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Sustainable urban farming: A case study on multi-crop vertical hydroponics

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Abstract
The concept of using chemical fertilizers and pesticides to enhance agricultural production is an age-old practice. Given the fact that food is a basic necessity, this paper tends to promote an urban-based sustainable solution to reduce the use of agrochemicals and water to grow vegetable crops. Though the idea of Hydroponics is known to the scientific world, the designed prototype of vertical hydroponics serves as an opportunity to minimize the space which makes it suitable in the context of Indian urban cities. Four different vegetable crops (Brinjal, Lettuce, Tomato, and Chilli) were grown in the prototype and it was observed that all the four plants in the hydroponics system grew faster with no agrochemicals and minimal economic costs of manufacturing. Given the situation when forests are consciously turned into agricultural croplands to meet the demands of the increasing population, this prototype can be expanded as a potential model to minimize forest degradation and provide chemical free crops to the larger population in the cities.

Keywords: Tropical crops, Multi-crop Vertical Hydroponics, Prototype, Sustainability, Urban (food) supply chain

Introduction

Being an agricultural nation, India owes significant share of its overall development to the agricultural sector (Borthakur & Singh, 2013). The Indian agricultural sector witnessed an increase of 222.38 million tons of food grain production from 1950 to 2017 (Yadav et al., 2019)- contributing maximum to India's GDP (Parashar, 2019). But Nature paid for this financial success when a 30% increase in agricultural land use occurred at the cost of 5% loss of Central Himalayan forests during 1963-93 (Semwal et al., 2004). Globally, forested lands are being extensively converted to agricultural fields, factories, and settlement areas, to meet various demands of the growing population (Tangtham & Sutthipibul, 1989).

In a related study, Jha et al. (2000) observed that there was a loss of 25.6% forest cover in the Western Ghats over 22 years (1973-95), owing to the degradation mostly to the conversion of forests to croplands and agricultural fields. In India, the agricultural productivity and geographical conditions are directly related to poverty (Nalwade & Mote, 2017)- in recent years, it is largely observed that the rural villages are rapidly gentrifying into urban villages with increasing urban sprawls in metropolitan cities like Delhi (Ali & Srivastava, 2017). Such a situation will demand increased food production in peri-urban areas, therefore stressing the importance of urban agriculture. In developing countries, the cities are vibrant centers of cultural evolution and human civilization (McAdams, 2007), but it shrouds urban poverty, alienation, and

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deprivation (Schnitzler, 2012). Resource inequality exists in cities based on financial imbalance (Glaesar et al., 2009) and more than 56 % of the global poor population resides in urban areas (Shackleton et al., 2009). Urbanization in developing countries has witnessed a growth rate of 3.6 % per year from 1950 to 2005 (Aubry et al., 2012). Bakker et al. (2000) predicted up to 80 % of the population would be living in cities of developing countries by 2025.

In many cities, urban agriculture/horticulture has been introduced to ensure food security (Eigenbrod & Gruda, 2015) and reduce the need for crop transportation from rural areas, thus, saving fuels, lowering CO_2 (greenhouse gas) emissions, and alleviating air pollution (FAO, 2010; Kulak et al., 2013). It also engenders positive effects on improving microclimatic conditions, water management, diet-related health, and stress reduction (Bolund & Hunhammar, 1999; Dixon et al., 2009; Barthel et al., 2015; Goldstein et al., 2016). Hydroponics, as an agricultural practice, falls as a significant attribute under urban agriculture. Hydroponics is closely associated with urban landscapes as it can be exercised in small spaces (Peuchpanngarm, 2016)- it renders the urban inhabitants with the possibility to be enamored with the feeling of a pleasing and healthy environment (Domurath & Schroeder, 2008). Hydroponics has been also observed to be potential remediation to avert forest degradation (Roberto, 2003; Albert, 2019) while accelerating the production of (crop) plants, mostly in urban areas (Albert, 2019). Hydroponics, in a broader sense, refers to raising plants without any soil medium (Hussain et al., 2014). The plants are grown in nutrient solutions with or without the presence of mechanical support like sand, gravel, vermiculite, coir, or sawdust (Jensen, 1997). Hydroponic systems are classified as open and closed based on reusability of nutrient solution open, if the nutrient solution is not reused after it is delivered to roots and closed, if the nutrient solution is recycled after being delivered to the roots (Jensen, 1997; Schröder & Lieth, 2002). Hydroponics has received global appreciation for its efficient resource management and food production, particularly since the arable cropland is reducing due to the increasing population worldwide (Sharma et al., 2018). This technique of growing plants is not influenced by environmental (abiotic) stresses like soil salinity, temperature, or soil composition (Polycarpou et al., 2005). Furthermore, crops grown through hydroponics can be raised throughout the year independent of any agrochemicals (Manzocco et al., 2011). The ability to nourish the crops with limited use of water (Chimonidou, 2000; 2002), limited labor (Jovicich et al., 2003) and no agrochemicals (Charoenpakdee, 2014) makes hydroponics a germane alternative to field based agricultural practices.

