is expected to increase by 2 billion persons in the next 30 years, from 7.7 billion currently to 9.7 billion in 2050 (by 25.97%) [1]. But agricultural land is expected to come down by 17% in the next 30 years, from 36.6% currently (Figure 1Figure 2Figure 2 World map showing the relative distribution of agricultural land [2].) to 19% in 2050 [2]. Hence, by 2050, the amount of agriculturally fertile land feeding people will be less than the number of people depending on it. Therefore, it is important to find an alternative method for producing food at this time. One of the methods of coping with the increasing food demand is by 'Aeroponics'. Hence this study is crucial for the future demands of the world on agriculture.

Some of the early works on the water-culture method for growing plants without soil was studied by Hoagland [3] whose objective was to understand the fundamental factors which govern the factors affecting the growth of plants, in order to deal with many complex problems of soil and irrigation. To facilitate the examination of roots, a method of growing plants (Pineapple plants) in water vapor was proposed [4]. In 1953, Apple trees were grown outdoors with their roots in boxes where they were fed with a nutrient solution through spray [5]. The technique for Growing Crops in the nutrient film was demonstrated using Hydroponics [6]. A pioneering study was conducted on Aeroponic growth and its efficiency by Nir [7] and its efficiency was further analyzed [8,9]. Klotz used a *Devilbiss* atomizer to provide a nutrient solution to the roots of the citrus plant [9]. An Aeroponics system of agriculture improves root growth, survival rate, growth rate and maturation time [10]. In

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1988, the regeneration of plants using nutrient mist bio-reactor was described by Weathers and Giles [11]. Mild-to-severe drought conditions, occurring naturally or man-made, motivated Hubick [12] to study and explore the Aeroponic agricultural system under a controlled environment. Massantini [13,14] described several types of Aeroponic systems. More importantly, he described [15] how to produce commercial crops in the Aeroponic system in 1970's.

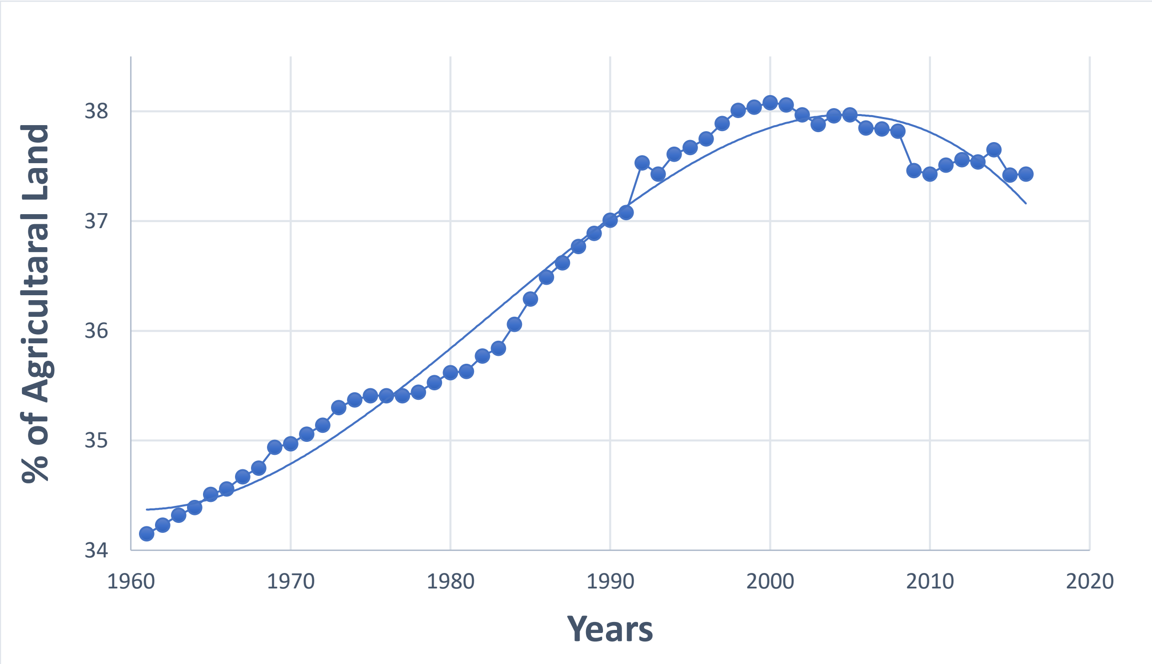


Figure 1 Plot showing annual relative agricultural land in the world [2].

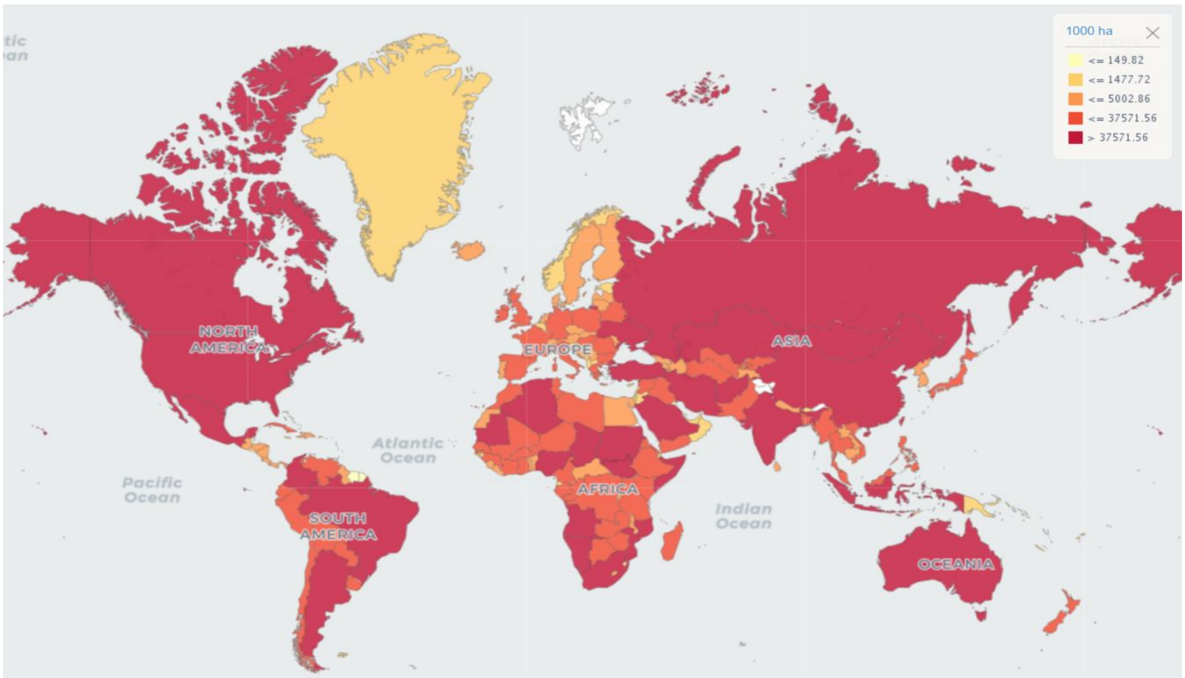


Figure 2 World map showing the relative distribution of agricultural land [2].

The study on the root, rhizome or tuber of crops in the fog-box was done in the year 1966 [16]. The works of Lloyd A Peterson in 1988 [17] showed that the root growth was rapid with good branching and root hair development: the plant was kept in a controlled environment using air conditioner systems. Further, roots-based research such as root growth and root diseases have also been investigated [18,19]. The Aeroponic system also allows the measurement of nutrient uptake overtime under varying conditions [20]. Further, the experimentations were extended to space flight applications for International Space Station [21]. Mass production of Potato mini-tubers using aeroponics technique was conducted and argued to be economical [22]. Further, research on the aeroponics growth system was developed using automatic ultrasonic atomizer [23]. The most important parameter in the Aeroponics study is Spray.

In the Aeroponics spray system, the nutrients are sprayed at regular intervals. In 1963, Muras [24] explored the use of the nutrient spray in culture of a number of vegetable species and discussed the role of spraying nutrients at finite targeted time intervals specific to a given plant. This work was followed by Shtrausberg [25], the significance of spraying nutrients mist at different intervals of time was analyzed for the tomato plant in the aeroponic chamber. The spinning disk system of Zobel [8] and "*Ein-gedi-system*" of Socher [26] are the systems other than nozzles which also form a thin layer of water (nutrient solution) on the surface of the root. The spray from the nozzle includes the development of thin films of nutrients and the droplet at the tip of the root. In the aeroponic system, the spray nozzles play a vital role; the nozzles should be maintained (cleaned) at regular intervals of time as suggested by Vestergaard [27]. The distribution of vegetation initially in the aeroponic growth chamber mainly depends on the spray characteristics. Hence the characterization of spray is crucial in application to aeroponics.

The main objective of this paper is to establish correlations concerning parameters of nozzle characteristics from the experiments and to show that these co-relations can be successfully employed in the future design and distribution of vegetation in the aeroponic growth chamber and to select suitable nozzles for different vegetation culture.

