Energy efficient cooling and heating of aquaponics facilities based on regional climate

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Abstract

An already existing aquaponics facility in Jordan, named *Khodra*, will be used to evaluate the cooling and heating profiles to provide the best environment for plants and fish to thrive. A replica of the 'Khodra' facility will be simulated to be built in Qatar. Good ventilation rate with 50% green color shading was sufficient to reduce the temperature down by almost 10 degrees in 'Khodra'-Jordan while using a heating, ventilation and air conditioning water-chiller based system reduced the humidity in the 'Khodra'-Qatar greenhouse yet using AC split units was cheaper for the small size, 360 m^2, of this specific greenhouse.

Keywords: aquaponics; HVAC; Qatar; Jordan; greenhouse

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1 INTRODUCTION

Greenhouses are usually built in such a way that disregards energy efficiency. Poor investment in the envelope's material and in an automation control system for the zone's thermal and hygienic requirements is a critical issue. Most commercial greenhouses are built from an inexpensive, highly transparent and poor insulating material, making all yearlong food plantations impossible. This is where aquaponics takes a transformative role; not only do they provide twice as plant harvest in comparison with conventional farming, they also use 90% less water than traditional farming, which is crucial in countries like Jordan that is ranked third in water scarcity.

An aquaponics is a system that combines both aquaculture and hydroponics (growing plants without soil) to create a balanced system. One can also benefit from vermiculture, which is the waste of plants to produce compost/fertilizers. Water, energy and fish feed are the three largest physical inputs for aquaponics systems. In most greenhouses, energy is the second largest cost after capital and labor cost.

A key point worth mentioning is that in aquaponics systems, 'Food Miles' is greatly reduced, meaning fewer gas emissions in food transportation when importing food into the country. This, in return, coincides with the ethical value of green and sustainable living. Smart cities and urban areas can benefit from the aquaponics farming practices that fit the sustainability trend and this case it would be a combination of sustainable energy and food production [1,2].

Aquaponics farming systems have been researched globally with over 500 publications on aquaponics since 1978 and 160 of those were published in the past 4 years with various trends and technologies [3]. Aquaponics systems are fairly new to countries in Africa and the Middle East as evident by an international survey conducted in 2014 where only a single response was received from each Ghana, Oman and South Africa [4].

A 2016 survey that yielded 44 responses from aquaponics farmers helped shed the light on the status of aquaponics in South Africa. Eighty-two percent of raised fish is tilapia and 75% of the farmed plats are leafy vegetables. The study classified the aquaponics farming stage in South Africa as an emerging practice [5]. In Vietnam, the swamp eel growth in the Mekong Delta can have a detrimental environmental effect on the area and aquaponics farming of those swamp eel can eliminate the destructive effect caused by their growth [6].

European aquaponics research only began recently and is classified as an emerging practice with only a few commercial facilities [7] yet it is still more advanced than in other regions of the world. In the past decades, multiple studies published to look at different technological and financial aspects of aquaponics systems in Europe [8–12]. In the USA, aquaponics systems are at a more advanced stage and are more spread out [13,14] The aforementioned global survey's responses [4] came, predominantly, from the USA. In many instances, when studying cases in the USA, all the materials and methods used are of direct benefit to systems built in the USA, great technologies and methodologies that are

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not transferable and are of no use to greenhouse development in the Mediterranean region.

The Middle East represents an interesting case where American and European practices cannot always be utilized due to climatic differences. The Middle East consists of territories in Mesopotamia, the Levant, the Arabian Peninsula, Egypt, Turkey and Iran. In the Kingdom of Saudi Arabia, researchers encourage the use of aquaponics to improve fish farming [15] and ensure food security [16]. The United Arab Emirates built the then world's largest aquaponics center, Baniyas. There is little research in aquaponics farming in the Middle East that renders any research in this subject of vital importance especially in a country like Jordan where water is scarce.