Hydroponics is not a widely popular practice in Indian society, though conventional farmers have expressed their interest towards the technique (Carruthers, 2013). It was first introduced by W. J. Shalto Duglas in Kalimpong, West Bengal in 1946 (Sardare & Admane, 2013) but there has not been much research effort on hydroponics in India and globally. Vertical farming, on the other hand, is not a new idea to the scientific community where it is defined as rearing plants and animals within skyscrapers or on vertically inclined surfaces or on vertically stacked layers (Despommier, 2010; De Anda & Shear, 2017). Vertical farming has been success stories in countries like the USA, Singapore, Canada, South Korea, Japan, Germany, Sweden (Kalantari et al., 2018) but there is a paucity of information on such agricultural practices in developing countries like India. Considering the research hitherto, this paper attempted to design a prototype of vertical hydroponics for multiple variety crop-production in the context of the Indian urban scenario. This laboratory-based, small scale prototype is inspected through growing four different vegetable crops with limited space, minimal water usage, no agrochemicals (fertilizers and pesticides), and no soil- the results of this case study are then compared with soil-based production of the same crops. Furthermore, we have deduced a budget break-up of the prototype to be further extrapolated for a bigger model, capable to be implemented above restaurants, malls, and hotels in Indian urban landscapes.

During the study, the authors developed a sketch of the potential prototype of multi-crop vertical hydroponics and articulated ways to grow four common vegetable crops whose saplings were easily available in the market. In practical applications, individuals using the hydroponics system will likely source saplings from local markets, primarily due to considerations of cost, availability, and convenience. While market-sourced saplings may not always meet the stringent criteria typically required for scientific research—such as genetic consistency, uniformity, and resistance to disease—they are reflective of the conditions under which the prototype would be applied on a larger scale. As such, the use of these commercially available saplings is an important factor in ensuring the broader applicability and scalability of the system. The objectives of the case study were as follows-

1. To build a prototype of multi-crop vertical hydroponics and grow four vegetable crops.
2. To statistically analyse crop growth in this prototype through plant physiognomic variables.
3. To determine the cost-effectiveness of designing the prototype and extrapolating those financial figures to establish a bigger model in Indian urban cities.

Materials and Methods

This research primarily focuses on developing a case study for building a prototype of multi-crop vertical hydroponics, its ability to grow four different kinds of vegetable crops over a period of 5 weeks, and calculate the expenditure to achieve the prototype at a bigger scale. The study was limited to a 5-week period. It focused on the initial growth stages of the crops to evaluate the hydroponic system's feasibility and early performance. The goal was to observe plant growth and assess the prototype's effectiveness in these early stages. While the study

