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# Design of a Water-Efficient Sand-Based Hydroponic System Through Capillary Fluid Dynamics

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## ABSTRACT

As the world progresses into the 21st century, water scarcity necessitates innovative water conservation and sustainable approaches to agriculture. This paper presents a novel sand-based hydroponic system that leverages capillary action to enhance watering and water retention efficiency, offering a cost-effective and water-efficient solution for sustainable plant growth. To study the physical characteristics (particle size distribution, capillarity, pore radius, uniformity coefficient, water retention) of the growth medium, a comprehensive particle study of three samples was conducted. Subsequently, a practical trial was employed to validate the proposed approach, which demonstrated promising results for large-scale adoption and use. Furthermore, the study explores potential extensions of the system, including the addition of essential nutrients to the water and investigating alternative set-ups for enhanced versatility and efficiency. By combining theoretical scientific analysis and practical experimentation, this research contributes to the advancement of sustainable agricultural and gardening practices and offers a viable path to mitigate water scarcity and food insecurity challenges.

## Introduction

Agriculture is, and has always been, the cornerstone of society. Contributing to billions of lives through food production, to livelihoods through employment generation, and even to global commerce through its significance in trade, agriculture is an important industry. However, plant growth and agriculture are both major causes and casualties of water scarcity (FAO 2019). Currently, at a global scale, agriculture consumes a substantial 70% of the world's freshwater resources (World Bank 2022).

In India, a country ranking 2nd in overall global farm output, (Dhawan 2017), 80% of water consumption contributes towards agriculture (Sandip Sen 2015). This large figure results from water management systems with inadequate policies, institutional under-performance, and financing limitations (World Bank, 2022). Scarcity of water, an overuse of fertilisers, and groundwater pollution has rendered the agricultural system inadequate to cater to the needs of a rapidly growing population. Agriculture, however, remains the backbone of the Indian economy. In 2021-22, agriculture accounted for 19.0% of GDP (Ministry of Agriculture & Farmers Welfare 2023), with 59% of the workforce employed in the agrarian sector (FAO 2023).

Given the pivotal role of agriculture in India and its substantial water requirements, it is imperative to prioritise the implementation of water-efficient agricultural practices through the development of novel, sustainable techniques. This becomes particularly crucial in the context of the global water scarcity crisis, which arises from a combination of factors, including the expanding global population, inefficient irrigation practices, the impacts of climate change, and excessive extraction and pollution of groundwater. Projections estimate the global population will reach approximately 9.8 billion by 2050 (United Nations 2023), necessitating a nearly 70% increase in food production to meet their demands. Thereby, the adoption of climate-resilient agricultural strategies also becomes increasingly vital, especially in arid and semi-arid regions facing escalating desertification challenges.

This paper proposes a practical solution to address the scarcity of water and soil for cultivation, as well as the wasteful use of water in plant growth, through the conceptualization of a hydroponic system that can be implemented both at the grassroots level with minimum costs, and equipment easily available. The same can be readily scaled up for industrial applications. By introducing a hydroponic system that relies on capillary action, we can promote more sustainable water usage, and enhance food security in water-stressed regions.

This research aims to develop a hydroponic system rooted in principles of particle and fluid mechanics to provide a cost-effective and sustainable approach to plant growth. Within this overarching goal, the study seeks to accomplish the following specific objectives:

1. Investigate capillary action and fluid dynamics to determine the ideal properties of a growth medium.
2. Conduct a comprehensive particle characterization of 3 growth media to identify the most suitable medium.
3. Design and construct a cost-effective hydroponic system engineered to conserve water resources effectively.
4. Perform a small-scale experiment to empirically demonstrate the advantages of the hydroponic system.

## Literature Review

### Hydroponic Systems

Hydroponic systems refer to one where plants are grown in a water-based nutrient solution as opposed to soil. Artificial media such as clay, brick shards, and wood fibre may or may not be used in place of soil (S. Umamaheswari et al. 2016). Also known as controlled environmental agriculture or, simply, indoor farming, a plethora of types of hydroponic systems have been developed for large-scale applications. since they have several advantages (Maucieri et al. 2017). The use of a hydroponic system allows for growth and higher yield, especially in regions where prevailing conditions challenge conventional plant cultivation and farming. Another benefit of the secure indoor growing environment is the protection it provides the plants against harmful pests and microbial diseases, due to the absence of the conventional soil medium. In contrast, traditional agricultural practices lean heavily on the excessive use of herbicides and pesticides, perpetuating concerns regarding their ecological impact and potential harm (Aktar, Sengupta, and Chowdhury 2009).

Large companies across the world, such as ‘Plenty,’ ‘Nutrifresh,’ and ‘App Harvest’ are setting up commercial hydroponically controlled farms and working to expand their services. However they are not extremely popular as of now. According to an IBIS World Business report (2023), the United States of America has 2,290 hydroponic farming businesses, out of the total over 2 million farm businesses in the country (USDA 2018). This reluctance for utilising hydroponic systems stems from the higher initial investment, skilled labour and technology required.

There are myriad options for the set-up of a hydroponic system. A brief overview is provided in this paragraph, with reference to several sources (Mamta D. Sardare 2013), (Arun Maurya et al., 2017), (Gaikwad and Maitra 2020), (Modu, Aliyu, and Mabu 2020). The ‘nutrient film technique’ is a popular hydroponic method, where a stream of water with a fixed flow rate (of usually 1 L $min^{-1}$) recirculates across plant roots. The necessary nutrients for plant growth are added to the water in specific concentrations. This method provides a high yield of high-quality plants or crops. The ‘Deep water culture’ is a similarly common hydroponic technique for achieving optimal plant growth and yield. It refers to the suspension of plant roots in a solution of water with essential nutrients; thereby indicating the absence of a medium other than water for the growth of a plant. This requires careful control of the properties of the water, including the quantity of dissolved nutrients, ions and the pH of the solution. Wick hydroponics is a passive system, which refers to a lack of necessity to utilise electrical or mechanical components like pumps or motors. Here, a connecting wick is attached to the growing medium, which allows the uptake and use of nutrients and minerals. The 'ebb and flow' system, often also referred to as the flood and drains system, is a relatively inexpensive method. Here, the growing area is periodically filled with water through a pump and reservoir; allowing time for draining. The system this paper proposes is a hybrid between 'wick hydroponics' and the 'ebb and flow' system, where in a passive system is used to maintain a periodic supply of water. Here, the primary feature used is capillary action.

An important sphere of hydroponics is that of smaller-scale systems that could be efficiently implemented in locations without much space or resources, and saving water, which is what this research paper aims to explore, through using a variation of the ebb and flow system as a proof of concept. It is essential to use the best growing medium possible with respect to fluid properties within it, as well as taking into account factors affecting plant growth.

## Plant Growth

A fundamental grasp of the prerequisites essential for optimal plant growth is imperative. Primarily, plants require light for photosynthesis, water for maintaining turgidity and transportation in vascular tissue, oxygen for respiration of roots, and a particular temperature that is not extremely hot or cold. Plants also require macronutrients (nitrogen (N), phosphorus (P), and potassium (K)) which play pivotal roles in the functioning of a vascular plant. Additionally, micronutrients such as iron, zinc, and copper become particularly critical in the later developmental stages. Capillary action is also a vital phenomenon that occurs in plants, as the result of cohesive and adhesive forces working within the plant's vascular system. As water evaporates from the tiny pores (stomata) on a leaf's surface, it creates a negative pressure that draws water molecules from the soil through the roots and up the plant's stem. Different stages of plant growth have differing levels of moisture requirements, and the same varies across plants. A generalised trend is moist conditions during germination, with a gradually increasing water requirement until the vegetative growth or flowering stage, after which the requirement decreases again.