Most literature in this regard is dedicated to building and determining the optimal design for a single greenhouse in a specific climate, mostly in Europe or East Asia. The aquaponics system is relatively new to the Middle East and so is the serious consideration of energy efficiency in buildings in general and in greenhouses in specific. Thus, one of the main objectives of this paper is to introduce a standard model that facilitates greenhouse energy management and design in climates like Jordan's while encouraging investors to take part in the country's food supply sector's self-reliance as well as creating communities that advocate for sustainable living and financial independence.

A key issue that sets developing countries behind in energy efficiency in buildings/greenhouses is the lack of consistent data, poor documentation or absence of documentation altogether. Twenty-five developing countries without energy regulatory standards were identified [17]. This point will be taken into consideration and data will be documented to track the progress of the system and to pass proper judgment on whether the assigned heating and cooling method was beneficial.

As alluded to earlier, the methods and technologies that are usually utilized in Europe are not transferable to the Middle East and from this key point comes the need of conducting more research and papers that are dedicated to the Mediterranean region in general and the Middle East in specific. The research should introduce technologies, methods and solutions that are suitable on an economic level and that are practical as well. Another major gap in research when it comes to greenhouses in the Middle East is the lack of efficient water usage. In countries like Morocco, that is part of the Mediterranean, water might not be a problem but water supply and sanitation in Jordan is severely scarce.

It is predicted that by 2050 the world's agricultural sector will have to double the water used to feed the world [18]. Aquaponics uses 90% less water than conventional farming [19] hence it should be taken as a serious model or practice that could draw investors' attention, especially in the Middle East. In many parts of the world, mismanagement of water is leading to rising waterwaste issues that are being neglected globally. One of the world's most famous proof of the disastrous and/or catastrophic sequence of mismanagement is the drying of the Aral Sea. Serious lessons were learned in water management and a whole new look to it was given as it influenced humans deeply both on an industrial and ecosystem level.

Management of natural resources and especially water is crucial. In hot climates, like the Arabian Peninsula, cultivating crops in such a hot climate is not easy and improper freshwater management jeopardizes food independence. A desiccation–evaporation process was introduced and in the proposed cycle, the air is dried prior to entering the evaporative cooler i.e. it is dehumidified [20], which is crucial for countries in the Arabic Peninsula. The cooling is then followed by using the regenerator to partially shade the greenhouse and the heat of desiccation is transferred/rejected at the outlet of the greenhouse.

In this paper, the heating and cooling methods chosen for an aquaponics facility called 'Khodra' in Jordan will be introduced; the facility's layout, as well as the inside of it, are shown in Figure 1a–d. The facility was in the process of determining which heating and cooling methods should be best utilized and therefore needed energy engineers and/or energy efficiency specialists to provide the facility with solid theoretical background/explanation on why they should choose a certain heating and cooling method over the other. In collaboration with 'Khodra', the heating and cooling method that has been chosen, taking into consideration feasibility and efficiency, will be discussed in details. Once the 'Khodra' facility's heating and cooling demands are met with energy-efficient systems, a replica of the facility is planned to be built in Qatar where the climate is different from that in Jordan.

Thermal performance of a greenhouse was modeled using TRNSYS dynamic simulation software; measured data from the experimental greenhouse were used to calibrate the model so that the predicted thermal performance matched the observed behavior [21]. Similarly, in this paper, the thermal performance of an aquaponics facility will be modeled using design builder and the measured data will be used to make the necessary changes that the facility needs to become an energy efficient greenhouse that can be a gateway to design commercial greenhouses with aquaponics systems. This will further expand the job employment circle, which will in return lead to financial independence.

Jordan's food production encounters two major problems, severe water scarcity [22] and not enough money for gross production, both of which do not exist in Qatar. Taking into consideration that Qatar's per capita water consumption is one of the highest in the world [23], which does not necessarily mean that Qatar is rich in water. Therefore, the model we will build will ensure that it does not fully depend on the country's water sources. This can be easily achieved since aquaponics uses 90% less water than conventional farming [24].