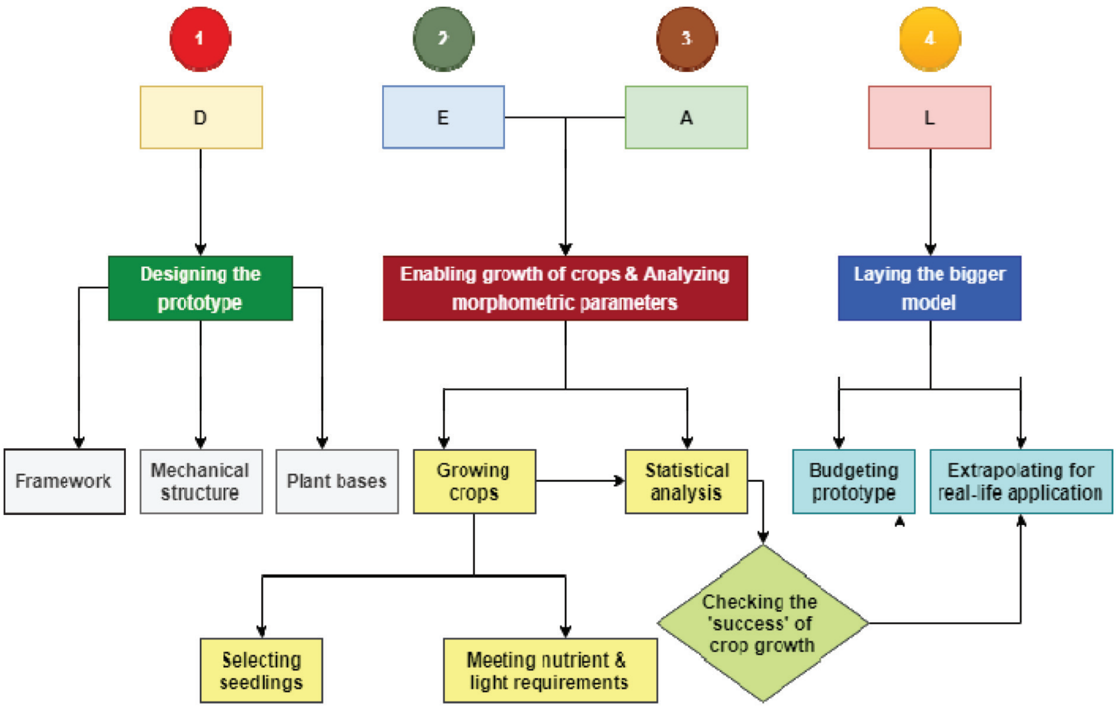

Figure 1. Methodological framework of the research

did not cover the entire growth cycle, future research will extend the observation period to provide a more comprehensive evaluation of long-term crop growth, yield, and system viability in real-world applications.

Research design

This study was conducted from June 2018 to December 2018 and was executed into three phases of construction, application, and extrapolation. The research design of the given study was outlined following the schema of DEAL (Fig. 1)
where,
D= Designing the prototype of multi-crop vertical hydroponics
E= Enabling the growth of vegetable crops in the prototype
A= Analysing the plant physiognomic parameters through statistics
L= Laying the financial plan for expanding the prototype into a larger model
The element of D came under the phase of 'construction' where the prototype was developed. The elements of E and A fell under the phase of the 'application' wherein the vegetable crops were cultured in the prototype and their morphometric (physiognomic) parameters were analysed. The element of L was clubbed under the phase of 'extrapolation' which dealt with drafting a budget for planning a bigger model of this prototype for real-life applications.

Designing the prototype of multi-crop vertical hydroponics

The prototype aimed at creating a rigid and effective structure for growing four different vegetable crops at the same time. Structure of the prototype was envisioned to be aconcise version for the given case study which can be expanded to a bigger model for real life implementation. Considering the concept of vertical hydroponics, the prototype was constructed in such a way that the bigger model will be just a mathematical extrapolation of the scale/ size ratio of this prototype.

Frame of the prototype

The frame was the backbone of the whole prototype which supported the individual components in their right places while carrying the weight of the structure. Based on load-bearing capacity and rigidity of the frame, an extended 3D triangular prism was finalized for the prototype. This frame was first developed in 3D- engineering design software, CREO, to check for load-bearing capacity. Wood was preferred for constructing this hydroponics setup for its rigidity and ease in machinability. For the prototype of the hydroponics setup, wood was chosen as the primary material due to its accessibility, ease of handling, and cost-effectiveness. Given its widespread availability, wood provided an ideal option for the initial phase of the design. However, we recognize that while wood is suitable for short-term use, its durability, particularly in humid or moisture-rich environments, poses a challenge for the system's long-term performance. Prolonged exposure to such conditions could potentially reduce the lifespan of the structure and increase maintenance costs. To address these concerns, future iterations of the hydroponic system will explore the use of alternative materials, such as treated wood or composite materials, which offer enhanced durability without significant cost escalation. Additionally, we will investigate protective coatings or treatments that can be applied to the wood to improve its resistance to moisture and extend its service life. These modifications will contribute to a more resilient structure, ensuring the hydroponic system's suitability for prolonged use in moisture-prone environments, while also maintaining cost-effectiveness in the overall design.