Materials and Methods

The experiments were conducted in a well-designed growth chamber with 625 mm x 620 mm as the cross-sectional dimensions and were 1808 mm high. The chamber was constructed using L-angle structures of mild steel and had a separate aluminum structure placed at its top. We covered three sides of the chamber with a semi-transparent sheet to avoid any water spilling out of the chamber, while the open side was used to perform the experiments. For better imaging contrast, the chamber was also covered with black cloth at all the sides except the filming (or imaging) side. The main components used in this study were: (a) Nozzle (Jain Company) having a diameter of 0.60mm, (b) Booster pump (Kemflo Ltd HF1200 with a nominal flow rate of 1.6LPM and maximum pressure of 110 PSI), (c) Pressure reducing valve (Suzhik Aira automation Ltd with a reading range between 0 and 10 kg/cm^2), (d) Adaptor (Resmed Ltd 370001 with a rating of 24V (DC)/5A, (e) Piping and accessories (including 12mm and 16mm PU tubes, 19.05 mm inner diameter CPVC pipes, Anti-Vibration rubber pads, U-clamps and Acrylic sheets), (f) a high power continuous (green) lasing system with sheet-maker optics, and (g) Water storage tray (1.5 m x 0.7 m x 0.4 m) placed at the bottom of the chamber to collect the falling water drops (or droplets). The tray was kept 194mm above the ground level. The complete assembly is seen in Figure 4 with a schematic of the experimental setup. We used Polyester sponge (94 x 146 x 64 mm and mass of 6g) to get the amount of water absorbed at different locations. First, a steel wire is twined at a require height to the L-angles of the aeroponic chamber support which helps in supporting the holder of the sponge to carry out the experiment. A sponge is held on an acrylic sheet that acts as a holder. We have used a mobile weighing pan which has a Least count of 1g and can measure up to 5Kg. This weighing pan was used in measuring the sponge mass after keeping the sponge in particular co-ordinate and for a particular time to analyze the amount of water absorbed by a sponge.

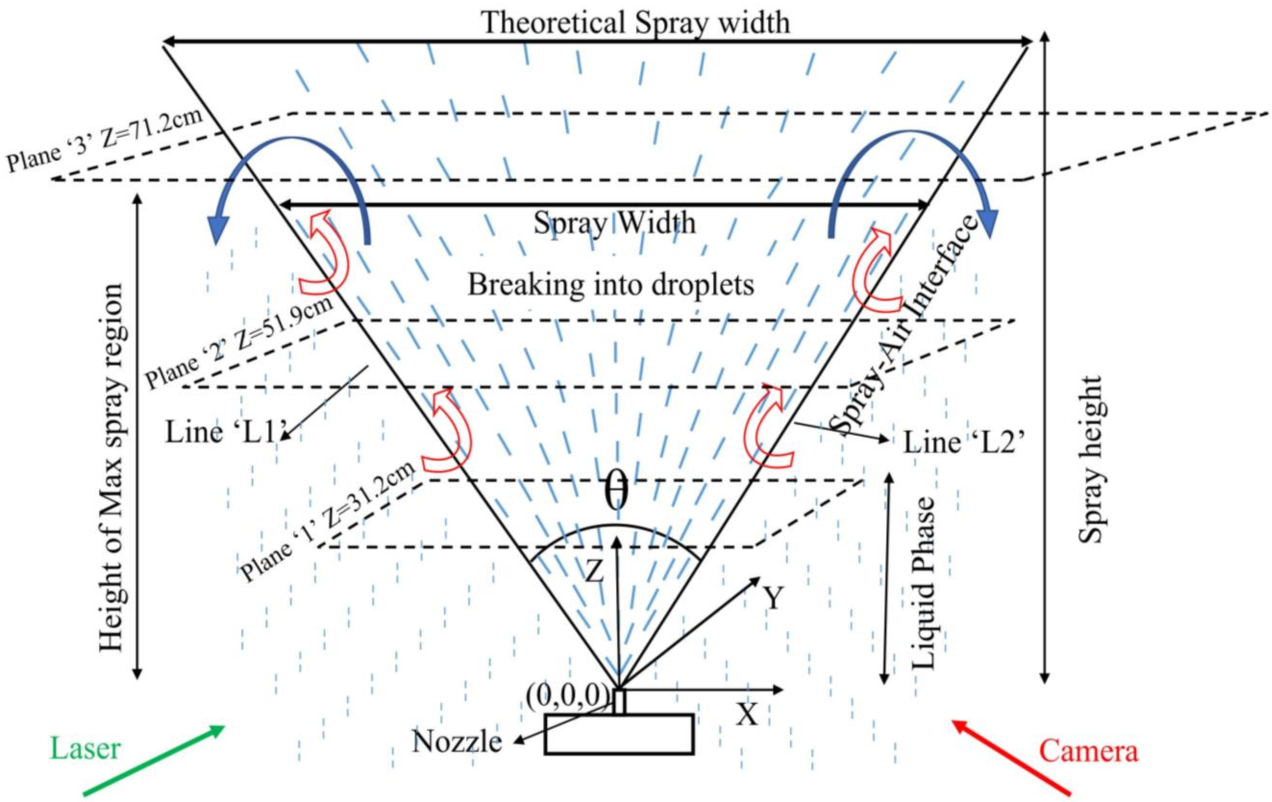


Figure 3 Schematic of the experiment setup

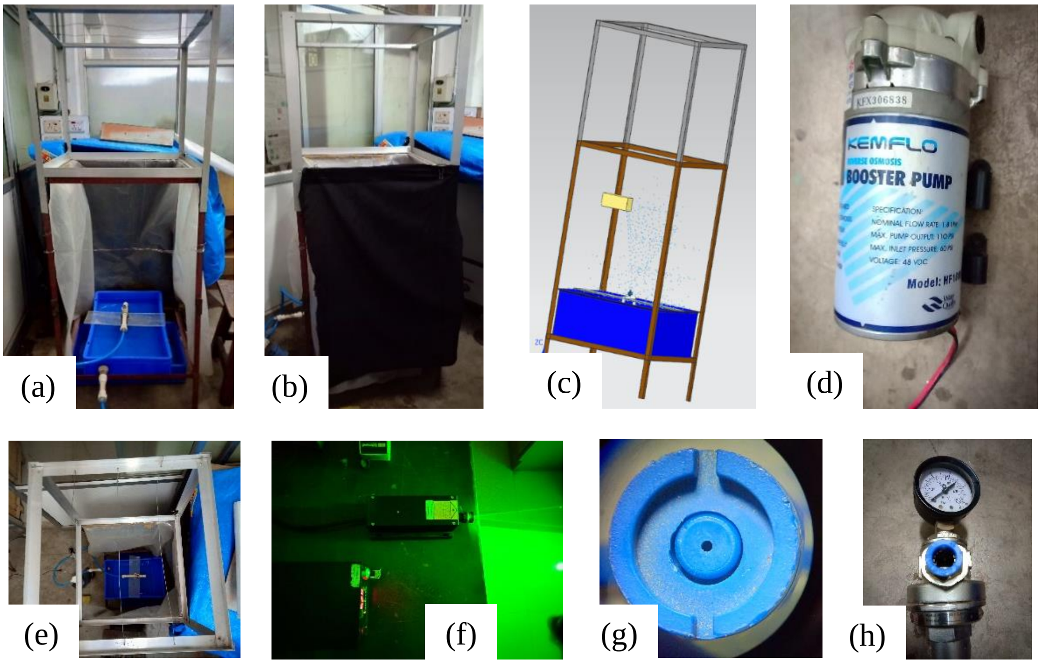


Figure 4 Components in the experimental study of the investigation on spray characteristics in relation to its application to aeroponic agriculture.

Working

Initially, the water is stored in the tub. A PU pipe, (high-grade polyurethane thermoplastic polymer) is connected to the tub, which is connected to the RO booster pump; this was used to increase water pressure. Booster pump was connected to pressure reducing valve which is normally an open, 2-way valve that allows fluid to flow through it at desired velocity and flow rates. Finally, a PU pipe was connected to a horizontal water pipe on which the nozzle was fixed. The entire assembly of the nozzle and horizontal water pipe was fixed to an acrylic plate in order to arrest its motion in running conditions. The acrylic plate was fixed to the water tub and a high friction rubber pad was put in between; this rubber pad nullifies all the vibrations occurring in the spray process.

Image Processing

To capture videos and images clearly, we used a combination of a high-power laser (Continuous type laser, 532nm Wavelength, 6.28A Current supplied and Power of 1Watt) and sheet optics at different sections of the spray jet. Precautions were taken to maintain the orthogonality during the image (or video) capturing process. Photographs and (slow-motion) videos were taken through a high-speed camera for all the inlet pressures in the present investigation. The films were converted into frames for the purpose of image processing using MATLAB. Eventually, the image processing yielded many spray characteristics such as spray height, width, angle, and droplet sizes.