Qatar has a very hot climate with high relative humidity rates. The problem almost all Middle Eastern countries have in common is the absence of climate control strategies that are designed to manage cost and energy effectiveness in the long run. Almost all literature that is now dedicated to climate control in greenhouses are designed for countries in the USA, Europe and Southeast Asia and not for countries with a Mediterranean climate like that in the Middle East. Therefore, the main objective of this paper is to discuss climate control strategies that can help Jordan, and if

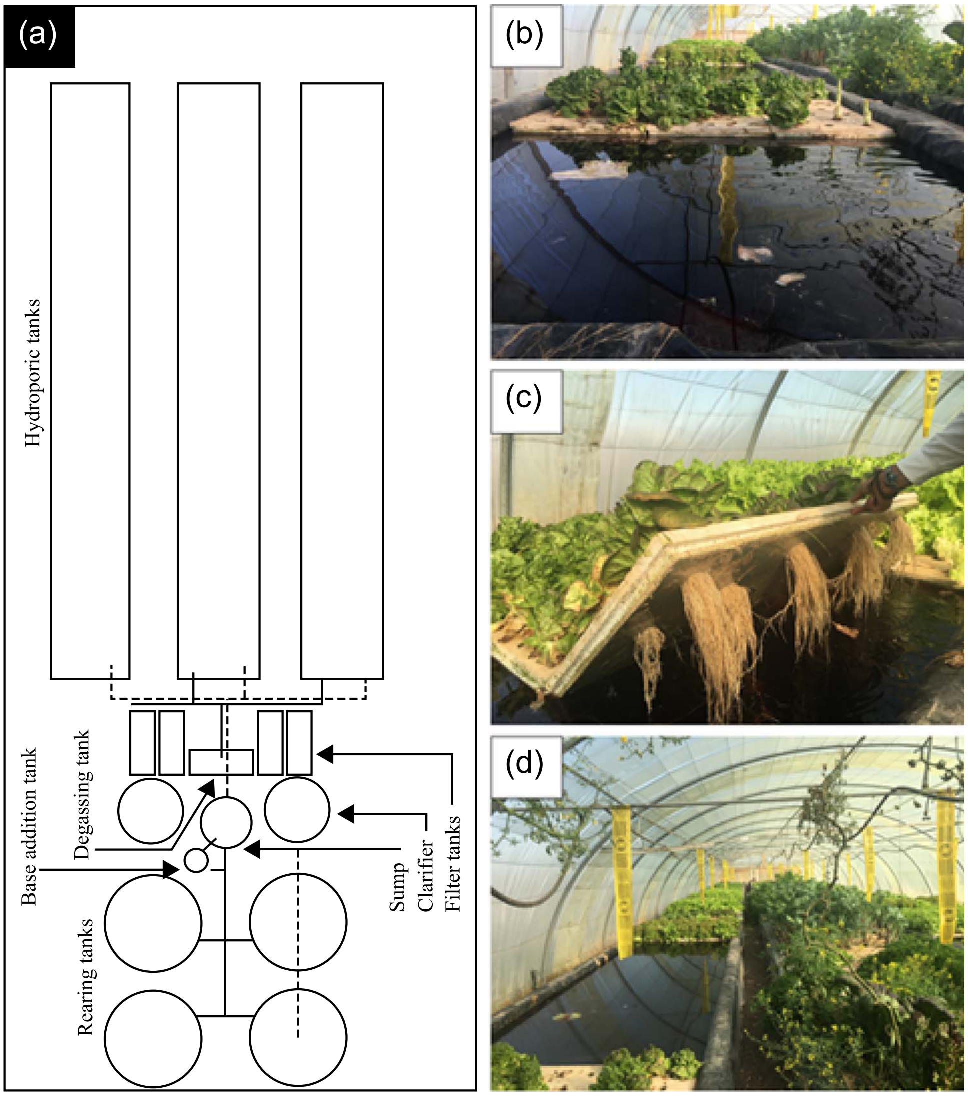

Figure 1. *The 'Khodra' facility in Jordan. (**a**) Layout, (**b**) view of the fish tank and the vegetation laid on top of it, (**c**) plants' roots submerged in fish tank's water, (**d**) zoomed out view of the facility's inside.*