Mechanical structure of the prototype

4 identical PVC pipes, each of diameter 4 inches and length 4 feet were employed to build the prototype. The 4 pipes made the 4 vertical tiers of the structure where in their ends were sealed with a small opening in the center. Each tier had a gap of 2 feet with the other tiers such that the last (fourth) tier was also above 2 feet from the ground. The

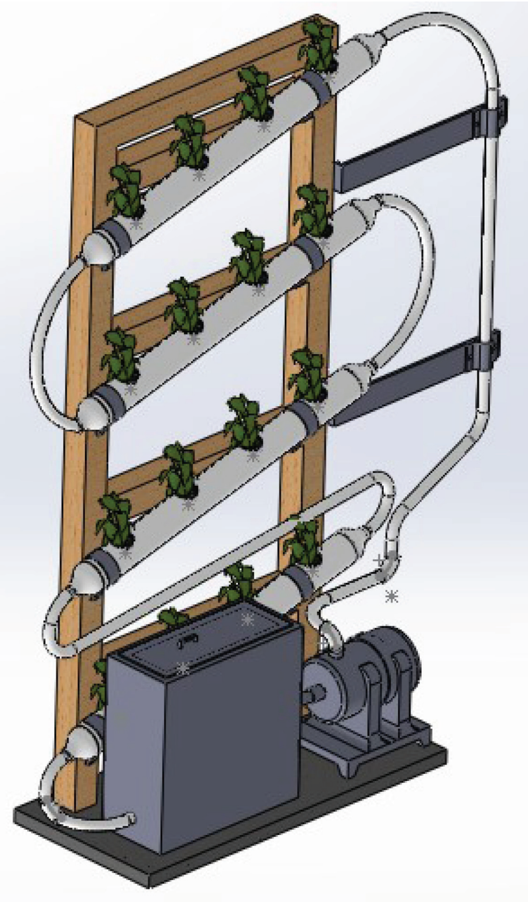

Figure 2. Prototype of the multi-crop vertical hydroponics

opening was meant to facilitate the movement of the nutrient solution- each of these bigger pipes, of 4 inches diameter, were connected to the successive ones through smaller garden PVC pipes of 1-inch diameter such that the end of one big pipe would be the starting point of another (Fig. 2).

Plant base(s) in the prototype

To ensure appropriate spacing between plants, holes were made in the PVC pipe with a distance of 1-1.5 feet. The PVC pipes were considered to be a perfect material for growing the sapling sowing to their durable and chemically inert nature. It was also water-resistant to any possible damage(s) from the continuous presence of nutrient solution inside the hollow structure. Netpots were inserted in these holes- the small net pots allowed the nutrient solution to flow through the roots of plants and at the same time they provided support to plants. To provide additional support to plants (especially, small saplings), hydrotons, or clay Pebbles, or LECA (Light Expanded Clay Pebbles) were used. These additional support structures were placed inside net pots and the saplings were placed between hydrotons for strong support.

Enabling the growth of vegetable crops in the prototype

Selection of vegetable crops

An outcome approach was used to select plants. Considering the larger objective of the study was to provide food to the urban population, four common varieties of crop plants were selected– tomato, brinjal, chili, and lettuce. The selection of plants was also biased by the plant heights since it was a vertical hydroponics structure to be conceived in a small space. We ensured that the spacing of 2 feet between the tiers should be enough for the plant to grow to its maximum height without interfering with other plants.

