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ASSESSMENT OF CROP RESPONSES AND CLIMATIC PARAMETERS BY DEVELOPING INDIGENOUS HYDROPONIC GREENHOUSES IN DIFFERENT REGIONS OF PUNJAB-PAKISTAN

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Because of exploding population and declining natural resources, innovative approaches are desired in agriculture to feed billions of hungry mouths. Hydroponic farming provides an opportunity for manifold production from limited land and water resources. Affluent nations have developed multi-storied hydroponic greenhouses that are beyond the capacity of resource-constrained Pakistan farmers. This demanded the development, manufacture, installation, and testing of indigenously designed greenhouses under various locations of Punjab Pakistan. Indigenously developed hydroponic greenhouses were installed at Faisalabad, Lahore, and Multan to examine their technical feasibility. Indigenous hydroponic greenhouse, measuring 30.5 m × 30.5 m with a gable height of 4.26 m, clad with 200 micron UV-stabilized plastic film overlapped with insect-net (40 mesh size), was developed and tested for maintaining temperature and humidity inside the greenhouse at various locations in Punjab-Pakistan. The temperature ranged from 21.6-29.5°C and humidity from 54.6-74.0% in two years of experimentation. The ranges were within the permissible limits for growing vegetables hydroponically. Crop growth parameters including plant height, cluster to cluster distance, and fruit yield were similar at various sites of the experiments suggesting the validity of shed design for various regions of Punjab. The average tomato yield remained 47-69 tons/acre (116-170.4 tons/ha) from the hydroponic unit during 2017-18 and 2018-19 as against 5-10 tons/acre in soil-based tunnel farming.
Keywords: Hydroponic, indigenous hydroponic, design of hydroponic, tomato, drip irrigation, crop, and climatic parameters.

INTRODUCTION

Due to the increasing population of the world, per capita, land availability is decreasing. Currently, 0.25 ha per person will reduce to 0.16 ha by the year 2050. With diminishing arable land due to urbanization, declining soil fertility, poor water management, and falling groundwater levels, it is not possible to meet global food production using conventional soil-based agriculture (Sardare and Admane, 2013). Therefore, it is needed to avail the potential of soilless agriculture. Soilless agriculture results in more yield with less use of water, quality of the product is good, fewer weeds infestation, and more income (Elkazzaz, 2017). Soilless agriculture has been practiced by the ancient people and recent history reveals extensive research relating the same idea under the discipline of hydroponic farming in which plants are grown in an inert medium like coconut fiber and rock pieces (Pradhan and Deo, 2019).

The concept of hydroponic farming has been introduced in Pakistan by establishing five state-of-the-art greenhouses with computer-controlled operations at *Rawat* 30 km from Islamabad. This system was established in 2006 by the Bio-blitz Company, Holland, and later operated by Pir Mehr Ali Shah, Arid Agriculture University, Rawalpindi (PMAS-AAUR). The system has produced tomato, capsicum, cucumber, and cherry tomato, etc. with yields comparable to international levels, 168 ton/ha of tomato on vine and 54 ton/ha of cherry tomato as quoted by Malik *et al.* (2018). The above European type greenhouse with tempered glass structure and 21 ft (6.4 m) ridge height developed at Rawat, Rawalpindi, Pakistan has a high capital cost which is nearly 296.4 million PKR/ha as explained by Haq *et al*. (2018). Apart from technology sophistication, the greenhouse is not energy efficient either. Both the initial and operational costs are high enough to be affordable by the local farmers according to Malik *et al.* (2018). Therefore, indigenization of hydroponic greenhouses was essential for their local adoption that necessitates the development of local design standards for fan and pad cooling system; the size of greenhouse, bay size, ridge height, gutter height, gutter slope, gutter material, structural design against local wind speed, column and truss specifications, foundation, cladding film, fan selection, cooling pads, fertigation and drainage etc.

There is no design developed in Pakistan for hydroponic farming systems except the indigenized system developed by Haq *et al*. (2018). This system was developed on a hit and trial basis for design calculations and operated at Pir Mehr Ali Shah, Arid Agriculture University Rawalpindi (PMAS-

AAUR). However, the adaptability and testing of such an indigenous system have not been carried out at various locations to evaluate its performance. In the absence of any design standards of indigenous hydroponic systems, there is a need to develop indigenous hydroponic greenhouses following standards and to test their performance and acceptability at other locations. Testing included measuring climatic parameters of greenhouse temperature and humidity apart from crop responses such as plant height, cluster to cluster distance and ripened fruit weight per plant, etc. The above-mentioned study was carried out with the following objectives:

1. Indigenization of hydroponic greenhouses for vegetables at different locations of Punjab
2. Assessment of crop responses and climatic parameters in the greenhouses

MATERIALS AND METHODS

***Site Selection*:** All sites for greenhouses in the present study were selected at points away from the shade trees, high buildings, and hills, etc. to capture long hours of sunshine. Greenhouses were located at a higher elevation on the farm to facilitate drainage. Road access for transportation of inputs/outputs was always considered. The sheds were North-South oriented for more sunshine. The selected locations in the study were Water Management Research Center, University of Agriculture, Faisalabad (WMRC-UAF), Governor House, Lahore (GH-Lahore), and Mian Nawaz Sharif University of Agriculture, Multan (MNSUA-Multan) as shown in Fig. 1.