## Water Properties

It is essential to underline some important physio-chemical properties of water to analyse its flow and movement. The surface tension of water is 0.072 $Nm^{-1}$ at 27 ºC, the kinematic viscosity of water is 0.0009 Pa s at 27 ºC, and the density of water is 997 kg $m^{-3}$ at 27 ºC. Water values are based on a temperature of 27ºC in consideration of the prevailing conditions at the experimental site. Furthermore, the polarity of water molecules coupled with its ability to form hydrogen bonds makes it an especially optimal solvent for ions and other small organic molecules. Thus, important plant nutrients can be dissolved in the same.

## Capillary Action

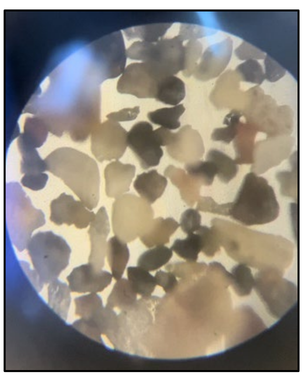
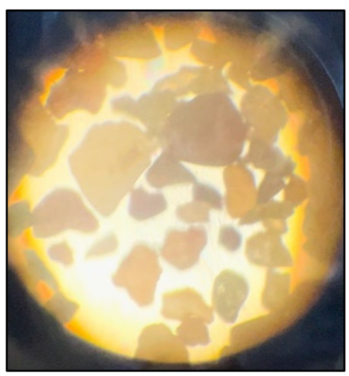
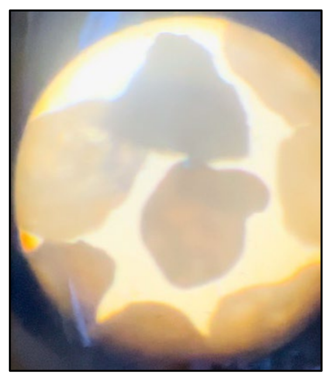
Capillary action is the ability of a liquid to flow upward in a narrow space, such as a thin tube or a small pore, opposing the force of gravity. It is influenced by forces of adhesion, cohesion, and surface tension. At a microscopic level, capillary action occurs when a liquid is in contact with a solid surface, such as walls of a narrow tube or pore, and the adhesive forces (attractive forces between the liquid molecules and the solid surface) are greater than the cohesive forces (attractive forces within the liquid molecules). The interplay between these two forces, alongside the phenomena of surface tension (a property causing the liquid's surface to behave like a stretched elastic membrane, minimising its surface area) results in a net force that opposes the force of gravity, and hence pulls the fluid upwards.

## Particle Characterisation

3 commonly available sand samples were analysed in order to determine methods to select the best growth medium for a combination between wick hydroponics and an ebb and flow hydroponic system.

The soil was subsequently analysed through particle and geomechanical means to determine important characteristics. After rinsing with water, they were placed to dry, photographed and observed. Subsequently, they were viewed with a microscope, with a magnification of 10X.

**Table 1**. Physical Characteristics and Qualitative Observations of 3 Sand Samples

| Name: Sea Sand | Name: Chowpatty Beach Sand | Name: River (Gujarat) Sand |
|---|---|---|
| Collection site: Sea, Alibaugh | Collection site: Beach, Mumbai | Collection site: River Bed |
| <br>**Figure 1.** Physical Sample of Sea Sand | <br>**Figure 2.** Physical Sample of Chowpatty Beach Sand | <br>**Figure 3.** Physical Sample of River (Gujarat) Sand |
| <br>**Figure 4.** Sea Sand under microscope | <br>**Figure 5.** Chowpatty Beach Sand under microscope | <br>**Figure 6.** River (Gujarat) Sand under microscope |
| Physical characteristics and qualitative observations:<br>Fine particles to the touch, smooth and sticky when damp. | Physical characteristics and qualitative observations:<br>Rough and grainy, similar sized particles by touch. | Physical characteristics and qualitative observations:<br>Larger particles to the touch, appears more rounded. |

The samples were characterised to obtain the average capillary radius, particle size distribution, uniformity coefficient, void space as a percentage and the water retention capacity.

## Methodology and Data Collection for Characterization

This section describes a brief methodology for each characterisation method, followed by the raw data obtained and associated error analysis.

### *Measure of Equilibrium Height of Capillary Action with Water*

To understand the dynamic properties of water in the medium, it is essential to obtain an idea of the radius of the capillary present in each sand. For the sake of numerical analysis, it is assumed that each capillary is perfectly cylindrical, and parallel to another. Following this assumption, capillary radius can be obtained from the equilibrium height water reaches after capillary action. Each of the sands were filled in a long test tube, with a porous medium at the bottom. The tube was immersed in water to a fixed level, and water was allowed to rise past the porous medium naturally. The height the water reached was measured by a ruler. This procedure was repeated 5 times, and an average was taken.

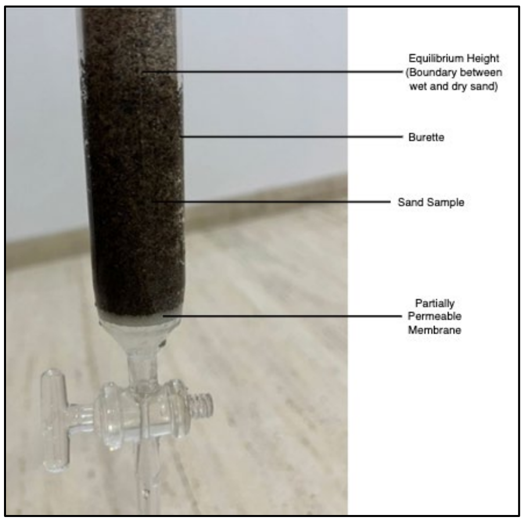



**Figure 7.** Measuring the radius of the capillary pore in sand

**Table 2**. Data obtained for mean equilibrium height of water following capillary action

| Type of Sand | Equilibrium height (m) | Mean equilibrium height (m) | Absolute Uncertainty (± m) |
|---|---|---|---|
| Sea Sand | 0.213 | 0.211 | 0.003 |
| | 0.209 | | |
| | 0.212 | | |
| | 0.209 | | |
| | 0.215 | | |
| Chowpatty Beach Sand | 0.121 | 0.121 | 0.003 |
| | 0.124 | | |
| | 0.119 | | |
| | 0.119 | | |
| | 0.121 | | |
| Gujarat Sand | 0.071 | 0.070 | 0.001 |

| | | | |
|---|---|---|---|
| | 0.069 | | |
| | 0.069 | | |
| | 0.070 | | |
| | 0.068 | | |

The absolute uncertainty for the measurements was obtained using the following formula:

Uncertainty in average = $\frac{Maximum\ value + Minimum\ value}{2}$

This collected data provides the equilibrium height water rises to in each of the tightly packed media, a characteristic that can assist in the determination of capillary radius through Jurin's Law, as derived from the Young- laplace equation. This analysis will be performed in the next section. While there are several time-dependent analysis techniques that can be used, they yield inaccurate results since the time period over which capillary rise was measured was short. Furthermore, as the radius of curvature of the meniscus becomes large, it balances the surface tension, hindering the applicability of a time-dependent equation, such as the Washburn Equation (Washburn, 1921).