Nutrient solution and its movement in the prototype

In a hydroponics setup, it is very critical that the flow system of nutrient solution is accurately designed according to the requirements of plants. Absorption rate(s) of nutrients were studied from multiple sources to calculate the frequency and duration of flow of nutrient solution. Knoop solution was considered for growing the plants (Knop, 1976) and the nutrient solution was circulated in the system thrice a day for 10 minutes duration in a time interval of 8 hours using a water pump. A water pump was used to regulate the flow of nutrient solution across all the levels. There was a uniform circulation of the nutrient solution across the tiers as the pumping was done from a reservoir. A 20 l reservoir with a 15 l nutrient solution ensured the circulation of the nutrient solution through the given structure. Plants absorbed nutrients from this flowing nutrient solution. The fresh nutrient solution was first pumped to the topmost (first) tier which flowed to the second, third, and fourth tiers. From the bottom most (fourth) tier, the excess nutrient solution reached the reservoir (Fig. 2). The frequency of the flow of nutrient solution was set at 12 vibration criteria (VC)- in this way, the old, nutrient consumed solution was flushed into the reservoir and fresh nutrient solution was circulated back to the structure from the reservoir. The composition of this nutrient solution was chemically checked at regular intervals and fresh solution were added in the morning hours of the day. Fresh nutrient solution was added after removing the existing content of the reservoir in order to avoid any miscalculations concerning the chemistry of the nutrient solution.

Lighting system for rearing of the plants

The plants chosen for the study included two long-day plants (lettuce and brinjal) and two day- neutral plants (tomato and chili)- there was no artificial lighting provided to the plants. The prototype was kept outdoors such that the plants receive requisite sunlight naturally. Considering the higher light requirement for brinjal and lettuce, they were grown in the first two tiers respectively followed by chili and tomato. Depending on the choice of crops, artificial lighting could be made in-house by using red-blue LEDs as these two colors generate the same wavelength of light as is absorbed by plants.

Analysing the plant physiognomic parameters statistically

The plant growth was monitored and recorded through different morphometric variables of plant height, number of leaves and branches, and length and width of leaves. These measurements were carried out from the week 3 after planting the seedlings. The data was statistically analysed through repeated measures ANOVA (and Tukey's post hoc tests) using PAST 3.20 software (level of significance= 0.05) to check for significant differences across the observations. We did not consider the yield of vegetables at this point since the entire estimation is based on the prototype and we focussed primarily on the system design. Initial experiments in this study were conducted in controlled environments to understand plant behaviour in hydroponics without immediately assessing yield. Yield assessments would come later as conditions are optimized.

Laying the financial plan for expanding the prototype into a larger model

This present case study on the prototype of vertical hydroponics was conducted to understand the feasibility of extra polating this structure to a larger dimension in reality. Itwas designed to observe the technical risks and financial demands concerning the terms of performance and compatibility of our approach. The prototype was built on a smaller scale. The final system for urban use is planned with a modular approach, wherein scalability could be achieved by multiplying the number of units of the final model basis requirement and space constraint. This modular strategy had a huge advantage as space utilization can be optimized in any urban area by changing number of units according to the availability of space.

Results and Discussion

Conception of the prototype of vertical hydroponics

The prototype was developed (Fig. 2) and the crop seedlings were obtained from the nursery. The identically-aged seedlings were potted in the respective tiers and the nutrient solution was circulated through the tiers as explained in the subsection. The plants were enabled to grow with all the basic necessities of photosynthesis and nutrition- light (solar radiations), water, minerals, carbon dioxide (from atmosphere)- provided to them.

Statistical analysis of crop growth

The performance of crop growth was statistically analysed through measurements of certain morphometric, physiognomic parameters. There was development in every parameter of the four crops in the prototype- there was no decreasing

Table 1. Mean (± SD) values of physiognomic parameters per crop grown in the prototype at weeks 3, 4 and 5 [Mean values within a row (for a given crop) followed by different lower-case letters are significantly different (Tukey's pairwise post-hoc test)]