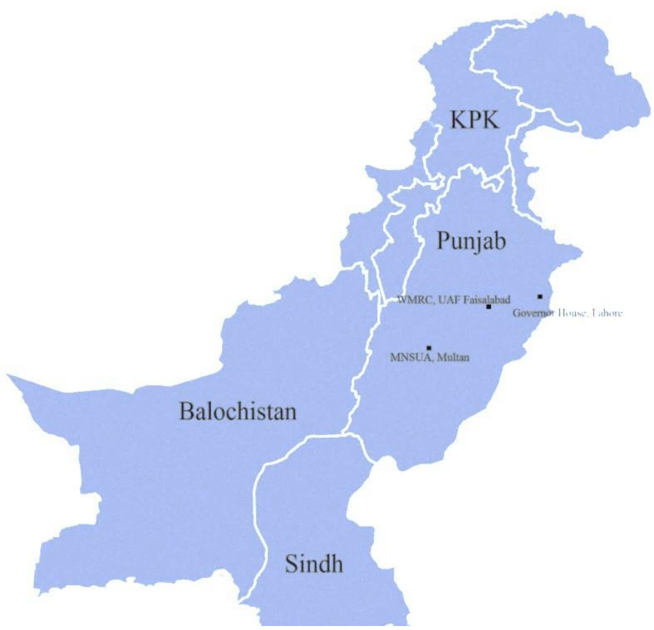

Figure 1. Selected locations of greenhouses at WMRC-UAF, GH-Lahore, MNSUA-Multan

These greenhouses were selected for intensive investigations in respect of climatic and plant growth parameters. The climatic treatments from the greenhouses included measuring temperature and humidity three times a day for the entire cropping season of 2017-18 and 2018-19. Plant heights, inter-cluster distances, fruit weights of the designated plants were measured quarterly. The data were statistically analyzed to find statistical significance among the greenhouses at different locations.

Experimental Design and Analysis: To examine the validity of greenhouse design, humidity and temperature inside the greenhouse were measured at 8 a.m., 12 p.m., and 4 p.m. during cropping seasons for 2017-18 and 2018-19. Descriptive statistics including mean and standard deviation were used to analyze the data of temperature and humidity. Besides, Randomized Complete Block Design (RCBD) was employed by designating sites as blocks whereas keeping temperature and humidity variations as treatments for both cropping years. This was done to find the statistical significance between treatments and blocks. Total observations for both temperature and humidity were 996 and 1336 during 2017-18 and 2018-19, respectively. Means and standard deviation of crop growth parameters (plant height, cluster to cluster distance, and plant fruit weight) were determined for both cropping years. Complete Randomized Design (CRD) was performed to analyze the data on crop growth parameters to check statistical significance among the sites.

***Design of different Parameters for Development of Indigenous Greenhouse*:** An indigenous greenhouse for a hydroponic system requires design and/or selection of structure, cladding material, growing media, cooling and ventilation system, and fertigation system, etc. according to local conditions. Various dimensions of greenhouse design were discussed as under:

***Structure Design*:** Various standards (ASABE, European, and Indian) were reviewed for adaptability according to suitability under local conditions of Pakistan. The Indian Standard (IS) was followed as a reference because of similar climatic conditions and geographical location with Pakistan as given in Table 1. Various components and dimensions of the indigenous greenhouse were shown in Fig. 2 and Fig. 3.

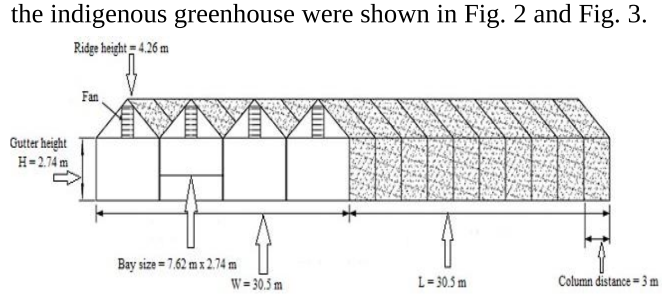

Figure 2. Front and side view of the greenhouse with four bays

Table1. Reference standards for different components of greenhouse structures

Component	Reference
Type of greenhouse	(Bureau of Indian Standards, 1998)
Size	(Bureau of Indian Standards, 1997), Range: 500-1000 m^2
Ridge height	(Bureau of Indian Standards, 1997), Range: 5-5.5 m
Bay size	(Bureau of Indian Standards, 1997), Width × gutter height: 8 m × 4 m
Gutter slope	(Bureau of Indian Standards, 1997), 2 %
Gutter material	(Bureau of Indian Standards, 1997)
Structure joining	(Bureau of Indian Standards, 1997) Structural members are joined by fasteners
Columns	(Bureau of Indian Standards, 1997), 76 mm OD, 2mm thickness
Trusses	(Bureau of Indian Standards, 1997) Bottom & Top cords 60 mm, 2 mm thick
Foundations	(Bureau of Indian Standards, 1997) Insert GI pipes of minimum 60 mm OD or more with a foundation depth of 75 cm depending upon soil type and prevailing wind conditions, grouted with cement concrete mixture of 1:2:4.
Entrance room size	(Bureau of Indian Standards, 1997): Entrance (L × W × H): 3 m × 3 m × 3 m need to be covered with 200-micron transparent plastic
Cladding material	(Bureau of Indian Standards, 2009), UV stabilized 200-micron
Fixing of cladding materials	(Bureau of Indian Standards, 1997), All joints of Plastic film need to be fixed with suitable locking arrangement along with curtain top
Curtain wall/Apron	Adopted (IS standard 14462; 1997) with minor changes
Curtains and insect screen	Adopted (Bureau of Indian Standards, 1997) with minor changes

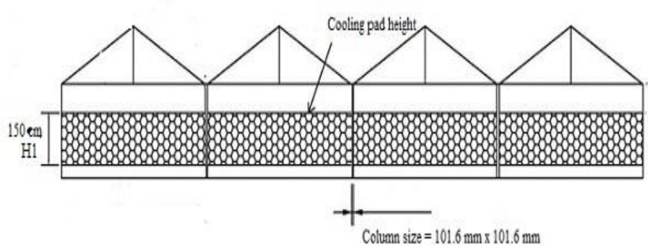

Figure 3. Back view of the greenhouse with cooling pads

Design of Exhaust Fan: According to standard design procedure exhaust, fans should remove air from the greenhouse in one minute to outside (Bucklin, 2014). Therefore, the volume of the greenhouse was calculated as follows:

L = Length of greenhouse, W = Width of greenhouse, H = Height of greenhouse up to the gutter, h = Height of ridge from gutters

Volume of the greenhouse = (L×W×H) + ½(h×W×L)

After calculating the volume of the greenhouse, a market survey was done to check the availability of exhaust fans. The survey included the size of the fan, the capacity of fans in Cubic Feet Per Minute (CFM) / Cubic Meter Per Minute, no. of blades, Revolution Per Minute, and motor horsepower.