### *Particle Size Measurements*

The process involved passing a sample of each sand through a series of sieves (meshed screens arranged in a stack with progressively smaller openings). The sample is placed on the top sieve, and manual shaking was applied to encourage particles to pass through the sieves. Meshes of BSS (British Standard Sieve) 16, 30, 60, 85, 150 and 200 were used. The weight in each cut was measured in order to obtain the particle size distribution for each type of sand.

**Figure 8.** Particle size distribution for Sea Sand

**Figure 9.** Particle size distribution for Chowpatty Beach Sand

**Figure 10.** Particle size distribution for River (Gujarat) Sand

**Table 3.** Particle sizes from sieve analysis - Sea Sand

| Mesh Used | Mesh Size (microns) | Average Mesh Size (microns) | Weight in each cut (g) | Weight Fraction % | Weighted diameter (microns) |
|---|---|---|---|---|---|
| 16 mesh | 2000-1003 | 1252 | 0.021 | 0.02% | 26.3 |
| 30 mesh | 1003 - 600 | 532 | 0.500 | 0.53% | 265.8 |
| 60 mesh | 600-250 | 425 | 3.000 | 3.16% | 1275.0 |
| 85 mesh | 250-180 | 215 | 32.042 | 33.77% | 6889.0 |
| 100 mesh | 180-150 | 165 | 0.093 | 0.10% | 15.3 |
| 150 mesh | 150-105 | 128 | 25.213 | 26.57% | 3214.7 |
| 200 mesh | 105-75 | 90 | 19.779 | 20.84% | 1780.1 |
| Smaller | 75-0 | 38 | 14.241 | 15.01% | 534.0 |

**Table 4.** Particle sizes from sieve analysis - Chowpatty Beach Sand

| Mesh Used | Mesh Size (microns) | Average Mesh Size (microns) | Weight in each cut (g) | Weight Fraction % | Weighted diameter (microns) |
|---|---|---|---|---|---|
| 16 mesh | 1500-1003 | 1251.5 | 1.765 | 1.61% | 2209 |
| 30 mesh | 1003 - 600 | 531.5 | 3 | 2.73% | 1595 |
| 60 mesh | 600-250 | 425 | 34 | 30.98% | 14450 |
| 85 mesh | 250-180 | 215 | 53.488 | 48.73% | 11500 |
| 100 mesh | 180-150 | 165 | 0.408 | 0.37% | 67 |
| 150 mesh | 150-105 | 127.5 | 8.681 | 7.91% | 1107 |
| 200 mesh | 105-75 | 90 | 6.367 | 5.80% | 573 |
| Smaller | 75-20 | 37.5 | 2.054 | 1.87% | 77 |

**Table 5.** Particle sizes from sieve analysis - River (Gujarat) Sand

| Mesh Used | Mesh Size (microns) | Average Mesh Size (microns) | Weight in each cut (g) | Weight Fraction % | Weighted diameter (microns) |
|---|---|---|---|---|---|
| 16 mesh | 2000-1003 | 1252 | 17.784 | 12.78% | 22256.7 |
| 30 mesh | 1003 - 600 | 532 | 29.000 | 20.83% | 15413.5 |
| 60 mesh | 600-250 | 425 | 74.000 | 53.16% | 31450.0 |
| 85 mesh | 250-180 | 215 | 16.247 | 11.67% | 3493.1 |
| 100 mesh | 180-150 | 165 | 0.432 | 0.31% | 71.3 |
| 150 mesh | 150-105 | 128 | 0.981 | 0.70% | 125.1 |
| 200 mesh | 105-75 | 90 | 0.494 | 0.35% | 44.5 |
| Smaller | 75-20 | 38 | 0.267 | 0.19% | 10.0 |

The weighing balance used had a high accuracy, with an associated absolute uncertainty of ±0.001g. Thus, the weight is given to 3 decimal places, and associated error is not significant enough to be visible on a graph.

### *Void Volume Measurements*

Void space refers to the air space or gaps between particles in a packed layer of the material. 2 methods were used to obtain an estimate of the void space present in each sand. First, water was allowed to occupy space through capillary action from below, and the volume of water uptake was measured. This was performed in an inverted test tube with a muslin cloth acting as an initial porous medium. Second, water was added from above and mixed with the soil sample to obtain an estimate of the composition of void spaces in the soil. Each method was repeated thrice for accuracy, and the average results were tabulated.

A B

**Figure 11.** Two methods for measuring void spaces; A - test tubes to be inverted in water, B - water added from above

**Table 6.** Calculations for volume of void space through water added from the top

| Type of Sand | Volume of Sand ($cm^3$) | Volume of water ($cm^3$) | Average volume of mixture ($cm^3$) | Volume of void spaces ($cm^3$) |
|---|---|---|---|---|
| Sea Sand | 50 | 50 | 78 | 22 |
| Chowpatty Beach Sand | 50 | 50 | 76 | 24 |
| River (Gujarat) Sand | 50 | 50 | 73 | 27 |

**Table 7.** Calculations for void space through capillary action

| Type of Sand | Volume of Sand ($cm^3$) | Volume of water initial ($cm^3$) | Volume of water final ($cm^3$) | Volume of water absorbed ($cm^3$) | Volume of void spaces ($cm^3$) |
|---|---|---|---|---|---|
| Sea Sand | 50 | 200 | 179 | 21 | 21 |
| Chowpatty Beach Sand | 50 | 200 | 177 | 23 | 23 |
| River (Gujarat) Sand | 50 | 200 | 172 | 28 | 28 |

### *Water Retention*

A water retention study was performed for all the sand samples, through weighing a soil sample saturated with water, before and after a fixed duration of time. The study yielded the following results:
Sea Sand: 24.5 hours, lost 6.3% of water
Chowpatty Beach Sand: 24.5 hours, lost 10.5% of water
River (Gujarat) sand: 24.5 hours, lost about 12.6% of water

These results will be evaluated in the next section.

## Data Analysis, Discussions and Results

This section uses the raw data obtained in the previous section and analyses important properties of the medium with reference to its interactions with water.

### *Radius of Capillary*

The radius of the capillary can be determined from the equilibrium height obtained in section 3.1.1, utilising a derivation of the primary governing equation for capillary action.

Equation 1: The Young-Laplace equation

$$\Delta P = \frac{2T \cos \theta}{r} \quad ;$$

where:
$\Delta P$ = pressure difference across the meniscus
T = surface tension of the liquid ($N\ m^{-1}$)
$\theta$ = contact angle between the liquid and the solid surface (º)
r = radius of curvature of the meniscus (m)

This equation relates the pressure difference across the curved meniscus of a liquid in a narrow tube or pore to the curvature of the meniscus and the surface tension of the liquid.

Derived from Equation 1, we get Jurin's Law (Siqveland and Skjaeveland 2021). This states that the height of the liquid column in a capillary tube is proportional to the diameter of the capillary.