Metrics	Tomato			Brinjal			Chilli			Lettuce		
	Week 3	Week 4	Week 5	Week 3	Week 4	Week 5	Week 3	Week 4	Week 5	Week 3	Week 4	Week 5
Height of plant(mm)	416.6 (± 7.057)[a]	550.82 (± 3.809)[a]	685.04 (± 1.890)[b]	70.8 (± 2.950)[d]	95.96 (± 2.770)[e]	118.06 (± 1.514)[f]	71.44 (± 2.76)[g]	98.18 (± 3.72)[h]	115.82 (± 3.88)[i]	140.2 (± 4.7)[j]	170.32 (± 3.98)[k]	200.32 (± 5.48)[l]
Length of leaves (mm)†	24.68 (± 1.377)[a]	35.88 (± 2.455)[b]	46.18 (± 1.195)[c]	101.76 (± 3.076)[d]	111.16 (± 3.733)[e]	128.76 (± 1.978)[f]	38.68 (± 1.52)[g]	50.6 (± 1.9)[h]	57.94 (± 1.96)[i]	64.02 (± 2.18)[j]	82.08 (± 1.92)[k]	88.94 (± 2.46)[l]
Breadth of leaves (mm)±	14.7 (± 1.162)[a]	21.06 (± 2.840)[b]	25.48 (± 1.318)[b]	66.38 (± 2.295)[d]	70.6 (± 2.824)[d]	77.08 (± 1.043)[e]	23.8 (± 0.9)[g]	27.34 (± 1.06)[h]	32.5 (± 1.1)[i]	38.6 (± 1.3)[j]	54.38 (± 1.32)[k]	59.28 (± 1.62)[l]
No. of branches	8.6 (± 1.140)[a]	12.2 (± 2.280)[b]	16.2 (± 1.304)[c]	-	-	-	4.2 (± 0.8)[g]	5.2 (± 0.8)[h]	6.8 (± 0.2)[i]	6.8 (± 0.2)[j]	9.2 (± 0.8)[k]	10.4 (± 0.6)[l]
Number of leaves (nos.)	107 (± 3.464)[a]	189.8 (± 64.794)[b]	313.2 (± 44.268)[c]	4 (± 0.707)[d]	5.4 (±1.140)[d]	6.6 (± 0.894)[e]	4.25 (± 0.75)[g]	5.25 (± 0.75)[g]	6.8 (± 0.2)[h]	6.75 (± 0.25)[j]	9.25 (± 0.75)[j]	10.4 (± 0.6)[k]

† Third leaf from the base ± Third leaf from the base

values with respect to the time. Table 1 showed the average values of physiognomic parameters of the crops per week. Tukey's post hoc tests revealed the significant differences across the parameters for a given crop as the weeks advanced. Table 2 summarized the F- and p-values of repeated measures ANOVA where the repeated measure is the time period. Significant differences were reported in majority of the parameters of crop(s) at the level of significance= 0.05. The survivability of the crops was 1- no individuals died during the study. From the findings, it can be attested that the performance of the crop growth in the prototype of multi-crop vertical hydroponics is appreciable to evolve into a bigger unit.

Budgeting of the multi-crop vertical hydroponics for real-life applications

This is the final segment of the research design where we interpreted the expenses in building the multi-crop vertical hydroponics system for bigger urban spaces based on the market prices of items. Four major classes of urban locations are defined and limited to the scope of this casestudy- the Prototype is a small setup to demonstrate the viability and functionality of a multicrop vertical hydroponics setup. This setup contains 4 levels each with one 4-foot-long pipe;at a combined level it has 16 running feet of length for vertical farming. This setup can accommodate around 29 plants in the current planned state. Secondly, the home-grown setup is specially designed for urban households, given lack of urban verdancy is a common grievance among the city dwellers. The structure is designed from the perspective that households should be able to fulfill a part of their daily demand with sustainable farming in this structure. This setup contains 6 levels each with three 4-foot-long pipes, at a combined

Table 2. F- and p-values for repeated measures ANOVA of physiognomic parameters of the four crops grown in the prototype

Metrics	Tomato	Brinjal	Chilli	Lettuce
Height of plant	$F_{2,12}$= 6.627 p= 0.02	$F_{2,12}$= 342.9 $p<0.001$	$F_{2,12}$= 494 $p<0.001$	$F_{2,12}$= 239.5 $p<0.001$
Length of leaves	$F_{2,12}$= 188.3 $p<0.001$	$F_{2,12}$= 77.75 $p<0.001$	$F_{2,12}$= 351.8 $p<0.001$	$F_{2,12}$= 208.3 $p<0.001$
Breadth of leaves	$F_{2,12}$= 10.74 p= 0.005	$F_{2,12}$= 23.62 $p<0.001$	$F_{2,12}$= 222.5 $p<0.001$	$F_{2,12}$= 371.8 $p<0.001$
No. of branches	$F_{2,12}$= 33.1 $p<0.001$	-	$F_{2,12}$= 46.91 $p<0.001$	$F_{2,12}$= 56 $p<0.001$
Number of leaves	$F_{2,12}$= 29.27 $p<0.001$	$F_{2,12}$= 6.959 p= 0.018	$F_{2,12}$= 8.389 p= 0.011	$F_{2,12}$= 7.308 p= 0.016