***Design of Cooling Pad*:** Area of the cooling pads (cellulose pad) with specific cell sizes was required for providing a laminar flow of cooled air into the greenhouse for maintaining temperature and humidity. The cooling pad height was calculated by the following standards (Bucklin *et al.*, 2014). The pad area was calculated as follows:

Area of the cooling pad (A) = Volume of air inside the greenhouse/ cellulose pad air exchange capacity

Cooling pad height (H_1) = Area of the pad(A)/back width of the greenhouse wall (L)

A market survey was done to check the availability of cooling pads their size and rate of air exchange per minute of the cooling pads. For most greenhouses, a pad height of one foot is required for every 6 m pad to fan distances (Bucklin *et al.*, 2014)

***Design of Pump for Cooling System*:** The capacity of the pump for spraying water on cooling pads was calculated following standards (Worley, 2009). The pump delivers water per linear foot of the cooling pad. The pump capacity was calculated as under:

Water requirement per linear foot of cooling pad = gpm

Length of pipe spraying water on cooling = width of greenhouse (m)

Total discharge required = Length of pipe × water requirement per linear ft or m

The pump was selected based on total discharge and required horsepower.

***Design of Drainage Sump (Reservoir)*:** Water from the cooling pads was drained into the drainage sump. The design of the drainage sump was done to address the flow of water coming from cooling pads. For the design of drainage, sump standards were followed (Worley, 2009). Drainage sump specifications were calculated as follows:

Area of the pads (m^2) = pad length × pad height

Water drain from pads = gallon/ft^2 or gallon/m^2

The total volume of water drained from cooling pads = gallons

Assume depth of sump = m

Surface area of the sump = Volume /assume depth = m^2

One side of square sump = m
Sump specification= width × length × depth = m^3

***Design of Irrigation System*:** The design of a drip irrigation system required pump design. The pump forces water of the required quantity at a certain pressure head with a specific prime mover horsepower (hp) into the irrigation system. A schematic diagram of the drip irrigation system is shown in Figure 4. The pump for the drip irrigation system was designed as follows:

Discharge of emitter = lph
The diameter of Lateral = mm
Length of lateral = ft (m)
Total number of lateral = Nos
Lateral to lateral spacing = ft (m)
Emitter to emitter spacing = m
The total flow in the system = lps
Total head loss (H) = $H_1 + H_2 + H_3 + H_4 + H_5$ (head losses are shown in Figure 4)
H = total head loss (m), H1 = head loss in lateral line (m), H2 = head loss in main/sub-main line (m), H3 = head loss in filtration (m), H4 = operating pressure for emitter = 10 (m)
The pump was designed based on the required discharge and head.

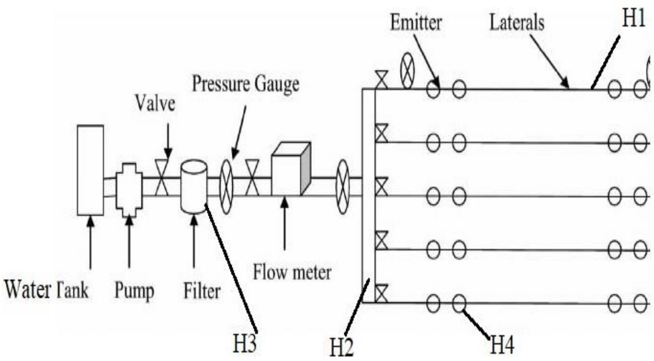

Figure 4. Schematic diagram of drip irrigation system

***Assessment of Crop Responses and Climatic Parameters in Greenhouses*:** Three greenhouses were constructed at three sites in the province of Punjab-Pakistan. These sites were to be evaluated for crop and climatic parameters. The sites of greenhouses for crop performance evaluation were at Governor House Lahore (GH-Lahore), University of Agriculture, Faisalabad (WMRC-UAF), and Mian Nawaz Sharif, University of Agriculture (MNSUA) Multan. The following variables were considered for measurements during crop seasons of 2017-18 and 2018-19.

Crop Responses: Plant height: Plant heights of 15 randomly designated plants were measured fortnightly in each of the three selected greenhouses at different sites. The variability of the observations was statistically analyzed for retrieving useful information.

Cluster to cluster distance: Cluster to cluster distance should be least for yield increases. Growers make all efforts to reduce distance so that the fruit clusters are maximum per unit height of the plant. Therefore, 15 plants were randomly selected and tagged for measurement of the cluster to cluster distance on all of the plants. At the end of the season, results were analyzed.

Yield per plant: Tomato yield values obtained fortnightly in (g) were statistically analyzed for the selected plants to check the statistical significance among various sites.

Climatic Parameters: Temperature: A temperature of 23-28 °C is required in the greenhouse for the better growth of plants (Shamshiri *et al*., 2018). A Digital meter (Figure 5) was used to measure temperature. The temperatures were measured at 8:00 am 12:00 noon and 4:00 pm a day throughout the growing season of the crop.

Figure 5. Digital meter for measuring temperature and humidity

***Humidity*:** The range of 60-90 % humidity is suitable for most tomato varieties as explained by ASABE (Shamshiri *et al.*, 2018). Digital meter (Figure 5) was also used to measure and record humidity at 8:00 am 12:00 noon, 4:00 pm.