Droplet-Droplet surface interaction – A theoretical picture

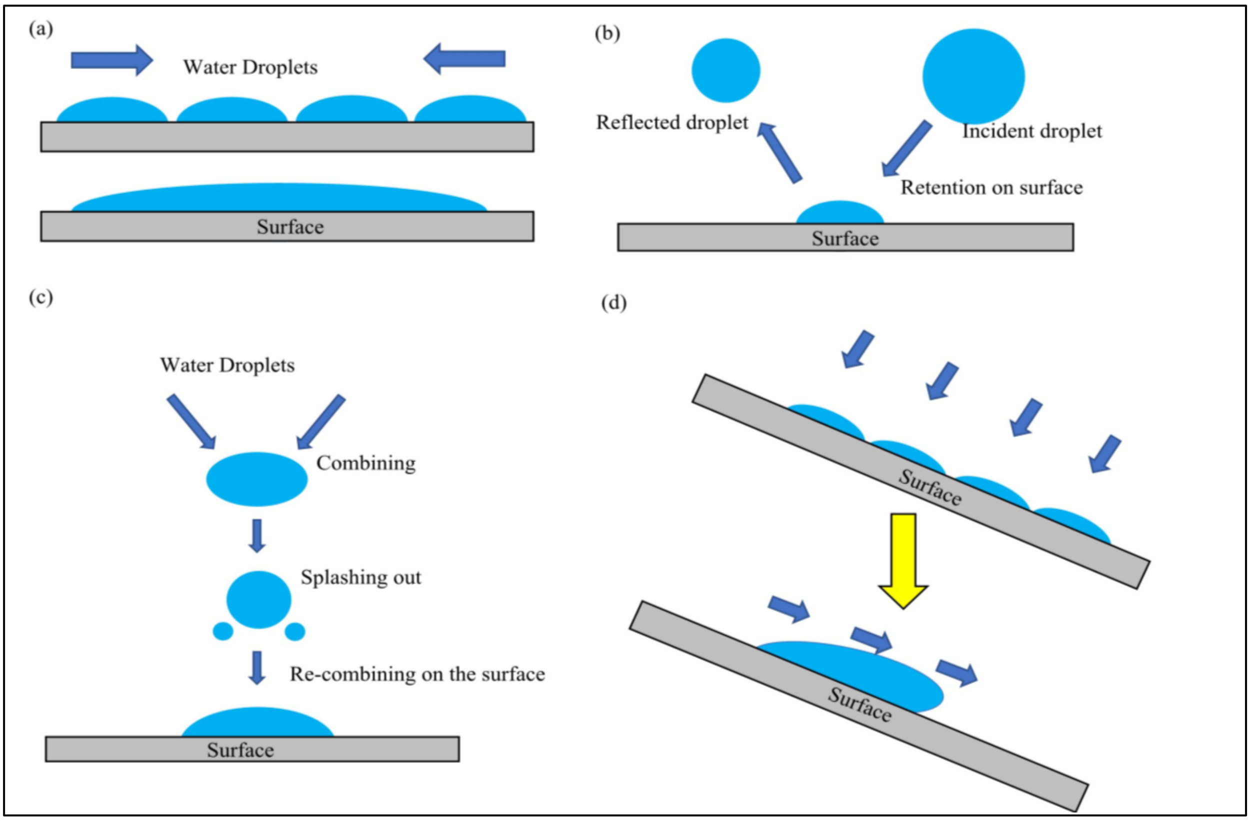


Figure 5 Different types of possible interactions between the droplets and the impacting surface.

For the horizontal surfaces, droplet-droplet and droplet-surface interactions can only be of three types (see Figure 5a-c); these are

1. film formation on a surface (like horizontal, vertical, inclined, rough, etc.),
2. bouncing-off of droplets from the surface, and
3. the collision between two or more droplets followed by the formation of a liquid film on a surface.

For the inclined surfaces, Droplet-Droplet surface interaction is by dripping of film exhibiting viscous nature (Figure 5d). In the case of actual root surfaces, any combination of the above-mentioned process may occur.

These interactions are of very high significance in delineating the physical mechanism/process of water absorption by plant roots in real conditions such as in aeroponics. Theoretically, this type of study is also of some relevance to print industries and in modelling or predicting cloud formation and rainfall/raindrops growth.

Results

Spray Height

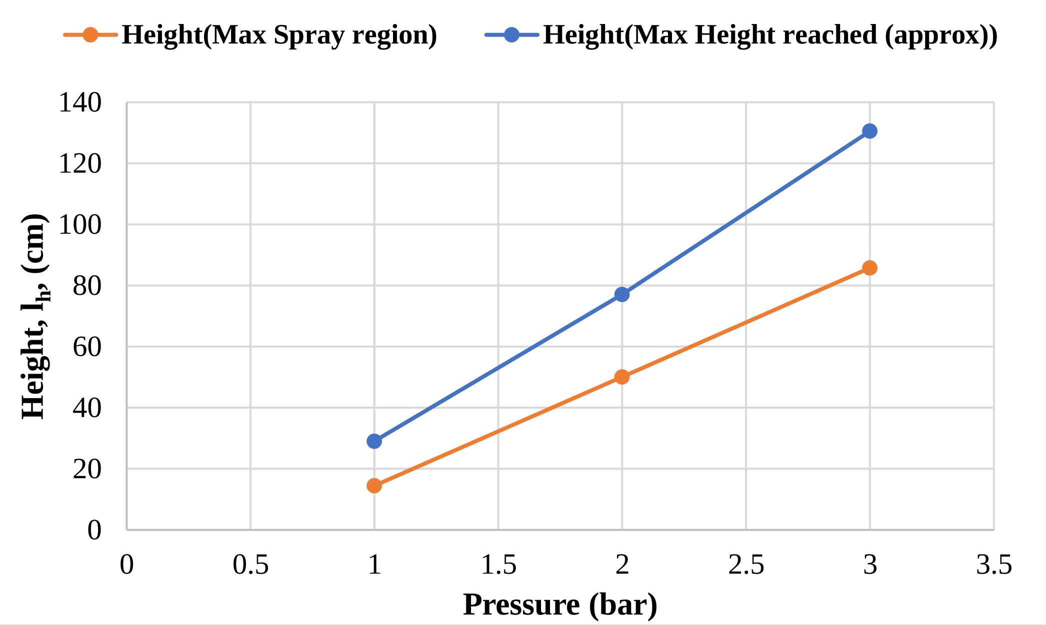


Figure 6 A plot of pressure versus two different heights – spray height and height of maximum spray. Spray height is more at all the pressures. The ratio of the two heights remains nearly the same viz. 0.62.

We identified two different heights of a spray. One is "Spray height", which is the distance between the nozzle orifice and the maximum distance travelled by jet (after this distance, the droplets were not seen). Other is "Height of the maximum spray region", which is the distance between the nozzle orifice and the region of maximum spray (here most of the droplets were observed). Figure 6 shows the variations of these two heights as the inlet pressure was changed. The maximum spray height and maximum spray region attained vary nearly linearly with the pressure. Two conclusions can be drawn from this figure – (a) spray height is more at all the pressure values and (b) the maximum spray region was covered within (50-65) % of the spray height. This is an interesting and non-intuitive result when the nozzle was kept vertical; in this case, the gravitational forces play an important role in the spray dynamics and droplet size distribution. This parameter may help in deciding the optimum distance between the plant roots (absorb water) and the nozzle.

Spray Width

Another important spray characteristic is "Spray width", which has been defined as the lateral span of the spray at the maximum spray location. In other words, spray width can also be defined as the maximum coverage of the spray. This parameter has been obtained by image processing. In short, first, we identified the maximum spray region and then mark the two extremes ($\{x_1, y_1\}$ and $\{x_2, y_2\}$) in MATLAB. Note that these two points lie nearly on a horizontal line (since the spray is exactly vertical and opposite to the gravity). The distance formulae gives the spray width as,

$$l_w = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (1)$$

Figure 7 shows the variation of the spray width at different nozzle inlet pressures. The actual spray width will be always lesser than the theoretical spray width for different pressures (Figure 3). Therefore, if the plant is placed at a greater height, higher pressure will be needed. On the supporting hand, when the roots of the plant are nearer to the nozzle, lower pressure would be sufficient for the roots. However, the number of plants in this case will be compromised.

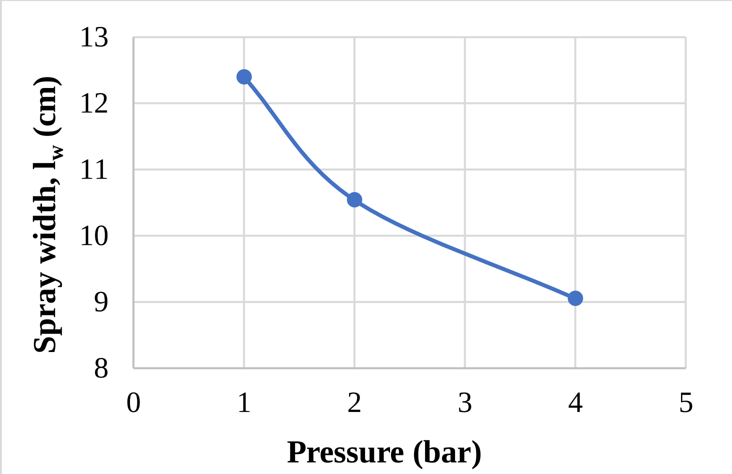


Figure 7 Variation of the calculated spray width with the nozzle inlet pressure. Spray width decreases drastically at higher pressures.

Spray angle

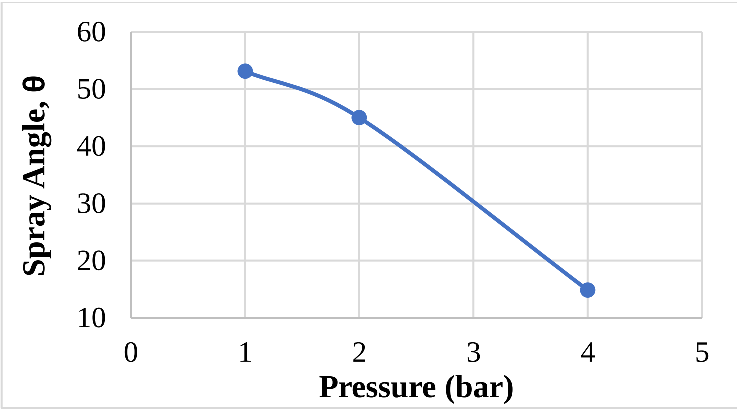


Figure 8 Variation in spray angle at different inlet pressures in the experiments.