the model is successful then Qatar too gets a step closer to food sufficiency as a country and be a model to neighboring countries that face similar difficulties. In the Middle East, blindly copying European or American architectural and construction techniques in either building, or like, in this case, a greenhouse, leads only to higher consumption rates in energy than conventional design [25].

2 METHODOLOGY

In Khodra, only leafy greens are being produced. Optimal greenhouse climate control is necessary to produce all types of vegetation (leafy and fruitful) all year long regardless of the climate conditions. Since farmers are not familiar with energy efficiency and have little knowledge of heat control, farming in Jordan is only seasonal and the country has to import vegetables/fruits if they are not their natural growing season. 'Khodra' has noted that, in the winter, keeping the fish warm was a problem, whereas the plants can survive the cold months. In the summer, however, the opposite occurs; the plants were sensitive to hot weather and they dry, whereas the fish survives. They have also noted that, in the summer, the temperature rose up to 37°C in the daytime and that the optimal temperature for both fish and the plants was between 23 and 27°C. Another observation was that at 13°C the fish dies. In addition, at 17°C, it refuses the food it is offered. The maximum temperature the fish can survive is 28°C. This shows how temperature is the most vital variable of greenhouses' climate control. The second important variable is the relative humidity. These parameters will be discussed in details in the following sections. Simply put, 'Khodra' is in need of climate control practices and strategies that would help them build a model in Qatar

Table 1. *The 'Khodra' facility's components and their technical specifications.*

Component description	Technical specifications	Quantity used
Fish tanks	Diameter: 3 mHeight: 1.2 mWater volume: 7800 L	4
Clarifier	Diameter: 1.8Height of cylinder: 1.2 mDepth of cone: 1.1 mSlope: 45°Water volume: 3785 L	2
Filter and degassing tanks	Length: 1.8 mWidth: 0.76 mDepth: 0.61 mWater volume: 700 L	5
Hydroponic tanks/rafts	Length: 38 mWidth: 1.8 mDepth: 41 cmWater volume: 28 044 L	3
Sump tanks	Diameter: 1.2 mHeight: 0.9 mWater volume: 606 L	2
Base addition tank	Diameter: 0.6 mHeight: 0.9 mWater volume: 189 L	1
Pump	1.7 kWFlow rate: 378 L/min	1
Blowers	1.1 kW (fish)0.74 kW (plants)	4

where there is a potential for greenhouse integrated aquaponics systems.

When the temperature rises, relative humidity drops. Relative humidity affects the health of plants' foliage, can have serious issues in the plants' harvest and limits the production's quality. Tomatoes, for instance, require a decent amount of heat to be in their desired red shape; therefore, balancing between humidity and temperature is a key element to creating the perfect environment for an Aquaponics–greenhouse integrated system that would produce all types of vegetation all year long.

In order to choose the most suitable cooling method for 'Khodra', design builder was used. The 'Khodra' facility model with all its dimensions and types of material in design builder was simulated twice, once with heating, ventilation and air conditioning (HVAC) system and another with conventional AC split units. A simulated consumption profile was created that aided in the selection of the most suitable cooling method. An investigation of the most suitable cooling method for 'Khodra'-Qatar was carried out as well.