RESULTS AND DISCUSSION

Three greenhouses each 30.5 m × 30.5 m were designed (Bureau of Indian Standards, 1997; Bureau of Indian Standards, 1998; Bureau of Indian Standards, 2009) and installed at three different locations in Punjab-Pakistan. Technical specifications of greenhouses designed in the present study are given in Table 2.

***Cladding Material*:** Greenhousecladding (Fig.6) comprises a plastic sheet of 200-micron (Bureau of Indian Standards, 2009) overlapped with a 40 mesh virus net. This combination was used for the roof as well as sidewalls of the greenhouse in the present study for giving extra strength from wind and rainfall damage. A 210 cm long locking profile is used to hold the plastic sheet and virus net in position.

Table2.Technical specification of greenhouse design in the study

Items	Specifications (Adopted/Selected) for present study	Reference
Type of greenhouse	Fan & Pad cooling	(Bureau of Indian Standards, 1998)
Size	30.5 m × 30.5 m	(Bureau of Indian Standards, 1997) , Range: 500-1000 m^2
Ridge height	4.26 m, Ridge height reduced from the standard for cost reduction	(Bureau of Indian Standards, 1997), Range: 5-5.5 m
Bay size	7.62 m × 2.74 m, (width × gutter height)	(Bureau of Indian Standards, 1997), Width × gutter height: 8 m x 4 m
Gutter slope	2 %	(Bureau of Indian Standards, 1997) 2 %
Gutter material	Galvanized iron sheet 1mm thick, trapezoidal with a perimeter of 500 mm	(Bureau of Indian Standards, 1997)
Structure joining	Structural members joined together by fasteners and welding	(Bureau of Indian Standards, 1997) Structural members are joined by fasteners
Columns	Squared pipe with 101.6 mm x 101.6 mm dimension, 1.65 mm thickness Reason: Market availability	(Bureau of Indian Standards, 1997), 76 mm OD, 2mm thickness
Trusses	Bottom & top cords 50.8 mm with 1.65 mm thickness., Reason: Market availability	(Bureau of Indian Standards, 1997) Bottom & Top cords 60 mm, 2 mm thick
Foundations	Insert GI pipes of 101.6 mm × 101.6 mm, (×-sec: 75 cm × 75 cm) with a foundation depth of 75 cm, grouted with cement concrete mixture of 1:2:4.	(Bureau of Indian Standards, 1997) Insert GI pipes of minimum 60 mm OD or more with a foundation depth of 75 cm depending upon soil type and prevailing wind conditions, grouted with cement concrete mixture of 1:2:4.
Entrance room size	Entrance room (L × W × H): 210 cm × 150 cm × 250 cm, covered with polyethylene of 200-micron plastic sheet and a door on one side	(Bureau of Indian Standards, 1997): Entrance (L × W × H): 3 m × 3 m × 3 m need to be covered with 200-micron transparent plastic
Cladding material	Polyethylene sheet of UV stabilized 200-micron	(Bureau of Indian Standards, 2009), UV stabilized 200-micron
Fixing of cladding materials	Polyethylene sheet overlapped by insect screen with 40 mesh size, fixed with the upper cords of the frame using locking profiles, Reason: Insect screen was overlapped for stiffness and strength	(Bureau of Indian Standards, 1997) All joints of Plastic film need to be fixed with suitable locking arrangement along with curtain top
Co-axial fan	Four co-axial fans of 1200 mm diameter containing 6 numbers of GI sheet blades, the frame of GI sheet material covered aluminum louver	Designed
Drip Irrigation System	The drip irrigation system originated from a water tank where a submerged filter was used to remove the suspended debris. PVC pipe with internal dia 76 mm conducts water to the mainline (76mm) from where laterals (16mm) are laid along the crop lines with one emitter (4lph) per two plants in rock wool block.	Designed
Cellulose pad for cooling	Cellulose pad 10 cm thick, 150 cm height 60 cm wide was placed on a channel of aluminum with a width of 184 mm and length equaling one side of the greenhouse. Channel was used as a drain to carry water beneath pads. Plastic pipe (13 mm dia) with perforations 2mm dia, and 38 mm apart was laid at the top of pads for water sprinkling.	Designed
Pump with accessories for a cooling pad	A pump of 1.5 kW was used to raise water from a sump of 1m × 1m × 1.5m, (L × W × D) with a masonry lining Pump delivered 3.5lps	Designed
Electric wiring	Copper wiring	Use copper wire to withstand the desired load of required electrical appliances with an ISI mark
Footpath	A tuff tile footpath of 1 m width and 50 mm thickness was laid all around the greenhouse	Adopted (Bureau of Indian Standards, 1997) with minor changes
Curtain wall/Apron	11cm brick wall 38 cm above ground level on all three sides of the greenhouse was erected to avoid water entering from adjoining fields	Adopted (IS standard 14462; 1997) with minor changes
Curtains and insect screen	40 mesh insect screen was overlapped on the plastic film already laid on the roof as well as sidewalls of the greenhouse to increase the strength of plastic and also to avoid insects from entering the greenhouse.	Adopted (Bureau of Indian Standards, 1997) with minor changes

***Cooling and Ventilation System*:** Cooling pads were placed at the back of the greenhouse through which air was sucked in with the help of exhaust fans fixed on the opposite wall. A distance of 100 ft (30.5 m) between fan and pad for efficient cooling was maintained (Bucklin *et al.*, 2014). Each cooling pad is 60 cm wide, 10 cm thick and 150 cm high. Water poured from a perforated PVC pipe on the top of the cooling pad trickles down into the GI-drainage channel (15 cm wide drainage channel as shown in Figure 7-point B), with a 15 cm depression of 10 cm width at the middle. The depression helps to collect and conveying drainage water from the cooling pads to the drainage sump. Channel is placed under the entire length of cooling pads. To hold cooling pads in a vertical position, pads are held near the top by two parallel pipes on both sides. An air filtration chamber is provided at the back of the greenhouse. The air filtration chamber is covered with insect net (Figure 7-point A) to avoid pests, viruses, dust, and airborne debris from entering into the greenhouse during air suction through cooling pads (Figure 7-point C) through exhaust fans.