Equation 2: Jurin's Law

$$h = \frac{2T \cos \theta}{\rho g r} \quad ;$$

where:
h = height (m)
T = surface tension of the liquid ($N\ m^{-1}$)
$\theta$ = contact angle between the liquid and the solid surface (º)
$\rho$ = density of the liquid in the representative column ($kg\ m^{-3}$)
g = acceleration due to the force of gravity ($ms^{-2}$)
r = radius of the tube (m)

Using this equation, the following graph was obtained, depicting that as the radius of the capillary pore increases, the equilibrium height increases.

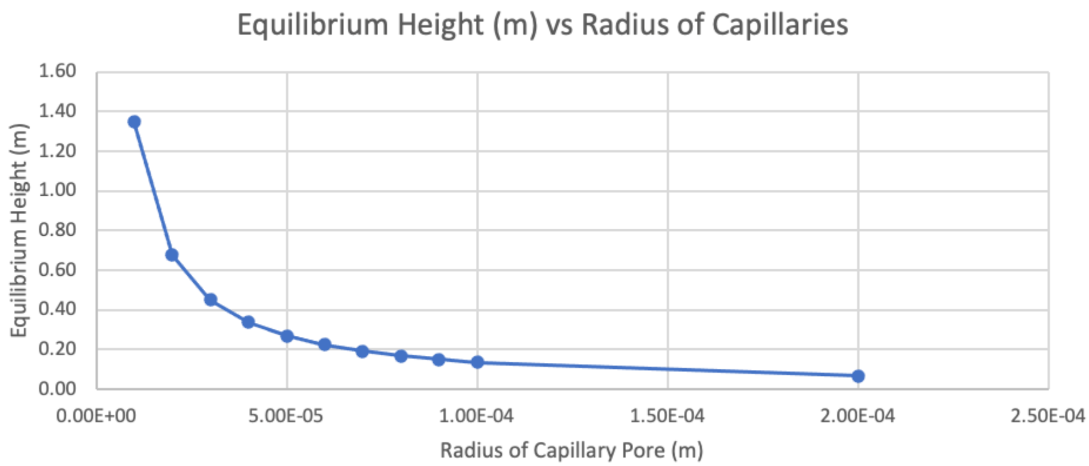



**Figure 12.** The correlation between the equilibrium height and the radius of a capillary pore for water

The equilibrium height for each sand was measured, and the calculations were performed, using values as identified in Table 1 (density of 998 Kg $m^{-3}$ and a surface tension of 0.072 N $m^{-1}$)

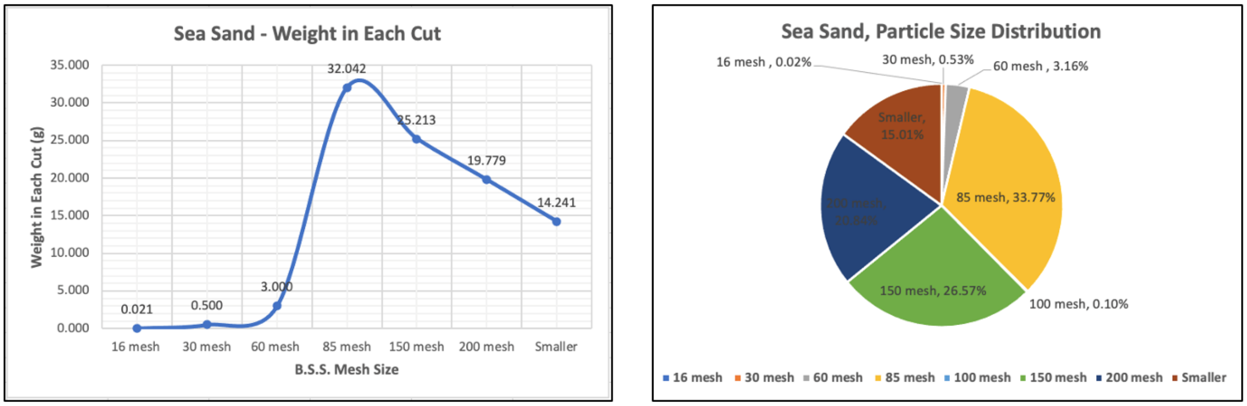
**Table 9.** Calculations of capillary radius through Jurin's Law

| Type of Sand | Mean equilibrium height (m) | Mean Radius of capillary (m) | Radius of capillary (microns) |
|---|---|---|---|
| Sea Sand | 0.211 | 6.35E-05 | 63.50 |
| Chowpatty Beach Sand | 0.121 | 1.11E-04 | 110.92 |
| River (Gujarat) Sand | 0.070 | 1.91E-04 | 191.42 |

However, there are some limitations and assumptions in the aforementioned equations (Barozzi and Angeli 2014), and thus they must be used with caution. An important assumption to note in this case is that the equations assume capillaries of uniform diameter that are perfectly cylindrical and vertical. In the case of a hydroponic growing medium, this may not precisely be the case, and the true values may deviate slightly from the calculated values. Furthermore, the value obtained is an average value for the radius of the capillary, individual capillaries may not be uniform.

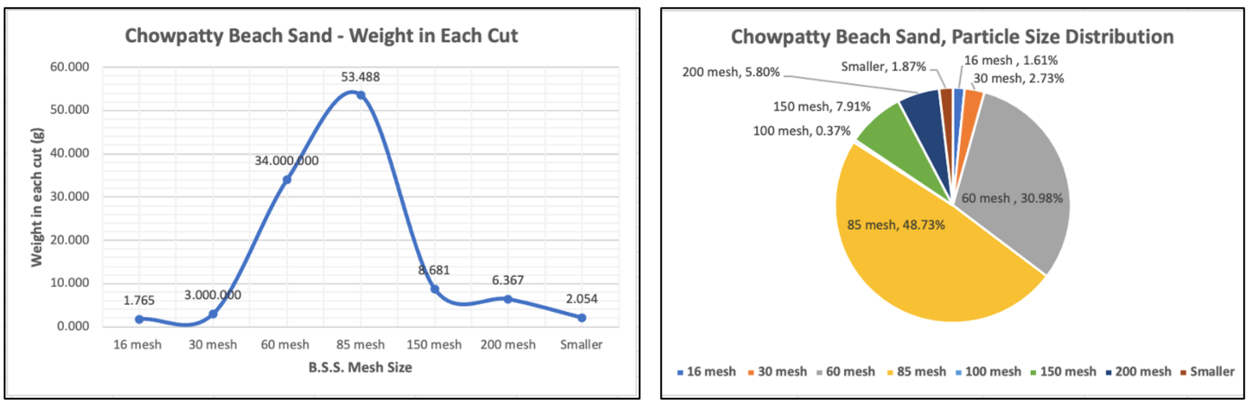
## *Particle Size Distribution Using Sieve Analysis*

Based on the raw data collected in the sieve analysis tables in section 3.1.2, a particle size distribution was performed, and the results were as follows:



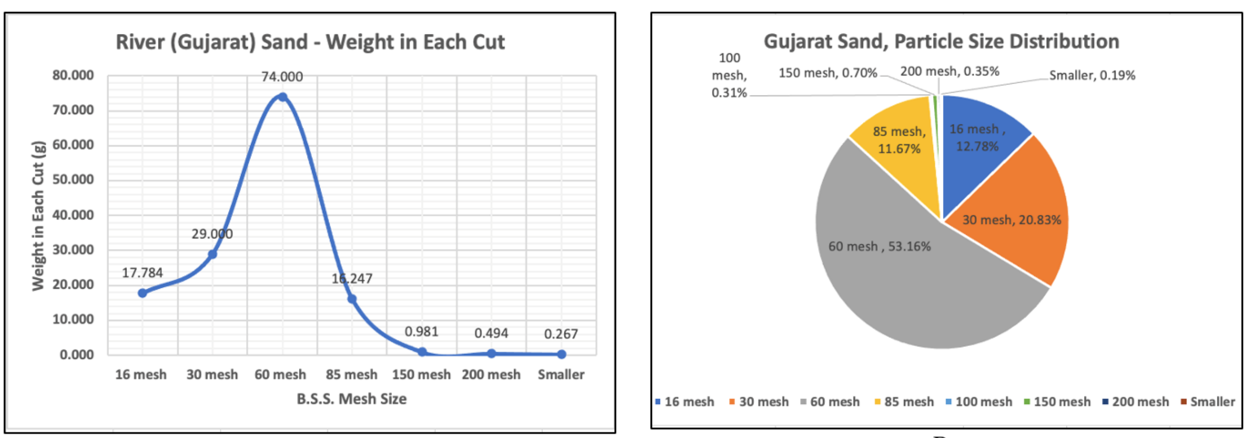

A B

**Figure 13.** Particle size distribution of Sea Sand




A B

**Figure 14.** Particle size distribution of Chowpatty Beach Sand.




A B

**Figure 15.** Particle size distribution of River (Gujarat) Sand.

The graphs reveal distinct characteristics among different sand types. Notably, River (Gujarat) Sand exhibits the largest average particle size, in contrast to Sea Sand, which displays the smallest particles. Among

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these, Sea Sand stands out for its high variance and close to even particle distribution, while Chowpatty Beach Sand and River (Gujarat) Sand showcase more concentrated distributions.

A uniformity coefficient ($C_u$) refers to a quantitative understanding of the range of particle sizes. A $C_u$ that is greater than 5 indicates a stable medium with a large range of particle sizes (well-graded), whereas a $C_u$ smaller than 4 indicates a material being limited to a narrow range of particle sizes.

An approximate value for the university coefficient was obtained through implementing the following formula:

Uniformity Coefficient = $\frac{D_{60}}{D_{10}}$

$D_{60}$ is the particle size (diameter) at which 60% of the material is finer

$D_{10}$ is the particle size (diameter) at which 10% of the material is finer

An average estimate of the uniformity coefficient was obtained for each sand through plotting gradation curves for each sand as follows:

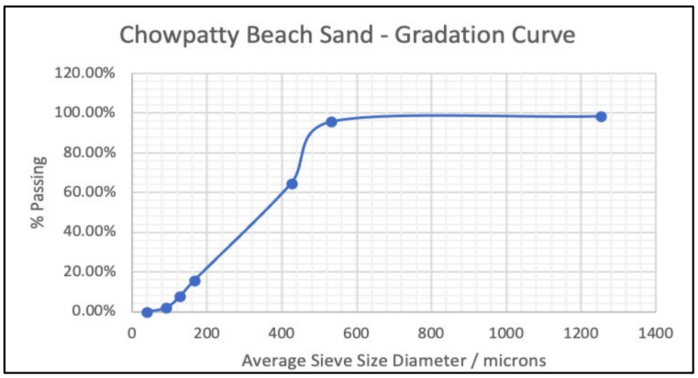


**Figure 16.** Gradation Curve for Chowpatty Beach Sand

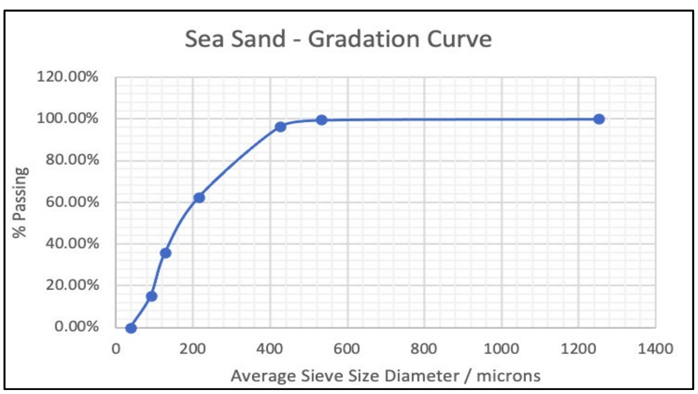


**Figure 17.** Gradation Curve for Sea Sand

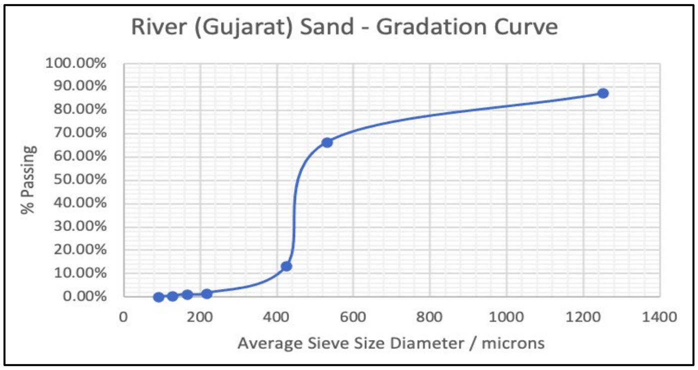


**Figure 18.** Gradation Curve for River (Gujarat) Sand

From these gradation curves, the following table was obtained:

**Table 10.** Estimated Uniformity Coefficients for 3 Media

| Type of Sand | Uniformity Coefficient (3 s.f.) |
|---|---|
| Chowpatty Beach Sand | 3.38 |
| Sea Sand | 2.62 |
| River (Gujarat) Sand | 2.42 |

This depicts that Chowpatty Beach Sand has the largest range of particle sizes and can be considered to be more heterogeneous than River (Gujarat) Sand, which has only a limited range of particle sizes.

### *Void Space Analysis*

The percentage of packed soil that contained void spaces was calculated through calculating the volume of void spaces as a percentage of total volume of water for each method (in section 3.1.3). These were then averaged to obtain the mean % void space.

**Table 11.** Average % void space of both methods

| Type of Sand | Average % void space |
|---|---|
| Sea Sand | 43 |
| Chowpatty Beach Sand | 47 |
| River (Gujarat) Sand | 55 |

These findings align consistently with previously obtained data. A larger capillary radius coupled with a low uniformity coefficient leads to an increase in the % of void space in the sand, due to the packing fraction, and vice versa. A sand with a larger % of void spaces provides more water to the roots, as well as allows the exchange of oxygen for roots, and is thus optimal.

### *Water Retention Analysis*

As calculated in section 3.1.4, River (Gujarat) Sand retained the least water, losing 12.6% of water in a 24.5 hour time period, as compared to Sea Sand which only lost 6.3% of water in that time period. For healthy plant growth, it is essential that there are periods where in the void spaces are drained of water to allow the roots to respire.