2.1 System's description

An aquaponics system is a system that combines aquaculture (rearing fish) and hydroponics (a soil-less method of growing plants). In this integrated system, the fish waste provides an organic food source for the plants and the plants, in return, filter the returning water for the fish. In order for this process to take action, microbes (nitrifying bacteria) are crucial. They convert ammonia from the fish waste into nitrites and then into nitrates. Nitrates are the form of nitrogen that plants can uptake and use to grow. Additionally, the fish waste can be also used to obtain high-quality vermicomposting that can either be sold individually or fed back to the plants.

2.2 Drawbacks of traditional soil-based gardening

Farmers, in traditional gardening, must have an experience or knowledge that enables them to determine when exactly they should water the plants as well as knowing how to fertilize and what is the composition of the soil to attain the best harvest. Since the soil plays an important role, traditional farms are usually located thousands of miles from where the food is consumed. Pesticides, weed and soil-borne insects are also three major drawbacks. 'Khodra' has conducted the constant height one pump (CHOP). In the CHOP configuration, the water is pumped from a sump tank to the fish tank that feeds the water by gravity into grow beds. The grow beds filter the water by the media and supply it back to the sump tank that pumps it back to the fish tank and so on. An extra filtration unit was added in the 'Khodra' facility.

The total system's water volume was 111 196 L. The total land area was 0.05 ha. An enhanced configuration of the CHOP system is CHOP2 where the pump sends the water to the grow bed as well as the main fish tanks simultaneously. The water is then fed back into the sump tank. It consists of two loops instead of one where the sump is the central mixing point. The advantage of CHOP2 configuration over CHOP is that the grow beds do not need to be perfectly level to function properly. This problem specifically occurs if multiple grow beds are running on an uneven ground leading to problems with the auto siphons. Since each grow bed has its own independent ball valve, the water flow can be regulated with greater control than gravity fed flow under the old CHOP system. Another benefit is if the farmer decides to alter his design from a media bed to a raft system, CHOP2 will accommodate the design shift.

A key difference that sets this project apart from any other passive greenhouse design is that the aquaponics was already built making the proposal of some changes on the exterior envelope a big challenge hence only low cost and effective recommendations are accepted. The 'Khodra' facility's components are listed in Table 1.

2.3 Climate control

2.3.1 *Ventilation*

One of the most convenient ways to balance outside and inside temperature is through ventilation. The first step to lower energy demand is using passive techniques/strategies to lower the energy demand and since Jordan has dry weather it does not face high relative humidity issues like in Qatar. This is advantageous for the 'Khodra'-Jordan model; however, it will differ significantly in the 'Khodra'-Qatar model because of the high outdoor humidity percentages and will create significant issues to the plant's foliage.

The distance between the two fans should not exceed 8–10 m, according to ASHRAE standards. The inlet opening on the opposite side of the fan should be 1.25 times the fan area. For the plant

Figure 2. *Green knitted 50% shading cloth used in 'Khodra'-Jordan.*

area, the airspeed should not exceed 0.5 m/s. In 'Khodra'-Jordan, four circulation fans and two exhaust fans were used.

2.3.2 *Shading*

Different methods of shading include shade cloths and partially reflective shade screens. Shade cloths (60%) offer a dramatic change in temperature reduction in the summer. Microgreens only need ambient light to grow especially during the summer's long daylight hours; it even induces the microgreens to grow taller to obtain more sunlight. There are two types of shading cloths, knitted and woven. The only disadvantage of the woven is that it would unravel minor cuts. The knitted range starts from 30% to 90% at 10% increments. In 'Khodra' facility, 50% green color shading is used as shown in Figure 2, the reason behind it will be discussed in further detail in the results section.