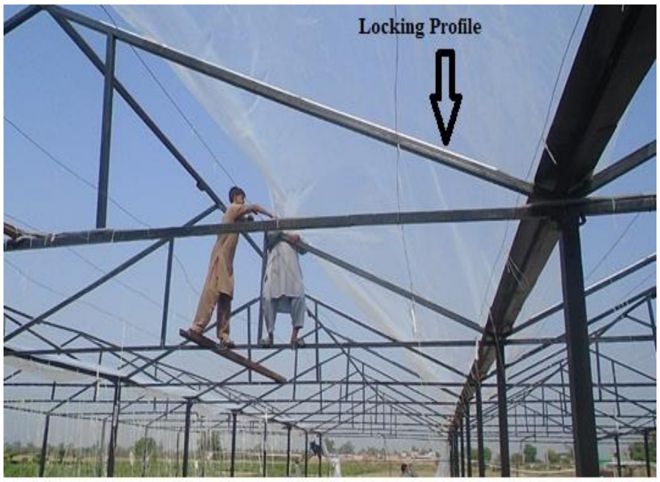

Figure 6. Greenhouse cladding film

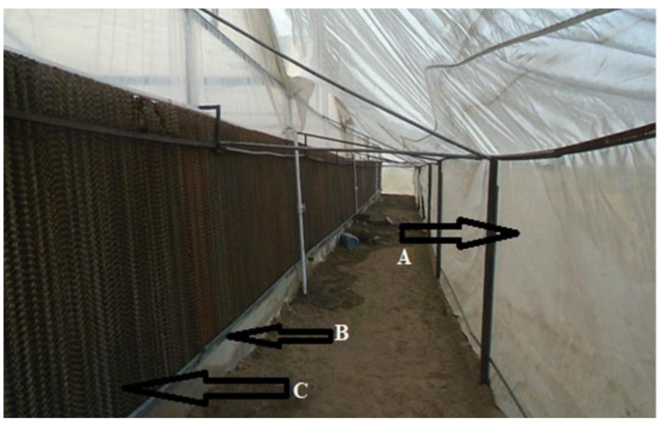

Figure 7. Air filtration chamber (A: Insect net, B: GI-drainage channel, C: Cooling pads)

The chamber is 150 cm wide, 175 cm high and 30.5 m in length. Virus-net of 40 mesh size spreads around the filtration chamber. Chamber houses a drainage sump and a submersible water pump for a cooling system. A small door is provided for entrance into the chamber for maintenance of these gadgets.

Design of Fan: Four exhaust fans were fixed at a height of 270 cm (gutter height) from the ground on the wall opposing the pads (Figure 8). Fans are placed 750 cm apart from each other (Bucklin *et al.,* 2014). Each exhaust fan has 28800 Cubic Feet Per Minute (CFM) capacity, co-axial in design, 150 cm dia, 1.5 kW, and 450 rpm. The size of the exhaust fan has been selected as follows:

L = Length of greenhouse, W = Width of greenhouse, H = Height of greehouse upto gutter, h = Height of ridge from gutters

Volume of the greenhouse = (L × W × H) + 1/2 (h × W × L)
= 100×100×9+[2 (50×5) /2] ×100 = 115000 ft^3 (10689 m^3)
Fan capacity = 28800 ft^3/min(816 m^3/min)
Rate of air exchange = 1 per minute (Bucklin *et al.*, 2014)
No. of fans = 115000/28800 = 3.99 =4

Therefore, four fans each with a capacity of 28800 ft^3/min (816 m^3/min) will cause one air exchange per minute as required by the greenhouse ventilation design.

Figure 8. Co-axial exhaust fans installed in each bay of greenhouse

Design of Cooling Pad**:** The pad and fan cooling demanded pouring water on a fibrous wettable material with small cells to restrict the turbulence of air and delivering it more smoothly. The area of the pads with specific cell sizes was required for providing a laminar flow of air in the greenhouse. The pad area was determined as next.

Air exchange required per minute = 115000 ft^3/min (3258 m^3/min)
(as calculated above)
Length of the wall for pads (L) = 100 ft (30.5 m)
4" (10cm) wide cellulose pad air exchange capacity = 250 ft^3/min/ft^2(0.65 m^3/min/m^2) (Bucklin *et al.*, 2014)
Area of the pad required (A) = 115000/250 = 500 ft^2(46 m^2)
Pad height = A/L = 500/100 = 5 ft (150 cm)

For most of greenhouses, pad height of one foot is required for every 20 ft (6 m) pad to fan distances (Bucklin *et al.*, 2014).

Water delivery of 0.5 gallons per minute (gpm) per linear foot of pad length is considered appropriate over a 4 inch (10cm) thick cellulose pad (Worley, 2009). A PVC pipe of 1.5 inches was laid over the top of pads, where the pipe had 1/8-inch (3mm) dia holes, 3 inches (7.62 mm) apart. Because of this pump size was selected as under:

Design of Pump for Cooling System**:** A pump for a cooling system was required to deliver water at a rate of 0.5 gpm per linear foot (304.8 mm) of 4 inches (101.6 mm) cooling pad (Worley, 2009). The pump capacity was designed as under:

Water requirement per linear foot of pipe = 0.5 gpm
Length of pipe = 100 ft (30.5 m)
Total discharge required = 0.5 × 100 = 50 gpm = 3.5 lps
The pump was designed with a discharge of 3.5lps and 1.5hp