Variation of spray height and spray width gives variation in “Spray angle”, this refers to the angle at which the sprayed fluid fans out from the spray nozzle. Sprays, in general, fans out after exiting the nozzle. This happens due to two reasons (a) atomization (droplets production) and (b) air entertainment. In principle, spray behaves like a ‘jet’ but with a multiphase system. Spray angle seems to be a characteristic property of the pressure of the working fluid (water). Spray angle is obtained by getting a co-ordinate at multiple points over the Spray-Air interfaces L_1 (slope m_1) and L_2 (slope m_2) as represented in Figure 3. The slopes of these lines give the spray angle, calculated as,

$$\text{Angle between two straight lines} = \theta = \tan^{-1}\left(\frac{m_1 - m_2}{1 + m_1 m_2}\right) \qquad (2)$$

An increase in the spray angle against pressure is exponential (Figure 8). A combination of actual spray width and spray angle gives the working area/volume for a plant root. This can be further extended to obtain optimum spacing between plants in both directions.

Mass flow rate

The mass flow rate is the amount of working fluid per unit time from the nozzle exit. It is measured in ‘g/min’. The mass flow rate of the system was measured by the method of weighing. This was done by comparing the weights of an empty beaker with that of a beaker filled with water after for a stipulated time period (in this case 120s). This was repeated for several trials and the mean of the quantity of water collected was plotted for varied pressure

(Figure 9). It is also been verified theoretically by the *Hagen–Poiseuille* equation. The mass flow rate increases linearly with the increase in pressure inlet value of the nozzle.

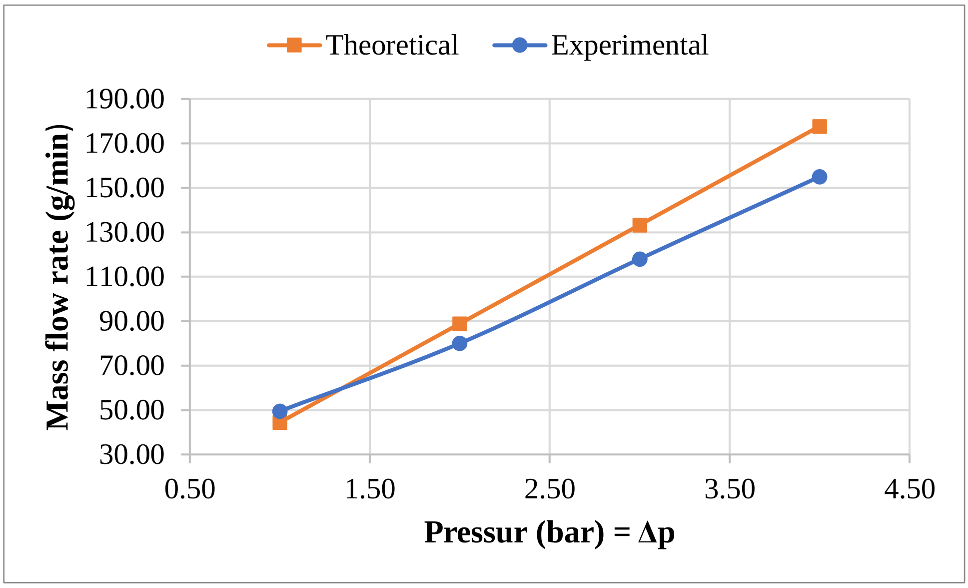


Figure 9 Variation of mass flow rate against nozzle inlet pressure. (Pressure ∝ Mass flow rate).

Discussion

Water droplet interaction with a plant root.

A real scenario is to study spray-root interaction. A careful study could be to characterize water absorption by counting "impacting water droplets" and "falling water drops" which is very much useful in the estimate of "*Plant Water Uptake*" (amount of water used by the actual plants). This interaction is very complex as it involves many uncertainties between droplets like (i)merging of droplets (ii)may bounce or any combination of this two and among rootlets and droplets, (Figure 10) (iii) may stick (iv) may bounce (due to electrostatic potential or its own weight or saturated water holding capacity of the root) which can be observed in Video-S1. The application of this study is majorly in spray technology (spray paints and electrostatic coating) which finds its applications in the field of Automobile sectors.

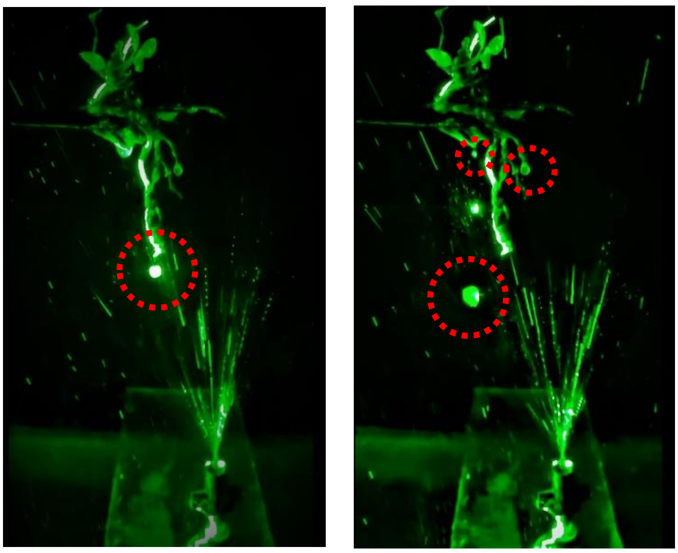


Figure 10 Combination of Droplet-Droplet-Root interaction in spray cone. Accumulation followed by falling-off of a water drop, circled in a dashed red ring, is also shown.

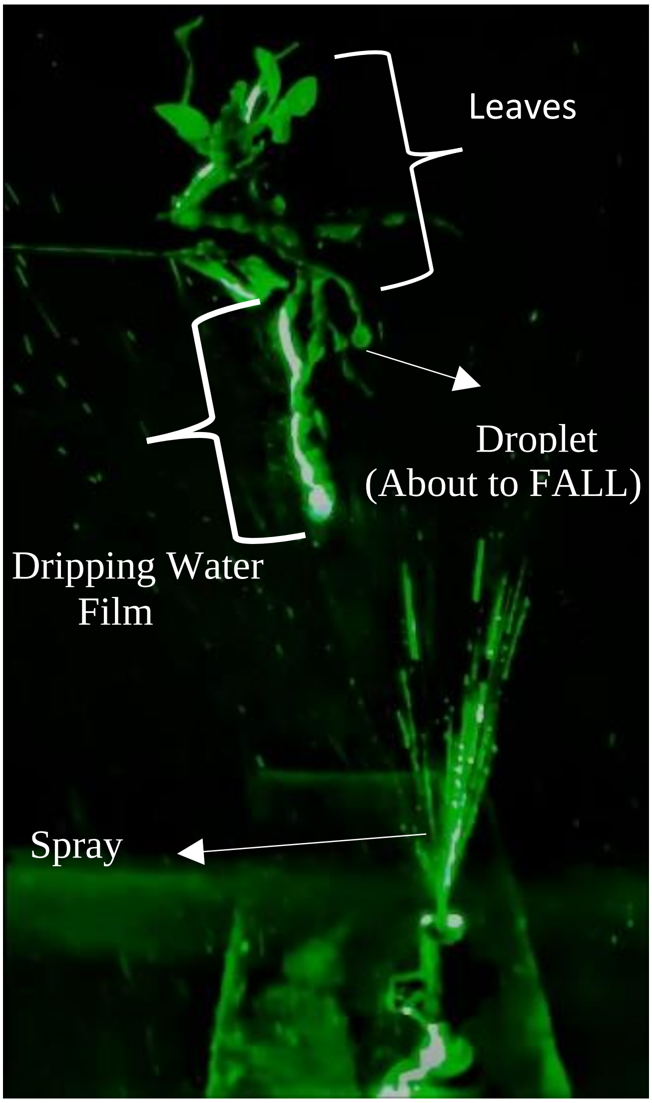


Figure 11 Film formation on a root in the aeroponic system.

A Video-S1 (duration 10 seconds) was captured to show the interaction of water droplets on the roots. At 1 second, we observed the formation of a water film around the root; we also observed the dripping of this water film (primarily driven by gravity) at ~2 seconds. Due to this, at 4 seconds, we observed a series of droplets falling from the root. Further, we observed the interaction of the water droplet dripping from the roots to that of the droplet emerging from the nozzle at the 5th second. Film formation on an adsorbent (such as roots) occurs due to a large number of interactions between droplets (Figure 5a). For this to happen a stable film has to be formed (Figure 11) which helps in a continuous supply of water to the roots.

Water droplet interaction with a glass surface.

In the previous section, we observed that roots-droplet interaction is highly complicated. One of the complexities was due to the geometry (local curvature + length scale) of the roots. A smarter study could be to observe the interaction between spray water with a flat large plate. Even better would be to use a plate with a high affinity to water. Mainly droplet size was affected by pressure, spray pattern, spray angle, nozzle type, the specific gravity of fluid, viscosity, air entertainment, and surface tension.