level it has 72 running feet of length for vertical farming. This setup can accommodate around 130 plants in the current planned state. At the third place is the restaurants- any Indian metropolitans and/or town is home to plenty of restaurants. This structure is designed from the point of view that restaurants should be able to utilize their empty spaces. In addition to being a source of fresh ingredients for customers, this setup can be visually pleasing to the aesthetic taste of customers- more to point, urban customers who are deprived of greenery throughout their lives. This setup contains 6 levels each with six 6-foot-long pipes, at a combined level it has 216 running feet of length for vertical farming. This setup can accommodate around 389 plants in the current planned state.

Lastly, this setup is specially designed to use by professional farmers interested in urban agricultural practices- contract manufacturing. The structure is designed from the opinion that farmers should be able to maximize their land efficiency by growing crops vertically. Additionally, it helps to do farming with significantly less usage of water and perform sustainable farming in this structure. This setup contains 10 levels each with ten 10-foot-long pipes, at a combined level it has 1000 running feet of length for vertical farming. This setup can accommodate around 1800 plants in the current planned state. Table 3 self-explains the approximate cost-related aspects of these four major categories upon inducing the multi-crop vertical hydroponics into a larger system.

Going by the numbers of Schnitzler (2012), out of 9.2 billion inhabitants globally, 6.3 billion will be living in the cities by 2050 and that reinforces the necessity of having an agricultural system like hydroponics. A recent study from India found that *Colocasia* and other underground vegetables like

Table 3: Comprehensive budgeting tabulation on costs associated with setting multi-crop vertical hydroponics *

Locations → Logistics ↓	Items	Units	Prototype 4x4	Home-grown 4x3x6	Restaurant 6x6x6	Contract manufacturing 10x10x10
PVC(s)	PVC pipe requirement	Feet	16	72	216	1000
	Cost/Ft	INR	50	50	50	50
	PVC pipe cost	INR	800	3600	10800	5000
Fixture(s)	Number of fixtures	Nos.	8	24	72	200
	Cost	INR	60	60	60	60
	Fixture cost	INR	480	1440	4320	12000
Connecting Pipe(s)	Connecting pipe requirement	Feet	36	68	174	440
	Cost	INR	30	30	30	30
	Connecting pipe cost	INR	1080	2040	5220	13200
Light Panel(s)	Light Panel requirement	Nos.	8	36	108	500
	Cost/Panel	INR	100	100	100	100
	Light panel cost	INR	800	3600	10800	50000
Nutrient solution	Vol. of nutrient solution/Ft	L	2	0.7	0.7	0.7
	Vol. of nutrient solution- pipe	L	32	50.4	151.2	700
	Vol. of nutrient solution- reservoir	L	16	25	76	350
	Total nutrient solution	L	47	76	227	1050
	Cost per L of nutrient solution	INR	10	10	10	10
	Cost of nutrient solution	INR	474	756	2268	10500
Other costs	Structure cost	INR	8000	8000	15000	30000
	Cost of reservoir	INR	2000	2000	4000	8000
	Motor cost	INR	1000	1000	1000	2000
	Consumables charge	INR	2000	2000	4000	6000
	Transportation	INR	2000	2000	3000	4000
	Labour	INR	4000	4000	6000	8000
	Fan, covering & exhaust	INR	12000	12000	15000	20000
Total cost		INR	34,634.21	42,436.00	81,408.00	2,13,700.00

* The costing does not include the charges associated with saplings since the choice of crops is dependent on the location and individual concerned

radish, turnip, and beetroot were growing nicely in the hydroponics system (Agarwal et al., 2021). On top of the serious aspects like food security and greenery, this urban-driven hydroponics model suggested in the paper, shall provide the city dwellers with fresh raw products which often undergo a series of human media to reach the consumers from villages. In a similar line, Romeo et al. (2018) reported that urban hydroponics can promote stability to the food chains in the cities of Europe. It would contribute lesser to the carbon emissions caused due to the transportation of crops and vegetables from distant rural regions to the cities. Nevertheless, this prototype is capable to save space and water owing to its verticality. There is a space paucity in every Indian urban area and this setup has more output per sq. ft. as compared to traditional farming. By utilizing the vertical aspect of space, which was not used in traditional farming, this setup can grow more plants and hence get more output from a similar size as compared to traditional farming. Even if we trace the evolution of the hydroponics system, there are more records of horizontal hydroponics; in this case study, the 3rd dimension of height is utilized. Given our proposed model is mostly indoors, there is no risk of crop harm from the elevated pollution levels of the city-this is in consociation with the findings of Domurath & Schroeder (2009). To the extent that hydroponics is an alternative to cultivated green fodder for the cattle (Kumar et al., 2018).