Design of Drainage Sump (Reservoir)**:** The volume of water required for spraying over the pads should be 0.75 gallons/ ft^2 of 4 inches thick cellulose pad (Worley, 2009). A sump (Figure 9) was designed as follows:

Area of the pads = pad length x pad height = 100 ft × 5ft = 500 ft^2 (5379 m^2)
Water drain from 4 inch pads = 0.75 gallon/ft^2 (Worley, 2014)
Total water requirement = 500 × 0.75 = 375 gallons
Volume for 400 gallons = 1500 liter = 54 ft^3 = 1.5 m^3
Assume depth of sump = 5 ft (1.52 m)
The surface area of the sump = 54/5 ≈ 11 ft^2 (1 m^2)
One side of square sump = 3.3 ft (1 m)
Sump specification = width×length×depth = (1m×1m×1.5m)

Figure 9. Drainage sump (Reservoir)

Roof Top Rainwater Harvesting in the Greenhouse**:** On the roof of the greenhouse, three rainwater harvesting drainage channels are provided which tap rainwater in the event of rainfall. Each channel (Figure 10) conducts rainwater directly into a pond dug by the side of the greenhouse. The channel was made with galvanized iron sheet 1mm thick, trapezoidal with a perimeter of 500 mm (Bureau of Indian Standards, 1997).

Figure 10. Rainwater harvesting drainage channel/gutter

Design of Irrigation System**:** For uniformity of irrigation, A dripper of 4 liters per hour (lph) discharge and drip line of 16 mm was selected (market availability) for application of the required quantity of nutrient solution (66.6ml/min) to a Rockwool block. Design of irrigation system requires pump design which forces water of required quantity at a certain pressure (head) with a specific prime mover horsepower into the irrigation system. The pump was designed as follows:

Discharge of emitter = 4 lph
Diameter of Lateral = 16 mm
Length of lateral = 90 ft (27 m)
Total number of lateral= 20
Lateral to lateral spacing = 5 ft (1.5 m)
Total no. of emitters = 1000
The total flow in the system = 1.2 lps
Total head loss (H) = H1 + H2 + H3 + H4 + H5
H = total head loss (m), H1 = head loss in lateral line (m), H2 = head loss in main/sub-main line (m), H3 = head loss in filtration (m), H4 = operating pressure for emitter = 10 (m)
Pump with Q (discharge) = 1.2 lps , H = 10 m and hp = 0.5 was designed

The head loss in the lateral line, mainline, sub-mainline was negligible and there was no filtration as the water was cleaned through the Reverse Osmosis (RO) plant before applying to the crop. Therefore, the head losses were equal to the operating pressure of the emitter which was 10 m.

Irrigation Plan**:** The irrigation plan included time clock scheduling plus an additional dose of 20-30 % extra water for drainage. The extra water 25-30 % of applied water must drain out of slabs (Mavrogianopoulos, 2015). The quantity of water was adjusted by increasing/decreasing the time of irrigation. The medium used for growing tomatoes hydroponically was imported coco-slabs as the best growing medium (Haq *et al.*, 2018). Drainage water from the slabs was conducted in fiber trays placed underneath the coco-slabs as shown in Figure 11-point A. Emitters were fixed on drip line of 16 mm, outer dia (OD) placed over coco-slab as shown in Figure 11- point B. Each coco-slab was equipped with two rock-wool blocks housing two tomato plants per rock-wool block as shown in Figure 11- point C. A pump with a capacity of 1.2 lps was designed for giving water to irrigation drip lines.

Fertilizer Application System**:** Water supply with appropriate nutrients is most essential for hydroponic greenhouses. All equipment such as reverse osmosis, micro (A), and macro (B) nutrients solution tanks with a 200-liter capacity each are placed inside a small room (2.4 m × 2.4 m) (Figure 12) for closer watch and ward of the grower. Another tank stores pumped groundwater (Figure 13). The RO unit sucks water from the groundwater tank, processes it, and delivers it to RO water storage tanks (Figure 14), where the recipe was prepared by mixing desired quantities of solution from A and B tanks.

Figure 11. Arrangement of drip line and fiber trays inside the greenhouse (A-Fiber trays for carrying drainage water, B-Drip line with the emitter, C-Coco-slabs with two rock wool blocks)

Figure 12. RO plant accessories, A: micro-nutrient tank, B: macro-nutrient tank

Figure 13. Groundwater storage tank

Figure 14. RO water storage tanks for recipe preparation

Climatic Parameters in Greenhouses**:** The ranges of climatic parameters for successful hydroponic cropping in greenhouses have been widely discussed in the literature. Humidity needs to be maintained 60-90 % for tomatoes as given in ASABE-2015 (Shamshiri *et al.*, 2018). Moreover, the optimal range of relative humidity during the entire growth stages of tomato is suggested to be between 50-70%. Studies also show the tomato pollination is significantly enhanced when RH is around 60% (Harel *et al.*, 2014). It should be underlined that plants exposed to higher temperatures require higher humidity as explained (Kittas *et al.*, 2005; Shamshiri *et al.*, 2018). The variations of climatic parameters in the present study have been discussed next.

Greenhouse Temperature**:** Temperatures observed in the present study are presented in Tables 3 and Table 4 for greenhouses at the three sites. Greenhouses were designed to keep temperature fluctuation from 23 to 32°C required for proper pollination in the case of tomato (Shamshiri *et al.*, 2018).