### *Comparisons and Discussions*

With respect to fluid properties, a large particle size implies and a low variance in particle size provides the ideal conditions for flow as inferred from Jurin's and Poiseuille's Laws. This can be ascertained from the correlation between the weighted average of the particle size of the sand (as measured through sieve analysis) and the capillary pore radius. Although the horizontal error bars are not visible due to their size, the error for both the radius of capillary pores as measured by Jurin's Law and the average weighted particle radius through sieve analysis was calculated.

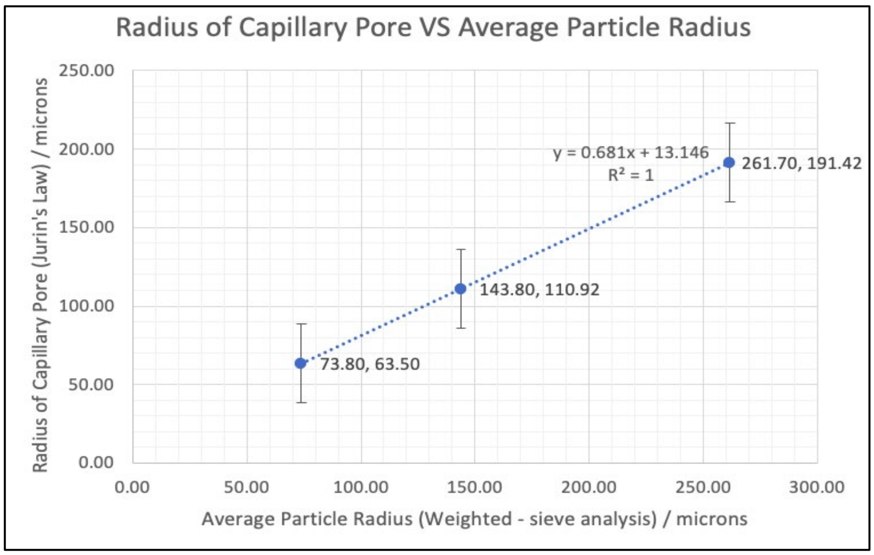


**Figure 19.** Correlation between the Average Radius of a Capillary Pore and the Average Particle Radius

As displayed, a positive correlation exists between the two variables: The larger the average particle radius, the larger the radius of the capillary pore.

Another important connection drawn while identifying the optimum medium for hydroponic growth is between the void space and capillary radius:

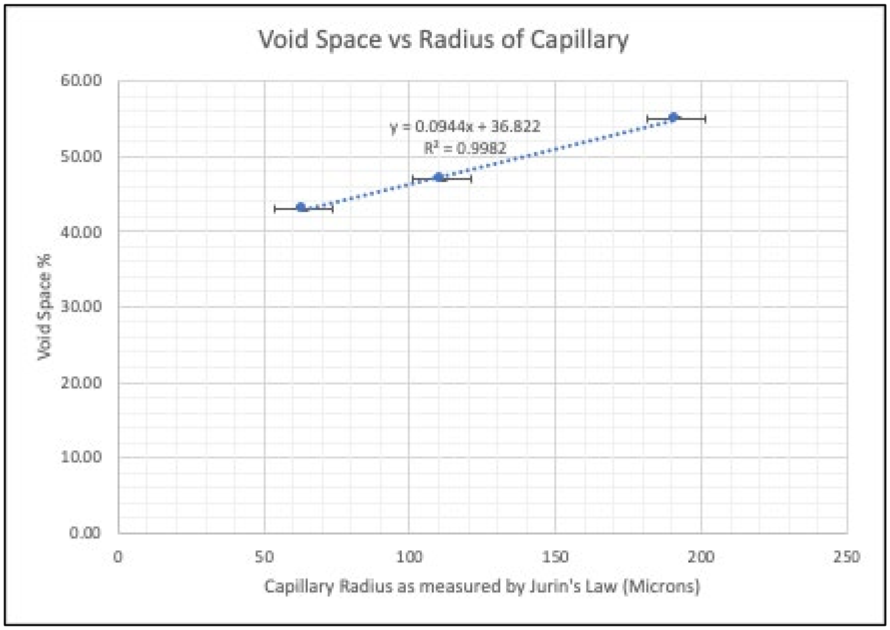


**Figure 20.** Correlation between the Void Space of the packed sand bed and the Average Radius of a Capillary

As can be observed, a positive correlation exists between the capillary radius and void space in a growth medium. Theoretically, the volume and radius should have a cubic relationship. However, in a packed sand bed, the cubic space transforms into a linear or one-dimensional space, having important implications on the mass transfer resistance (which decreases). This is a result of being reduced down to a nanoscale. For fluid (capillary) flow, both parameters are optimal, and thus must be maximised.

## Discussion of Characterisation Results

After characterising each sand sample, the River (Gujarat) Sand was chosen as the ideal growing medium in a hydroponic system. With the largest capillary pore radius and void space, of 191.42 microns and 56% respectively, lowest water retention capacity and lowest uniformity coefficient, this medium provided the optimum conditions for capillary flow. Its features would assist in easy drainage of water for oxygen absorption by the roots, as well as provide a high flow rate of water and allow water to completely penetrate the growing medium.

## Experimental Set-Up

Following this deduction, an experiment was set up with three identical containers placed in the same environment, with the following specifications:

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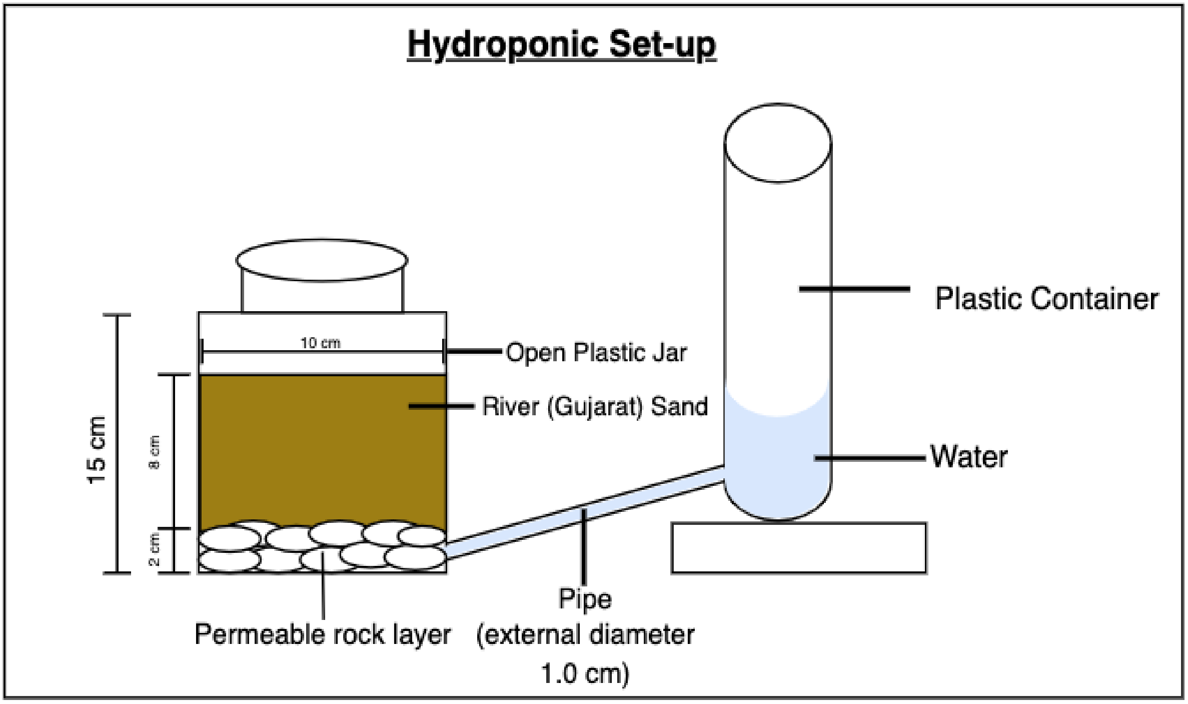