Hydroponics system is credited for saving plants from diseases and pest infestation which is utterly common in soil-based agricultural practice (Swain et al., 2021).There is no or less use of pesticides in hydroponics-based crop rearing as conducted in the given study, thereby plummeting the effects of these chemicals known to cause environmental problems like biomagnification and eutrophication. Following the Sustainability Development Goals (SDGs) 2: Zero Hunger and 9: Industry, Innovation, and Infrastructure, this multi-crop vertical hydroponics addresses multiple sustainability issues to promote health and better life. Through this study, it is suggested that we encourage the development of such multi-crop vertical hydroponics at a bigger scale to remediate many social and environmental problems.

Conclusion

This paper was based on a case study where a working prototype of multi-crop vertical hydroponics was engineered. The effectiveness of the prototype to enable the growth of crop plants was studied over five weeks and it was observed that the crops were growing appreciably well in this system. The crops chosen in this case study are prevalent yet not scientifically tested for their growth pattern in a hydroponics system in the Indian context. In the end, an elaborate (and approximate) financial blueprint was prepared to enlarge this prototype for real-life applications.

This study focused primarily on developing and testing a proof-of-concept prototype for multi-crop vertical hydroponics, with an emphasis on design, functionality, and basic feasibility in an urban Indian context. Due to the exploratory nature of the research and the limited study period, the primary objective was to demonstrate the system’s viability and observe initial plant growth, rather than conducting a comprehensive economic analysis. A full assessment of the Benefit-Cost Ratio (BCR), including detailed information on unit costs, space requirements, nutrient usage, and water efficiency, was not feasible within the scope of this study. Such an analysis would require extended data collection across multiple growing cycles, as well as consideration of variable cost factors—such as local pricing, crop types, and scale of the setup—which would influence the BCR. Another limitation of this study is that the prototype did not fully account for the varying nutrient requirements of each crop type (tomato, brinjal, chilli and lettuce). These crops have distinct nutrient uptake patterns, especially in terms of nitrogen, phosphorus, and potassium ratios needed for optimal growth. In this initial prototype, a single nutrient solution was used across all crops to assess overall feasibility. However, this approach may not provide the ideal nutrient balance for each plant type, potentially affecting growth rates and yield quality. Future iterations of the system could address this by incorporating separate nutrient reservoirs or a modular nutrient delivery system, enabling customized nutrient solutions to better meet the needs of each crop.

We acknowledge the importance of understanding the economic implications and space requirements for scaling the prototype to a larger operational unit. The primary focus of this study was to validate the prototype's feasibility within a limited timeframe and budget. A comprehensive economic analysis, including detailed cost assessments, space requirements, and resource efficiency, will require additional data gathered over multiple growth cycles, considering factors such as yield consistency and maintenance needs. Furthermore, large-scale implementation costs can vary significantly based on location, market conditions, and specific urban constraints, making it challenging to offer a universal analysis at this stage. Future studies will address these aspects by testing a larger unit under real-world conditions, which will provide the necessary data for a thorough evaluation of the system's economic viability and scalability. This follow-up phase will enable us to conduct an in-depth economic and spatial analysis, critical for assessing the broader potential for scaling the system. There are opportunities for further research lining our findings like automating water flow in vertical multi-crop hydroponics system by building a system to connect sensors and motor, enabling remote operation and monitoring of the system, so users can not only access information but can regulate the system from anywhere in the world, and exploring the impacts of environmental factors like temperature and humidity on the crop growth in this hydroponics system. As research progresses and the system is refined, evaluating yield will become increasingly important to assess the overall effectiveness and viability of hydroponic methods for vegetable production.

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