Table 3. Mean temperature values inside the greenhouse at various locations during 2017-18

Site	**Temperature (°C)**			
	8 am	**12 pm**	**4 pm**	**Mean**
WMRC-Faisalabad	24.71	28.70	25.94	26.45 a
GH-Lahore	24.29	28.69	26.83	26.60 a
MNSU-Multan	26.22	31.07	30.73	29.34 b
Mean (SD*)	25.07 (3.91)	29.49 (2.26)	27.83 (3.21)	-

SD* = Standard Deviation *Different alphabets refer to statistical significance among sites at α = 5 %

Table 4. Mean temperature values inside the greenhouse at various locations during 2018-19

Site	Temperature (°C)			Mean
	8 am	12 pm	4 pm	
WMRC-Faisalabad	19.11	25.80	24.95	23.29 a**
GH-Lahore	19.99	27.87	26.66	24.84 b
MNSU-Multan	26.00	29.63	28.08	27.90 c
Mean (SD*)	21.70 (4.24)	27.72 (2.12)	26.56 (2.10)	-

SD* = Standard Deviation **Different alphabets refer to statistical significance among sites at α = 5 %

The temperature averages (Table 3 and Table 4) suggest a similar trend at all three locations with minimum temperatures in the morning and slightly higher temperatures at mid-day as well as in the evening hours. The temperature remained within the normal range of 23 °C to 32 °C suggesting the validity of various dimensions of greenhouse design at all three sites. The temperatures remained significantly higher at Multan (Table 3 and 4) compared with other sites due to higher atmospheric temperatures in the region as temperatures go up to 50 °C during daytime(https://en.wikipedia.org/wiki/Climate_of_Multan).
High temperatures at Multan site may be associated with its nearness to Cholistan-desert where the mercury touches high extremes. Average temperatures were quite similar at Lahore and Faisalabad sites since the cities are less than 150 km apart. The means and their standard deviations at three different times of the day (Table 3 and 4) suggested that 95 percent of the temperature values fall within the acceptable range of 23°C to 32°C. Temperatures in sheds at all three sites fall within acceptable ranges thus approving shed, fan, pad designs, and selection of 200-micron, UV-stabilized polyethylene cladding film.

***Greenhouse Humidity*:** Higher humidity values in a greenhouse effect crop growth due to reduced transpiration inviting fungal attacks, minimizing flowering and pollination resulting in retarded plant growth. Humidity measurements were taken three times a day throughout the cropping season. Means of greenhouse relative humidity at the three sites are given (Tables 5 and 6). Humidity means-tested statistically significant at α = 5% for sites whereas, humidity at Multan was 12 and 15 percent higher compared with those of Faisalabad and Lahore respectively during the year 2017-18. On the other hand, the means of humidity values at different hours of the day are 68.26, 54.64, and 55.69% for the morning, noon, and evening hours. Humidity was higher in the morning hours compared with noon and evening due to condensation vapors on the cladding film during the night. Values of standard deviation further suggest that 95 percent of the data values would fall within permissible limits of 60-90 % as recorded in ASABE 2015 (Shamshiri *et al.*, 2018) for greenhouse farming.

Table 5. Mean humidity values inside the greenhouse at various locations during 2017- 18

Site	Humidity (%)			Mean
	8 am	12 pm	4 pm	
WMRC-UAF	65.79	54.96	53.42	58.06 a**
GH-Lahore	63.51	51.11	54.93	56.52 a
MNSU-Multan	75.5	57.87	61.73	65.03 b
Mean (SD*)	68.26 (13.31)	54.64 (9.39)	55.69 (10.11)	-

SD* = Standard Deviation**Different alphabets refer to statistical significance among sites at α = 5 %

Table 6. Mean humidity values inside the greenhouse at various locations during 2018-19

Site	Humidity (%)			Mean
	8 am	12 pm	4 pm	
WMRC-UAF	71.76	64.61	65.21	67.19 a**
GH-Lahore	74.38	67.85	67.32	69.85 b
MNSU-Multan	76.14	71.17	70.59	72.63 c
Mean (SD*)	74.09 (9.49)	67.88 (7.14)	67.71 (7.38)	-

SD* = Standard Deviation **Different alphabets refer to statistical significance among sites at α = 5 %

Again, the average humidity values measured during 2018-19 (Table 6) indicate the trends similar to earlier years suggesting that humidity values are statistically different at the sites. However, humidity values remained within the acceptable limits for proper crop growth. Humidity values at different hours of the day also suggest that 95% of the data falls within permissible limits as evidenced from the standard deviations (Table 6). Data averages at all the sites were suggesting the suitability of these regions for hydroponic vegetable farming in greenhouse settings.

***Plant Responses*:** Plant growth and yield are the ultimate goals of crop husbandry. In the present study plant height, inter-cluster distance, and fruit yields were measured to determine differential responses among sites for both cropping seasons of 2017-18 and 2018-19. The measurements were also made to examine the suitability of the structural design at different locations of the study.

***Plant Heights*:** Heights of randomly selected fifteen plants, at each site, were measured quarterly. Plant heights (Table 7 and 8) were statistically tested to examine the differential response of sites. Sites tested statistically insignificant for both cropping seasons 2017-18 and 2018-19. However, differences in overall mean values at the sites during 2017-18 suggested that plants at Lahore were 30 and 38 percent taller than Faisalabad and Multan respectively. The higher values of height at the Lahore site may be associated with the length of the cropping season, which were 227, 212, and 266 days at Faisalabad, Multan, and Lahore sites during 2017-18. It may be noted that the extra 54 days of cropping season at Lahore have paid back in terms of plant height, which is 38% higher than Multan sites.

The data values and their analyses during the cropping season of 2018-19 were similar to that of 2017-18 except the heights were similar at Faisalabad and Multan sites due to a smaller difference between their crop days.

Table 7. Mean values of plant height (cm) inside the greenhouse at various locations during 2017-18

Site	Mean
WMRC-Faisalabad	355 a*
GH-Lahore	461 a
MNSU-Multan	335 a

*Different alphabets refer to statistical significance among sites at α = 5 %

Table 8. Mean values of plant height (cm) inside the greenhouse at various locations during 2018-19

Site	Mean
WMRC-Faisalabad	372 a*
GH-Lahore	355 a
MNSUA-Multan	371 a

*Different alphabets refer to statistical significance among sites at α = 5 %

The crop keeps on yielding up to 266 days if properly managed as indicated at the Lahore site. whereas the financial gains/losses with time shall be considered.