**Figure 21.** Diagram of the passive sand-based hydroponic system

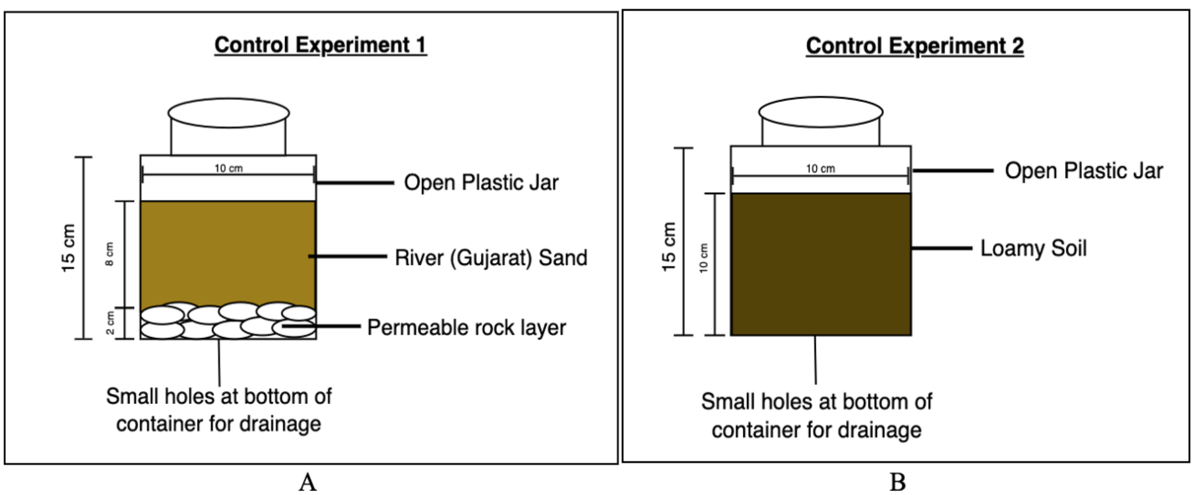


**Figure 22.** Diagram of the control experiments

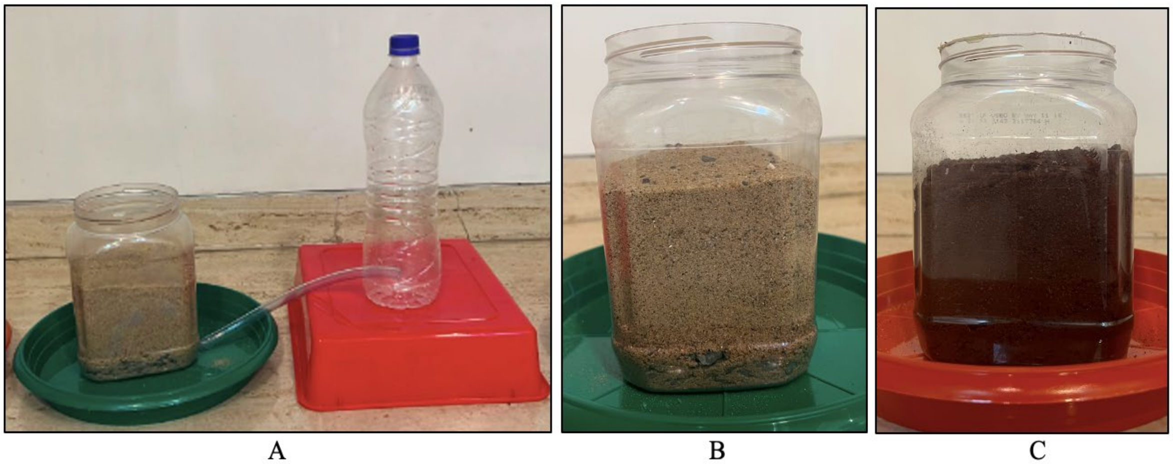

**Figure 23.** The hydroponic set-up and the two control experiments

For the hydroponic system, the water was provided from beneath the sand and allowed to rise through capillary action. The pipe was removed for a duration of 2 hours every day to allow for drainage. The two control experiments provided a source of comparison for the plant germination and growth.

Fenugreek (Trigonella foenum-graecum) seeds were planted - at a fixed depth of 1 cm below the surface of the growing medium for each container, and their germination was monitored through qualitative observation. A moisturemeter was integrated into the experimental design to monitor water levels and optimise irrigation intervals. The probe of the moisturemeter was entered 1.5 cm into the growing medium. The plants were checked with a moisturemeter twice a day (9am and 9pm). Plants were given water when the moisturemeter displayed a value under 'dry (1 to 4)' until the reading changed to 'moist - 6/7.' Data for the same was collected over a 3 week (21-day) growing period.

## Results and Observations

**Table 12.** Quantitative observations of volume of water added to each experimental set-up

| Date | Time | Water Added / ml | | |
|---|---|---|---|---|
| | | Hydroponic Set-Up | Control 1 (Sand) | Control 2 (Soil) |
| 26/07/23 | 9:00 AM | 150 | 150 | 150 |
| 26/07/23 | 9:00 PM | 5 | 7 | 10 |
| 27/07/23 | 9:00 AM | 0 | 10 | 10 |
| 27/07/23 | 9:00 PM | 0 | 0 | 0 |
| 28/07/23 | 9:00 AM | 20 | 30 | 25 |
| 28/07/23 | 9:00 PM | 0 | 40 | 0 |
| 29/07/23 | 9:00 AM | 40 | 30 | 45 |
| 29/07/23 | 9:00 PM | 50 | 30 | 0 |
| 30/07/23 | 9:00 AM | 0 | 40 | 40 |

| | | | | |
|---|---|---|---|---|
| 30/07/23 | 9:00 PM | 0 | 0 | 0 |
| 31/07/23 | 9:00 AM | 0 | 20 | 25 |
| 31/07/23 | 9:00 PM | 40 | 25 | 50 |
| 01/08/23 | 9:00 AM | 50 | 0 | 0 |
| 01/08/23 | 9:00 PM | 35 | 35 | 50 |
| 02/08/23 | 9:00 AM | 30 | 30 | 0 |
| 03/08/23 | 9:00 AM | 30 | 30 | 40 |
| 04/08/23 | 9:00 AM | 0 | 0 | 40 |
| 05/08/23 | 9:00 AM | 30 | 50 | 40 |
| 06/08/23 | 9:00 AM | 0 | 25 | 0 |
| 07/08/23 | 9:00 AM | 30 | 30 | 30 |
| 08/08/23 | 9:00 AM | 20 | 0 | 0 |
| 09/08/23 | 9:00 AM | 20 | 30 | 35 |
| 10/08/23 | 9:00 AM | 20 | 30 | 0 |
| 11/08/23 | 9:00 AM | 25 | 25 | 30 |
| 12/08/23 | 9:00 AM | 0 | 0 | 0 |
| 13/08/23 | 9:00 AM | 20 | 30 | 25 |
| 14/08/23 | 9:00 AM | 0 | 15 | 20 |
| 15/08/23 | 9:00 AM | 0 | 10 | 0 |
| **Total Volume of Water** | | **615** | **712** | **665** |