2.3.3 *Cooling*

The cooling method that was used in 'Khodra'-Jordan was evaporative cooling (fogging system). One of the advantages of the fogging system over the sprinklers is that the foliage will keep dry and no disease will spread. The reason the fogging system was chosen over the wet pad system was that the climate condition would be uniform across the greenhouse unlike that in the wet pad cooling system where forced air is required. The fogging system works by forcing water through nozzles with high pressure, the water droplet size would be as little as 5 microns and this creates a surface area larger than a football field from only 1 gallon

Figure 3. *A sample of the nozzle of the fogging system chosen in 'Khodra'-Jordan.*

of water. These small water droplets absorb the heat from the environment and evaporate. Another key point that must be taken into consideration is the relative humidity. It is defined as the amount of moisture/water in the air compared to the amount of moisture the air could absorb at the same temperature.

The lower the relative humidity, the more water is vaporized and the cooler it gets. The fogging system works best when the temperature is between 29°C and 46°C and where humidity is low. To calculate the effectiveness of mist/fog cooling, one must first know the real humidity during the time of day the fog system is needed. The humidity obtained from the weather report is only the highest humidity level for that day. Humidity drops as the temperature rises. This leads us to the conclusion that the fogging/misting system is not preferable in Qatar where 'Khodra's' greenhouse is projected to be replicated. Figure 3 shows the nozzles that were used in 'Khodra'-Jordan.

Figure 4. *Water tank (left) and olive Mill furnace (right).*

2.3.4 *Heating*

In order to achieve the greenhouse's goal, heating is necessary for plant growth all year long. In the 'Khodra' facility, the current heating method used is thermal solar heaters. If the energy from the sun is insufficient for heating, an olive mill furnace, shown in Figure 4, starts operating. Not only do plants need well-maintained climate control for growth, the fish also are very sensitive to temperature, light and noise; that is why the pump is not placed inside of the fish tank to pump the water to the plants, it is rather placed in the sump tank away from the fish to not scare them away. Fish stop eating food provided for them when the temperature is below a certain degree; not only do they need a perfect temperature to live, but they are also sensitive to temperature that if it is not in the desired range.

As seen in Figure 4, there are two thermostats, one of is placed on the water tank that is connected with the solar thermal pipes and the other is placed on the olive mill furnace. The furnace automatically turns on when the water tank goes below a certain degree and similarly it stops burning the olive mill when it exceeds a certain temperature limit. An advantage of this method is that the oven mill is not discarded rather it is used for heating the fish tanks.

The water heated from the furnace or the solar thermal collectors, shown in Figure 5, which is located inside the greenhouse and above the plants, is then fed into the fish tanks via a loop pipe at the bottom of the fish tanks with heavy holders to be able to sink inside of the large fish tank.

2.3.5 *Humidity*

If the relative humidity is desired to be a specific value, decentralized systems are not suitable because they only heat or cool the zone without taking ventilation and humidity into consideration. HVAC systems use no refrigerant and they take humidity, heating, cooling and ventilation all into consideration. For adequate advice and suggestions for building a greenhouse with an integrated aquaponics system, the high humidity factor in countries like that in the Arabian Peninsula, where Qatar is located, must be considered. One of the most convenient methods to dehumidify such climates is by using a direct expansion coil (DEC). DEC exposes the humid air to evapotranspiration that is the evaporation of water inside plants.

3 RESULTS

Design builder allows users to choose the standards they prefer. For the results of this paper, the ASHRAE Standards 62.2 was