In view of the above argument, we conducted experiments focused on studying the impact behaviour of the spray width with a flat smooth glass plate. One side of the glass plate received spray while the other side was pasted with a graph sheet. The transparency of glass ensured the measurements of the collected/adhered droplets/drops under a microscope (Figure 12).

The time of impact is a crucial parameter in this study. Notice (Video-S2) that if the plate is placed for a long duration, then a continuous film forms. Similar to the observations in the root case, here also the film ends at the plate edge and finally, falling drops were observed. It is obvious that long-time duration does not indicate the true droplet size striking the plate. Hence, it is crucial that the plate should be placed in the spray for a short time duration (not more than 5 seconds).

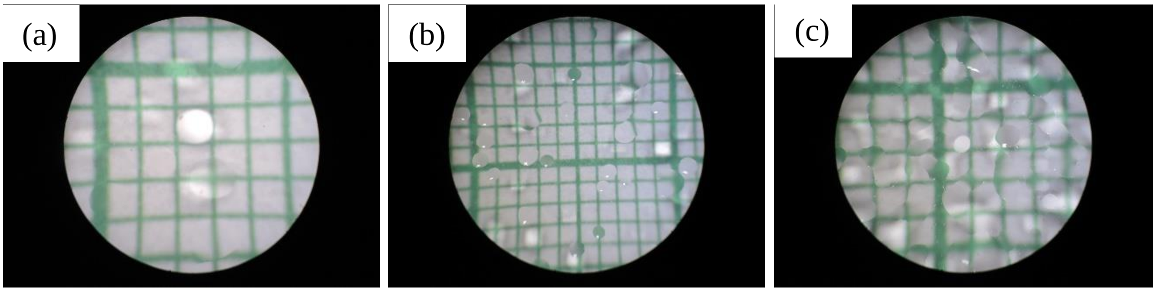


Figure 12 Droplet sizes at different pressures. (a) 2bar (b) 3bar (c) 4 bar.

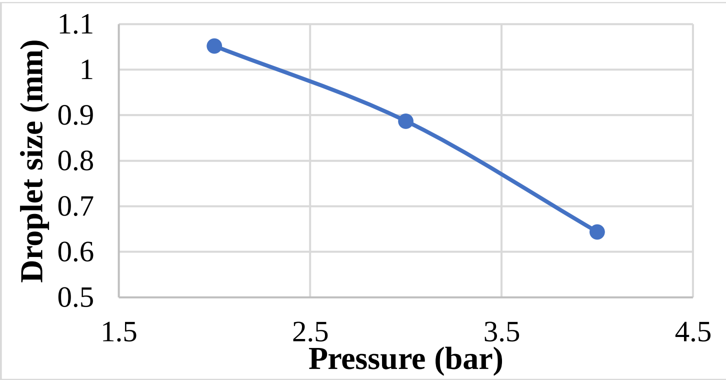


Figure 13 A plot of analysis on droplet size(diameter) over different nozzle inlet pressure.

This important characteristic would help in studying the effect of root geometry. Sticking of droplets seems to be stronger when they are less in size. In our view, a water film is unnecessary/waste of water and nutrients. Ideally, the droplets should not merge and form film(s). As the droplet merges weight of the drop increases due to which they start detaching from the roots due to gravity. However, thin film aids in the continuous supply of water to the roots. As observed in the plot (Figure 13), it is clear that as the pressure increases the film formation decreases (almost linear) due to the atomization.

Sponge experiment to determine the amount of water absorption

As an extreme case of water-retaining features of a porous medium and its coupling with the roots, here, we quantify the amount of water trapped in a simple sponge. The dimension of the sponge was $96 \times 151 \times 66\ mm^3$ and its weight was ~6 grams. Its density, thus, was $0.00627\ \frac{g}{cm^3}$. In this experiment, we had placed the sponge in such a way that the larger dimensions of the sponge take part in the droplet-sponge interaction. Note that, these dimensions are extremely large compared to the plant roots.

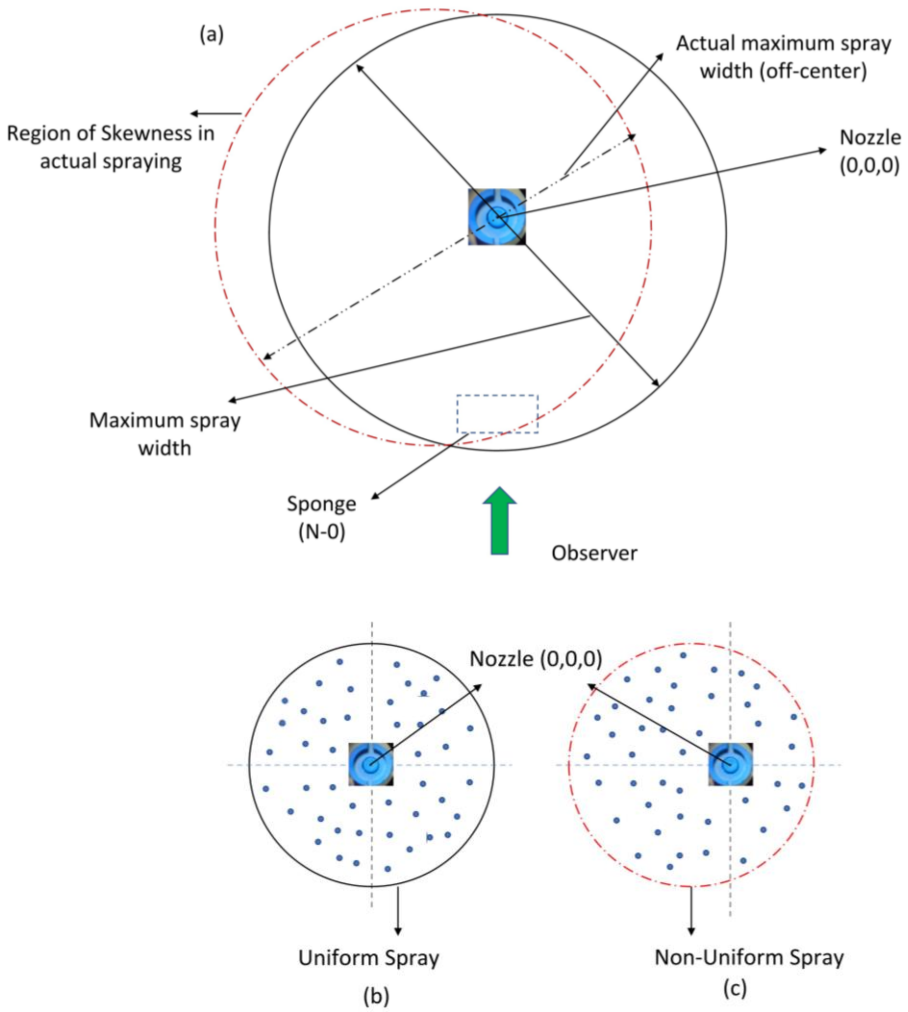


Figure 14 (a) Aerial (top) view of the spray showing both ideal and asymmetric (dotted) cases at the maximum spray width. (b) Ideal droplet distribution and (c) asymmetric droplet distribution showing skewness.

During the experimentation, we observed the non-symmetric nature of the spray ejecting out of the nozzle about the Z-axis (Figure 14). We fixed the sponge and rotated the nozzle in order to quantify the amount of water trapped in a given plane and at multiple points. For this, 8 different points (Figure 16) on 3 different planes (Figure 3) (a total of 24 locations) were selected.

Initially, a steel wire is twined at a required height (planes) to the L-angles support (Figure 4c) of the aeroponic chamber. The wires allowed the placement of a light acrylic plate onto which the sponge was fastened. Note that the reference point (origin) is the tip of the nozzle (Figure 3). During the experiment, the sponge retained some amount of water and reached a saturation state.

The amount of water trapped/retained in the sponge with time is discussed next. The water retained in the sponge was measured using a digital weighing scale whose least count was 1g. The measurement was taken every 10-20 seconds.