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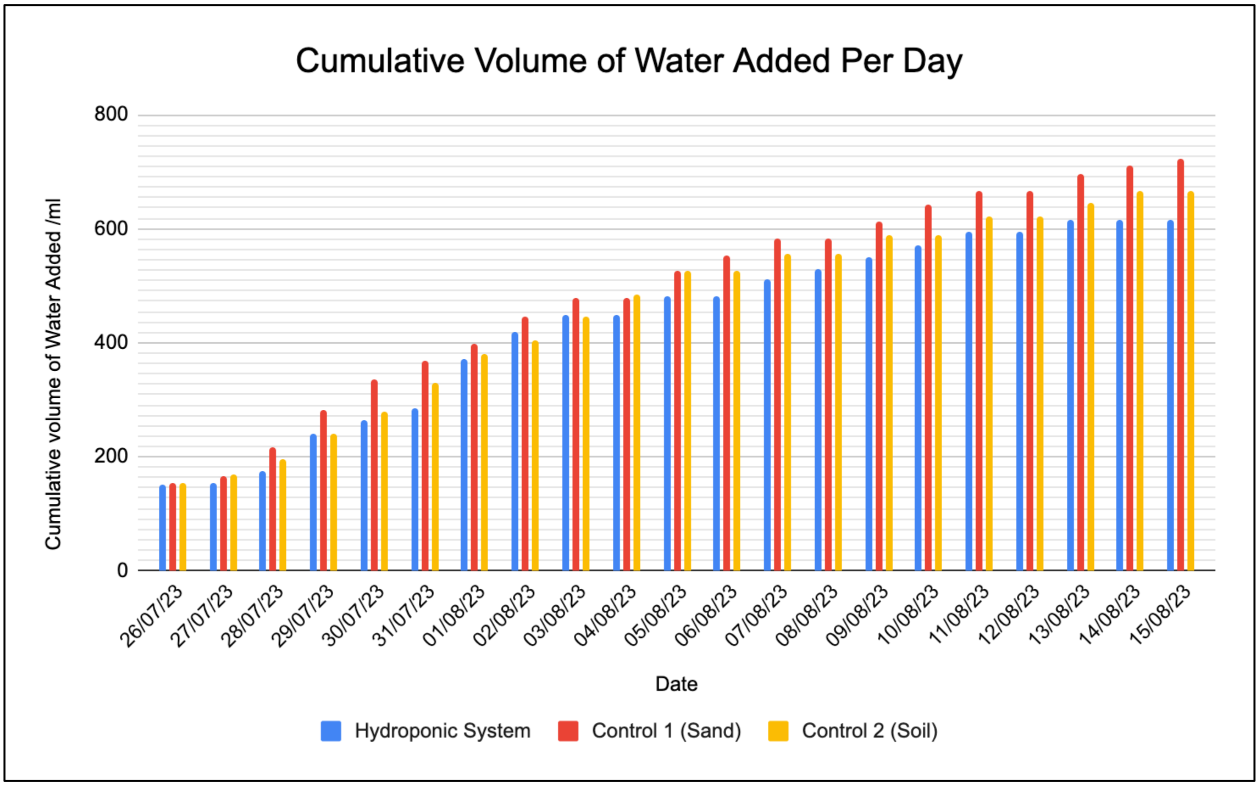


**Figure 24.** Bar graph depicting the cumulative water input for each experimental set up per day.

Qualitative observations: Over this period, all three containers saw approximately equivalent growth in all three containers. However, there were slight differences observed: the density of growth in the control experiment with loamy soil was the highest, followed closely by the hydroponic system. In the control experiment with sand as the growing medium, a much lower growth density was observed.

**Table 13.** Growth results for different set-ups

| Time | Hydroponic set-up | Control 1 | Control 2 |
|---|---|---|---|
| Day 3 |  |  |  |

| | | | |
|---|---|---|---|
| Day 12 |  |  |  |
| Day 20 |  |  |  |

Another qualitative observation made, which is corroborated by the quantitative data, is the moistness of the growing media. The hydroponic system stayed sufficiently moist, as did the loamy soil. The control experiment with sand as the growing medium dried out the fastest, requiring increased watering.

## Discussion of Results

The hydroponic system required watering with a lower frequency compared to the control experiment with the sand. In the 21-day growing period, it required water for 15 days (same frequency as the control experiment with loamy soil), while the control experiment with the sand required water for 18 days. With respect to the volume of water required, the hydroponic soil was the most efficient. It required 615 ml of water, a lower volume than required by the control experiments: the control experiment with sand required 712 ml, while the control experiment with loamy soil required 665 ml. Thus, using the hydroponic system saved 7.52% of water as compared to using a set-up with loamy soil, and saved 13.62% of water as compared to watering a fenugreek plant in sand from above. These observations can be attributed to the controlled delivery of water to the plant roots through capillaries in the growth medium, which optimises moisture distribution and minimises wastage. In contrast, the higher water requirements of the sand and loamy soil controls signify the less efficient water retention and distribution in traditional practices through watering from above, highlighting the significance of capillary-driven hydroponics in achieving sustainable and resource-efficient plant cultivation practices. However, the plant growth was the densest in the loamy soil. This limitation can be attributed to the micro nutrients (NPK) present in the soil. The same could be added to the hydroponic water to provide increased growth in a hydroponic system.

## Conclusions

In conclusion, the principles of capillary flow elucidated by Jurin's Law has displayed the mechanics of water ascent through capillaries, an advantageous phenomenon in passive hydroponic systems, where the optimal capillaries of the growing medium will have a larger radius. Thus, the careful characterization of particle parameters such as particle size analysis, void space analysis and water retention, followed by subsequent selection of a medium for hydroponic growth is essential. The differences in cumulative volume of water utilised between capillary-driven water movement and conventional top-down irrigation are elucidated in this paper, with the capillary driven movement increasing water conservation by 13.72%. By harnessing these insights, the potential to achieve amplified water savings and sustainable cultivation practices on a larger scale becomes not only feasible but also imperative for future resource-efficient endeavours. As global concerns about water scarcity intensify, harnessing these insights becomes not only feasible but also imperative for the pursuit of sustainable and resource-efficient agriculture on a larger scale.

To further advance our comprehension of the possibilities offered by fluid dynamics in water-efficient agriculture, future studies can explore several avenues. Firstly, investigating the scalability of capillary-driven hydroponic systems for large-scale agriculture could provide invaluable insights into their practicality and potential impact. Secondly, crop-specific studies focused on understanding the nuanced water requirements of different plants within such systems could facilitate targeted and optimized cultivation practices. Lastly, the development of algorithms for cost-effective automated control systems that adapt water delivery based on real-time environmental conditions represents a promising avenue for future research, aligning with the growing trend toward precision agriculture.

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