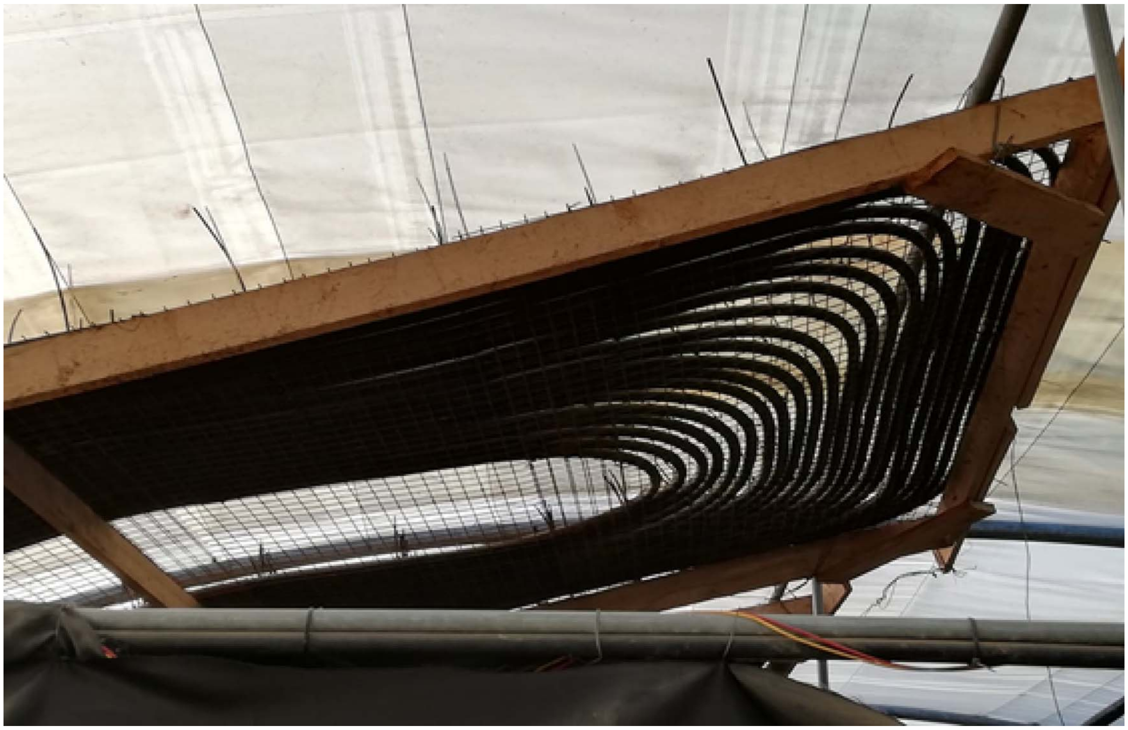

Figure 5. *Solar thermal collectors in the 'Khodra'-Jordan facility.*

selected. In aquaponics, a temperature range of 23–27°C is most recommended. The relative humidity, on the other hand, must be anywhere between 50% and 70%.

3.1 'Khodra'-Jordan

Figure 6 shows 'Khodra's' construction model on design builder. The plantation area where the vegetation is held is on the left with the dimensions of 40 m × 9 m × 3.2 m. The construction right next to it is where the rearing tanks are 9 m × 10 m.

The cooling method chosen for both 'Khodra'-Jordan was evaporative cooling while AC split units were chosen for 'Khodra'-Qatar. For 'Khodra'-Jordan, a shading cloth of 50% green color was chosen since it does not block the sun completely, but it still reflects a good amount of heat. This shading cloth, together with the misting system, enabled the reduction of temperature of the greenhouse to a recorded temperature range between 22°C and 26°C. This, however, is not applicable for 'Khodra'-Qatar where humidity is very high where it lowers the efficiency of the misting system.

3.2 'Khodra'-Qatar

Figure 7 demonstrates the average temperature profile in Doha, the capital of Qatar, in July. For reference, on July 11, the hottest day of the year, temperatures in Doha typically range from 31°C to 42°C.

The weather forecast in Doha, shown in Table 2, shows humidity in the range of 26–55%. With the respiration of plants inside the vegetation area as well as the fish tanks, which produce a lot of humidity, the internal humidity inside the greenhouse in total would be high; therefore, dehumidification is needed.

A simulated consumption profile was generated using design builder. Figure 8 shows the cooling consumption rates of an AC split unit's system. Another simulation will be conducted to evaluate how it will behave if the cooling method was a water-chiller based HVAC system. The average daily consumption taken from the first day each month in kWh is 663.42. Each column in Figure 8 represents the total air conditioning required for the month including heating and cooling; keeping in mind that these are, solely, simulation outputs.