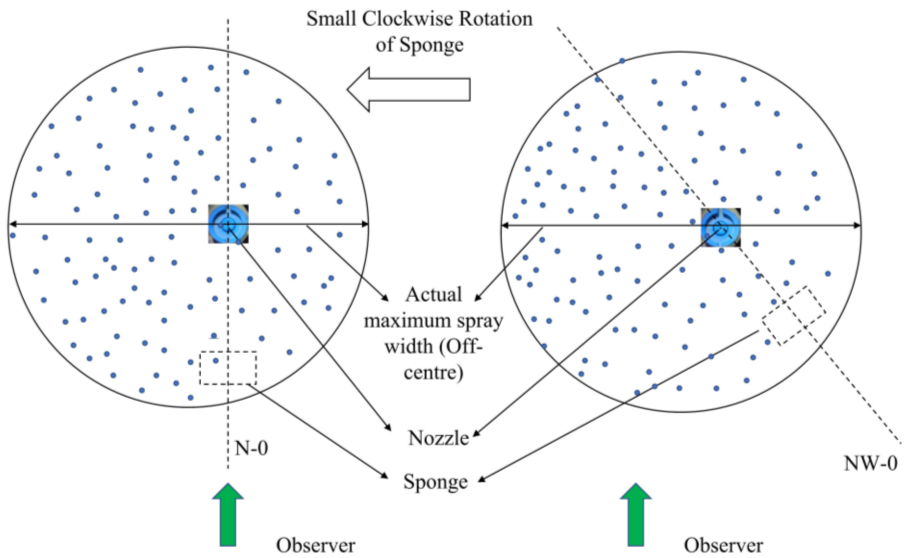


Figure 15 Orientation of the sponge in the spray cone

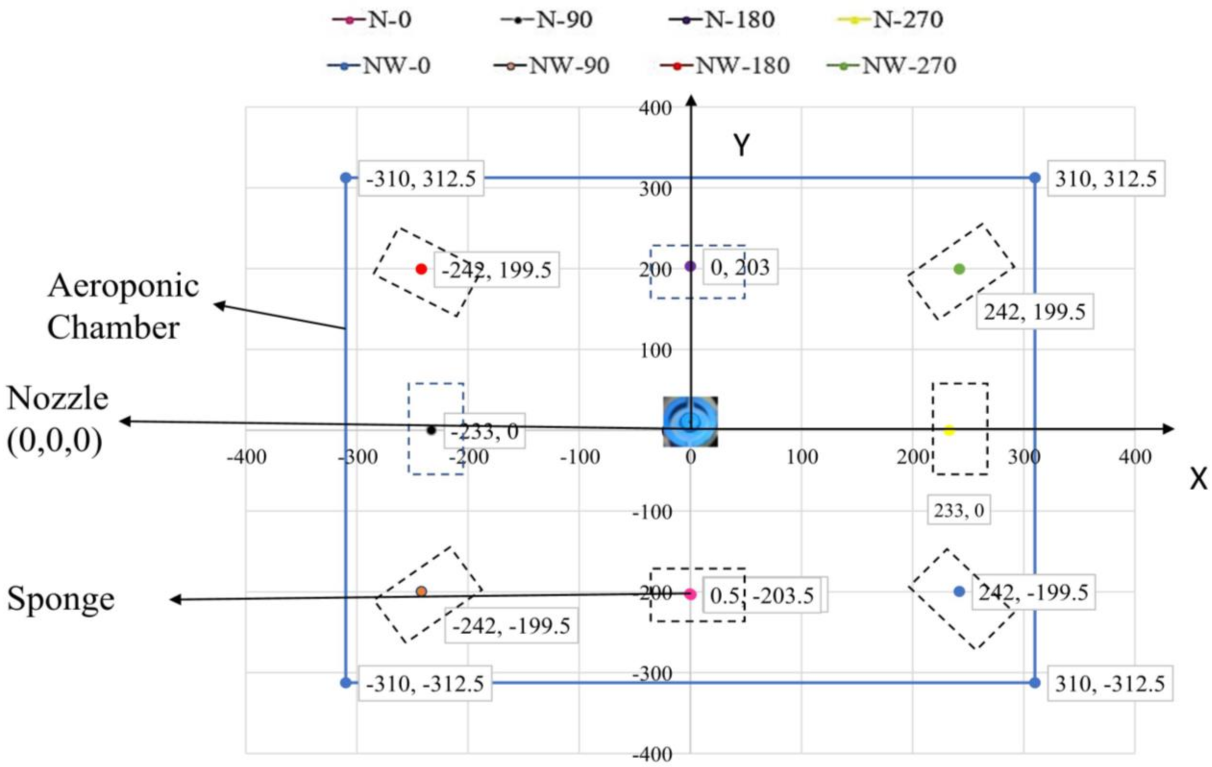


Figure 16 Experimental co-ordinates of the sponge at three different planes.

The smarter way to characterize the effect of the angular locations is to fix both the observer and the sponge and rotate the nozzle. The fixative position for sponge was an edge (N-0) and a corner (NW-0) (Figure 15). The nozzle was rotated in the step of 90° and covers various locations (N-90, N-180, N-270, NW-90, NW-180, NW-270).

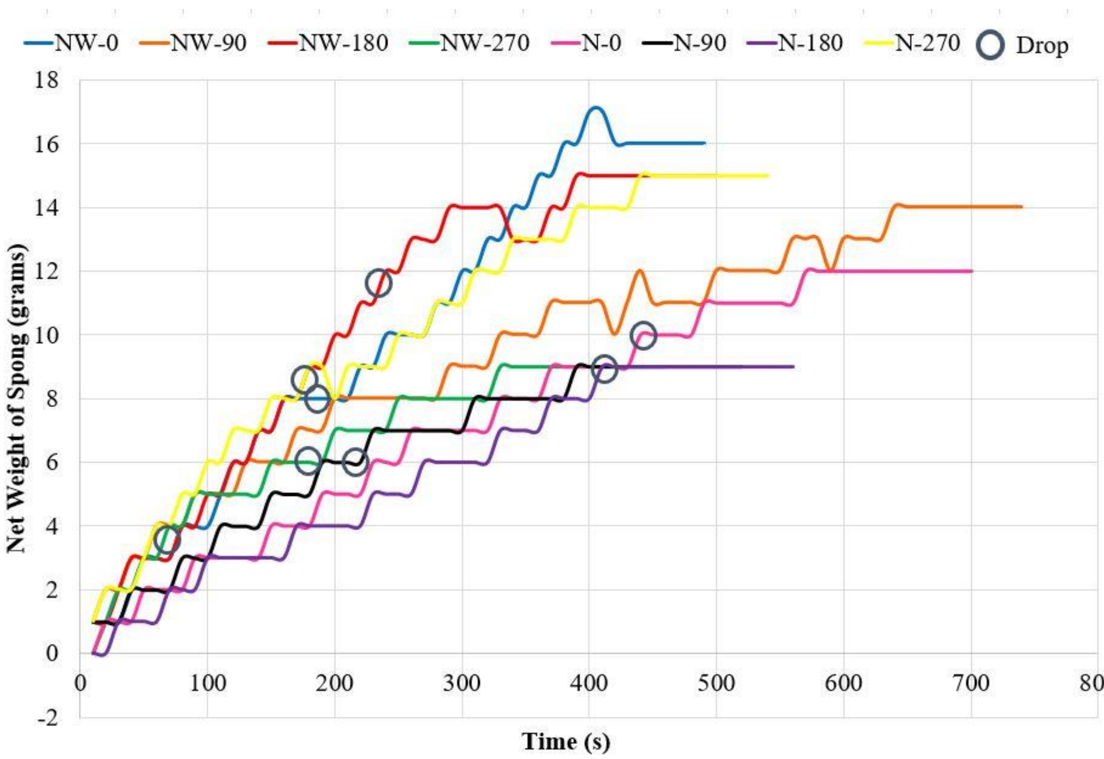


Figure 17 Variation with time of the amount of water retained by the sponge at 8 locations in plane 1 (z=31.2cm). The markers (Circular) indicate water dripping from the sponge.

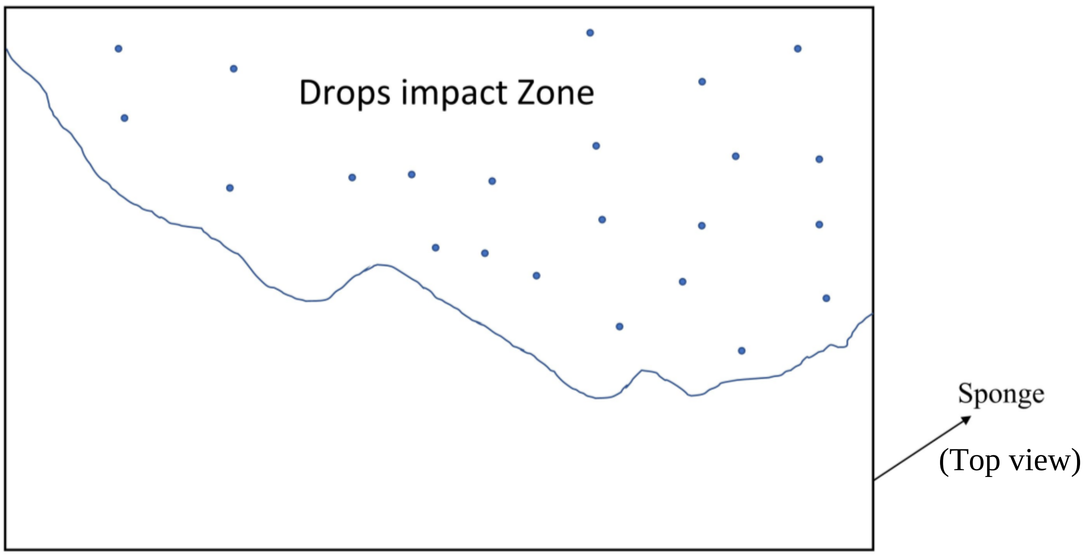


Figure 18 Schematic representation of the droplet impact region on the sponge at a given location.