***Plant cluster to Cluster Distance*:** Cluster to cluster distance on the plant is an indicator of its yielding capacity, that is, the lesser the distance more the clusters and more is the yield. Therefore, efforts were made to reduce the distance through management techniques. Generally, well-thought management keeps the distance at the minimum. Because of the importance associated with the cluster to cluster distance, they were quarterly measured on 15 randomly selected plants at each site. The data were statistically analyzed to detect differential responses among sites. Means of the cluster to cluster distance are given in Tables 9 and 10. The sites tested significantly at α = 5% during 2017-18 and cluster to cluster distance was 13 to 14% less at Faisalabad compared with Multan and Lahore sites during 2017-18. It can be seen that the cluster to cluster distance was not significant at Lahore and Multan whereas this distance was significant in Faisalabad in comparison with the other two locations. The differential responses among the sites were many and varied including, the experience of the grower for timely management of recipes and fertigation, etc. (Hochmuth and Hochmuth, 2001; Hochmuth and Hochmuth, 2012; Hochmuth and Hochmuth, 2016). However, the differential responses of the cluster to cluster distance among the sites were insignificant during the 2018-19 cropping season (Table 9). It may also be noted the cluster to cluster distance, on average, decreased by 16% during the second year of experiments, and the decrease may be associated with experience growers gained over time by managing inputs such as timely fertigation, EC, and pH controls. This suggested that the management techniques and their timeliness considerably contributed to the cluster-to-cluster distance and ultimately the crop yield.

Table 9. Mean values of plant cluster to cluster distance (cm) inside the greenhouse at various locations during 2017-18

Site	Mean
WMRC-Faisalabad	27.5 a*
GH-Lahore	32.2 b
MNSUA-Multan	32.1 b
Mean	30.6

*Different alphabets refer to statistical significance among sites at α = 5 %

Table 10. Mean values of plant cluster to cluster distance (cm) inside the greenhouse at various locations during 2018-19.

Site	Mean
WMRC-Faisalabad	25.9 a*
GH-Lahore	26.4 a
MNSUA-Multan	27.0 a
Mean	26.4

*Different alphabets refer to statistical significance among sites at α = 5%

***Plant Fruit Weight*:** Ripened fruits were harvested from the designated plants and weighed quarterly. The analysis of variance of yield data resulted in statistical insignificance of the sites (Table 11). Tomato yields vary 44 to 51 tons/acre at different sites with Multan producing 15.9 % and 8.5% more yield compared with Faisalabad and Lahore in 2017-18. The yields were again statistically insignificant during 2018-19 (Table 12). However, the average yield at Faisalabad was 7.4 and 4.3% higher than Lahore and Multan. These variations could be associated with the experimental error.

Table 11. Mean values of fruit weight (kg) per plant inside the greenhouse at various locations during 2017-18.

Site	Mean	Estimated yield/acre (tons)
WMRC-Faisalabad	4.4 a*	44
GH-Lahore	4.7 a	47
MNSUA-Multan	5.1 a	51
Mean	4.7	47

*Different alphabets refer to statistical significance among sites at α = 5 %

The insignificant variations of yield at the three sites were interesting and reflected on precise and well-managed temperature and humidity inside the sheds at all the locations. Generally, the crop parameters including height, cluster to cluster distance, and finally yields indicated indifference to the location of site suggesting the suitability of different regions of Punjab-Pakistan for hydroponic farming. Furthermore, invariability of crop parameters established the validity of the indigenous design of greenhouse and its parameters such as structure height, width, length, cooling & ventilation, fertigation, cladding film, etc.

In Holland the hydroponic tomato production is 100 kg/m^2 (404 tons/acre) and in Australia 65 kg/m^2 (263 tons/acre) (Ly, 2011) in case of this study, it was 18 kg/m^2 (72 tons/acre). The yields in the present experiment are 4-6 times short of achievable targets. It was evident that yields in the second year, on average, yields were 48 % higher compared with the first year. This difference might be associated with the experience of the grower in managing temperature, humidity, EC, pH, timely sowing, fertigation, cooling & ventilation, etc. Therefore, the gap between the achieved and achievable could be minimized by continuing consistent hydroponic farming practices.

Table 12. **Mean values of fruit weight (kg) per plant inside the greenhouse at various locations during 2018-19**

Site	Mean	Estimated yield/acre (Tons)
WMRC-Faisalabad	7.2 a*	72
GH-Lahore	6.7 a	67
MNSUA-Multan	6.9 a	69
Mean	6.9	69

*Different alphabets refer to statistical significance among sites at α = 5 %

Conclusion and recommendations

***Conclusions*:**

1. Three greenhouses each at Faisalabad, Lahore, and Multan were established following international standards and were found suitable for Punjab conditions
2. Temperature and humidity measurements made during two cropping seasons remained statistically significant but within range of 21.6-29.5 °C and 54.6-74.0 %, respectively, and they were within permissible limits required for successful hydroponic farming validating the indigenous design of greenhouse
3. Plant growth parameters including plant height, cluster to cluster distance, and fruit weight measured during experimentation remained statistically insignificant and established similarity of climatic conditions in the study sites of Punjab for raising hydroponic vegetables. The tomato on average, yielded 47 tons/acre (116 t/ha) during 2017-18 whereas production increased to 69 tons/acre (170.4 t/ha) the following year. The increase was associated with management experience without changing any design parameters during the second year

***Recommendations*:**

1. Optimization of greenhouse design parameters should be carried out through simulation considering real-time local climatic conditions
2. The heating system should also be designed and studied for maintaining temperature and humidity during the winter months
3. Future studies relating to the indigenous hydroponic system should be carried out for small and large scale farming by changing design parameters accordingly

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