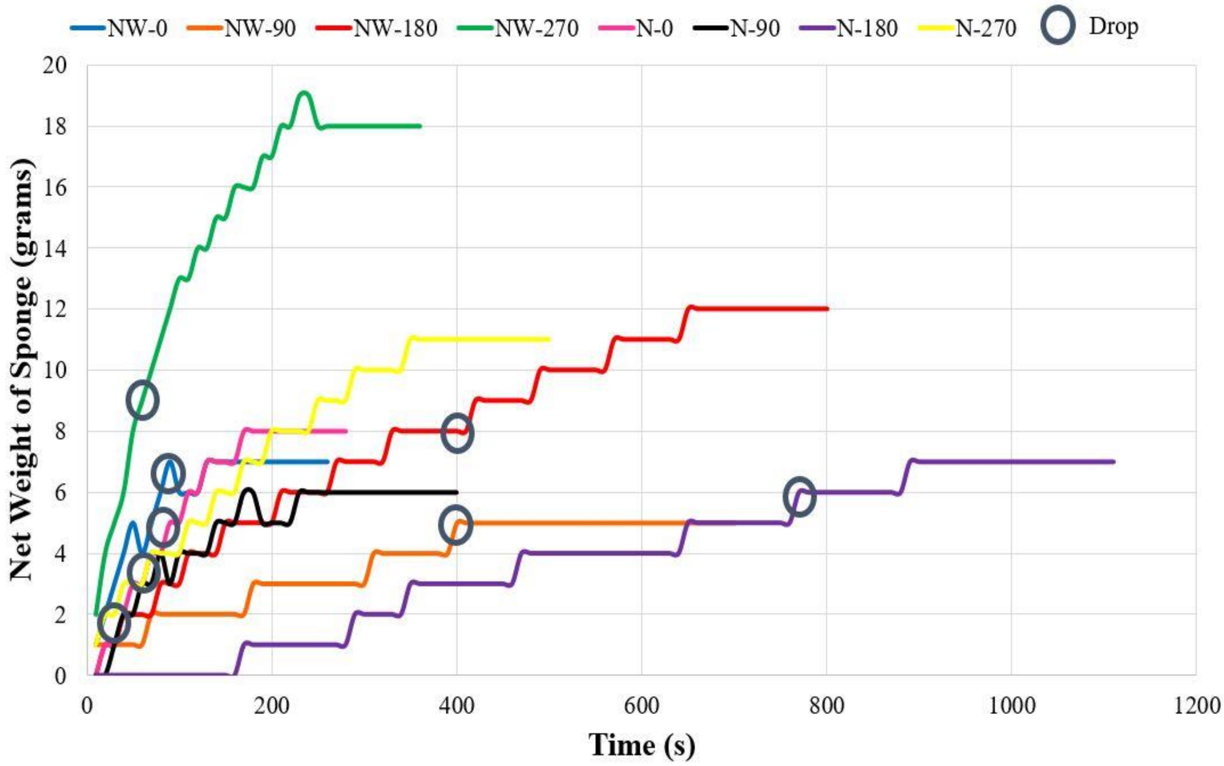


Figure 19 Variation with time of the amount of water retained by the sponge at 8 locations in plane 2 (z=51.9cm). The markers (Circular) indicate water dripping from the sponge.

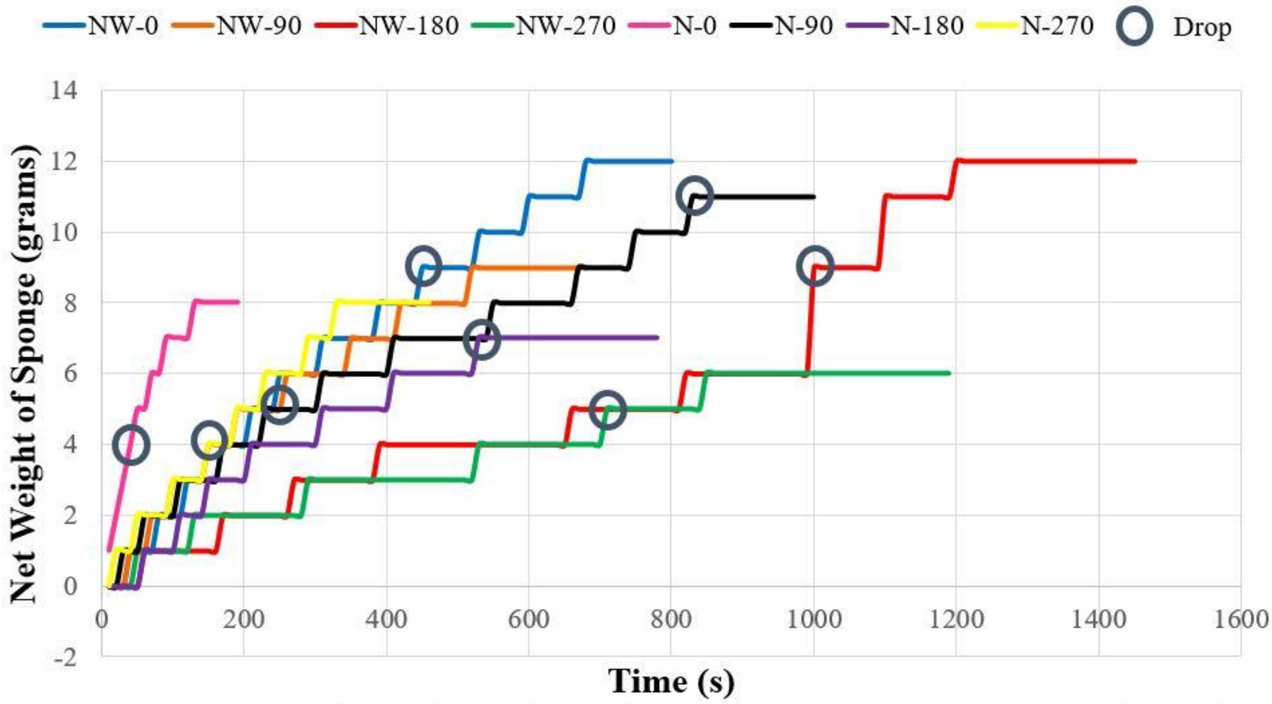


Figure 20 Variation with time of the amount of water retained by the sponge at 8 locations in plane 3 (z=71.2cm). The markers (Circular) indicate water dripping from the sponge.

From the above plots (Figure 17, Figure 19 and Figure 20), we can infer that the nozzle selected is not axis-symmetric (Z-axis) in terms of spray cone. The amount of water trapped in a sponge varies per unit time across different planes. In the same plane, if the spray was axis-symmetric about the z-axis then the locus of all the position equidistant from the x-axis would have received the same amount of water and would reach the steady state in the same time. From plots (Figure 17, Figure 19 and Figure 20), we can conclude that the tilt of spray cone plays an important role in deciding the various parameters like height and tilt itself. The higher amount of water trapped at a chosen location depends entirely on the impact area (Figure 18) of the drops on the sponge and mass flow rate. The mass flow rate was kept constant throughout the experiment (2 bar pressure). During the experiment with the sponge, we observed dripping of water from the sponge, primarily from one of its vertices. This dripping must have been accompanied by water film(s) forming in the sponge matrix. Smaller droplets combine to form larger droplets and eventually drops. These drops combine to form the film. This film is primarily driven by the gravity (‘g’) as the pore sizes are small (weak capillary forces). Further, as the altitude increases, the amount of water trapped in the sponge is seen decreasing. This must have happened due to the loss in the impact area compared to the cases with lower altitudes. Hence, at the highest point, time taken to saturate in the sponge is higher compared to that of lower altitudes. These results would help in determining the root-nozzle-drop-height relation.

Porosity of sponge

Porosity is defined as the ratio of the volume of the pores to the total volume of the porous material and it is generally expressed as either a percentage or a decimal. Few ways of finding porosity of sponge are discussed below,

Theoretical Method

The mean porosity of a particular volume (chosen manually) of sponge ($96 \times 151 \times 66\,mm$) was obtained using image processing (Figure 21a). First, the sponge solid material (strands) was identified in the chosen region of the image. This region is seen as a polygon, whose area can be estimated by,

$$= \left| \frac{(x_1y_2 - y_1x_2) + (x_2y_3 - y_2x_3) + (x_3y_4 - y_3x_4\,) + \;\dots\dots + (x_ny_1 - y_nx_1)}{2} \right| \tag{3}$$

Upon substituting n=4, we get

$$\text{Area} = \left| \frac{(x_1y_2 - y_1x_2) + (x_2y_3 - y_2x_3) + (x_3y_4 - y_3x_4) + (x_4y_1 - y_4x_1)}{2} \right| \tag{4}$$

Note that these polygons have been marked as pink colour in Figure 21a. Similarly, the other polygons were also marked. The packing fraction was estimated as the ratio of the sum of the solid areas to the selected region. This gave a mean value of porosity as ~**85.6%.**

Experimental Method

A sponge soaked in deionized water saturated with water for an entire day (Figure 21b). On the next day, the excess water drained. The difference in the weights of the measured completely wet and fully dry sponge is indicative of the overall porosity. By experimentation, the porosity of the sponge was calculated using the formula,

$$\text{Porosity} = \frac{\text{Volume of water absorbed by sponge in 1 day}}{\text{The total volume of the sponge}} \tag{5}$$

$$= \frac{\text{Mass of fully wet sponge} - \text{Mass of fully dry sponge}}{\text{The density of Water} \;\times\; \text{Total volume of sponge}}$$

$$= \frac{741 - 6}{1 \times \; 878.336} \sim \mathbf{0.837}$$

The two completely different methods yielded nearly the same overall porosity. However, method 2 is recommended for practical purposes.

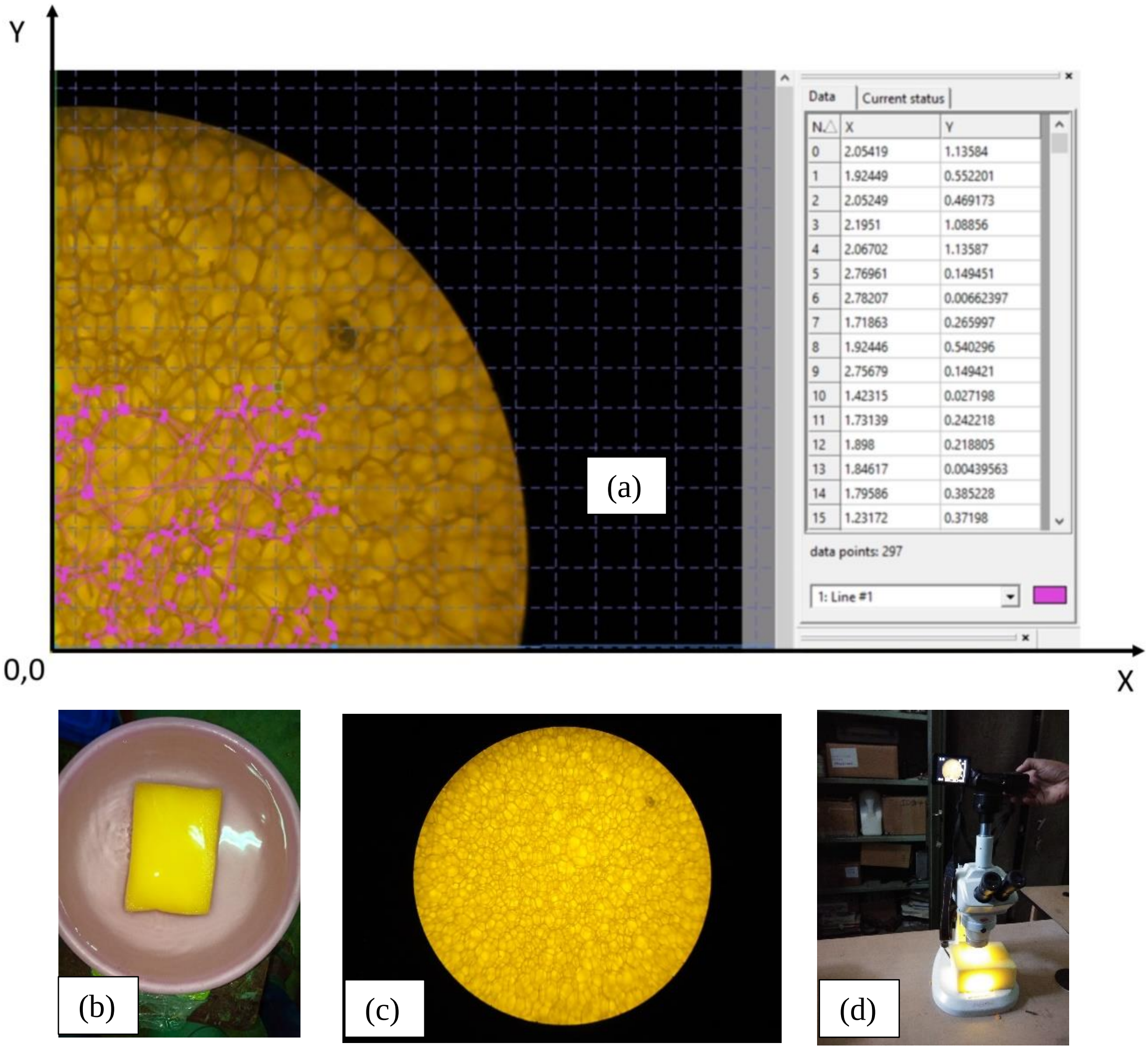


Figure 21 Experimental and Theoretical determination of porosity of sponge.

Visualization of droplet impact on coffee filter paper:

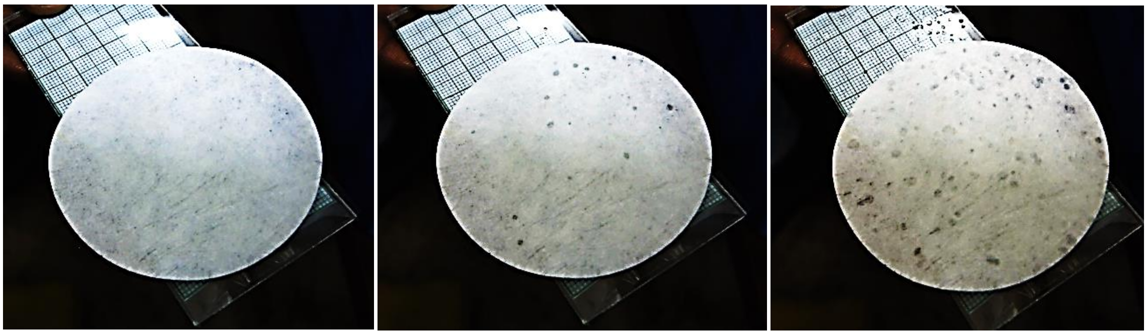
Even simpler than complicated 3-D sponge – droplet (drop) interaction, we used a 2-D flat and thin highly hydrophilic material – a coffee filter paper – to further understand the interaction between solid porous surfaces and water droplets. The filter paper was visualized under an optical microscope (Figure 21c) whose cylindrical strands like features were seen. The geometric length scale of the strands seems to be of the order of tens of microns. The dimension of circular coffee filter paper was ø63mm and its dry weight was 0.16293g. The thickness of the filter was 0.14±0.01mm (measured using a digital Vernier). Its average volumetric porosity was ~63%.

The filter paper was made to rest on a floating-type plate and the experiments were conducted by setting the desired pressure and placing the filter paper at desired locations (desired height and minimum droplet visibility region). This was done to avoid immediate wetting. A few major observations in this case are,

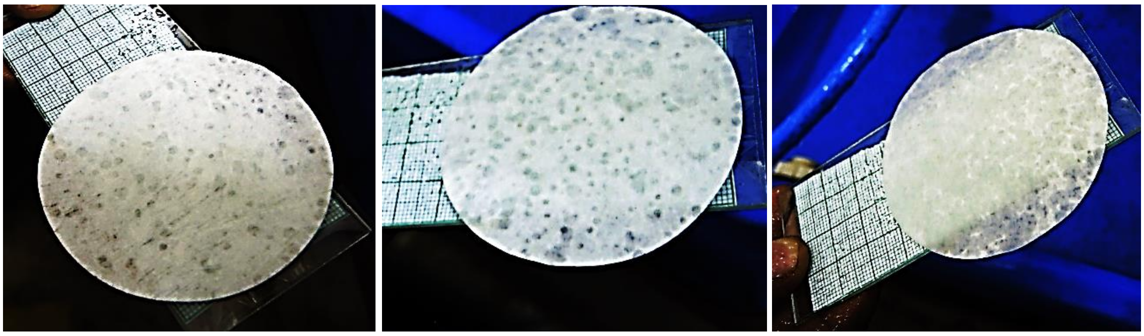
(a) Droplets impacting the filter paper were absorbed almost immediately.
(b) This absorption was observed as the quick spreading of water droplets on the filter paper. This point-sized water spreading is seen as black dots in Figure 22.
(c) With time, increase in the number of these black dots was seen.
(d) Eventually, the filter paper was completely wet.
(e) Once the filter paper was completely wet, it was removed and the time was noted.

(f) We didn't observe any significant bounce-off of the droplets; this may be due to the high hydrophilic nature of the filter paper.

For visual purposes, a video of the droplet and the filter paper interactions has been shown in the supplementary information.



(a) t = 0.00 s (b) t = 1.933 s (c) t = 4.566 s



(d) t = 8.833 s (e) t = 10.733 s (f) t = 14.533 s

Figure 22 Spray spread distribution at a point is observed on filter paper over time.

Conclusions

The ideology behind the experimentation is to characterize the nozzle and find the optimal positioning and array of effective distribution of the plantation in aeroponic to maximize the yield and to distribute the irrigation and nutrition to plants. The visualization is carried using a standard nozzle and few roots-like materials (Filter paper - 2D/Surface spreading Visualization and sponge - 3D/Bulk raise absorption visualization). Spray height linearly depends on the inlet pressure of the nozzle. The ratio between spray height and inlet pressure is constant. Spray width drastically reduces with a gradual increase in the inlet pressure. Spray angle increased non-linearly with pressure and the actual spray-width of this nozzle (actual span of the spray) is lesser than the expected (or theoretical) span width.

Interactions between the droplets, coming out of the nozzle, and different surfaces were experimentally observed in order to understand the behaviour of the plant roots in Aeroponic systems. For this purpose, real roots and some other root-like porous materials were used. The experimental observations clearly showed highly complicated interactions. The droplets impact the roots (and its other parts) and form a liquid film; this film led to continuous dripping of large drops at the root edges. However, the formation of a film may be required for the continuous supply of water and the nutrients in Aeroponic systems.

This type of interaction was also seen in the simplistic porous sponges and 2-D porous (coffee) filter paper. Dripping of drops was also seen in the case of the sponges. However, in the filter paper cases, we observed unique features. One, the droplets were absorbed almost immediately by the paper probably due to low pore sizes (high surface tension) and better affinity towards the water droplets (hydrophilicity). With time, the filter paper was completely soaked with water; a phenomenon not seen with the 3-D sponges and (probably) roots as well. Different types of droplet-surface interactions were therefore studied in order to understand root-drop coupling, a feature important in Aeroponic systems. We expect this fundamental study to be useful in an aeroponic system, a new type of trend in Urban and precision agriculture.

Conflict of Interest

The authors have no conflict of interest relevant to this article.

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