Taking 17 July to be the hottest day in summer, Figure 9 shows the temperature and relative humidity profile of the system using AC-split units as the cooling system based on a sub-hourly analysis.

Simulating the same model by taking the water-chiller HVAC system as the cooling method resulted in a similar temperature range that is healthy for the greenhouse's environment and is in the desired range.

The second scenario was using an HVAC system (water-chiller based HVAC system) as the cooling method. Figure 10 shows the simulated consumption rate of the integrated system.

The average daily consumption taken from the first day each month is 846.75 kWh. Comparing the two consumptions of both the AC-split units and the HVAC system, it can be deduced that the AC-split unit system has a lower consumption rate. Therefore, a photovoltaic (PV) system was sized that would correspond to this load. Using Blue-Sol program, a PV system was designed for

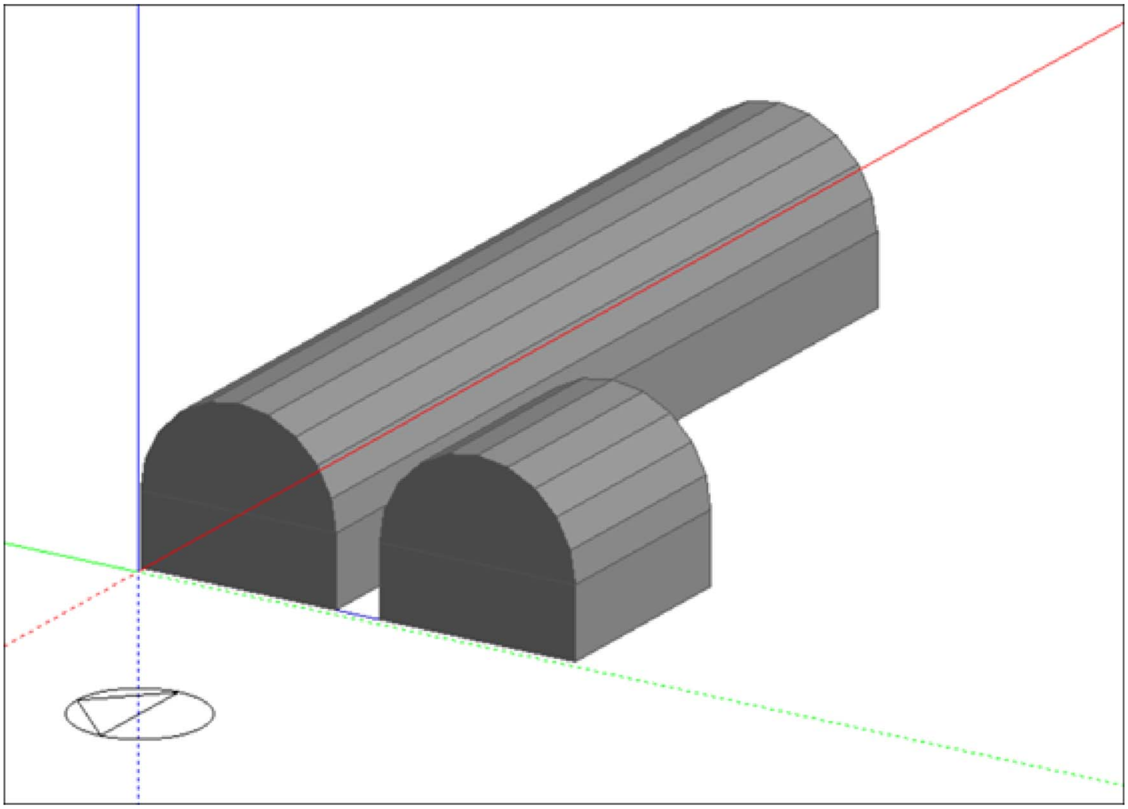

Figure 6. *'Khodra'-Jordan model in design builder.*

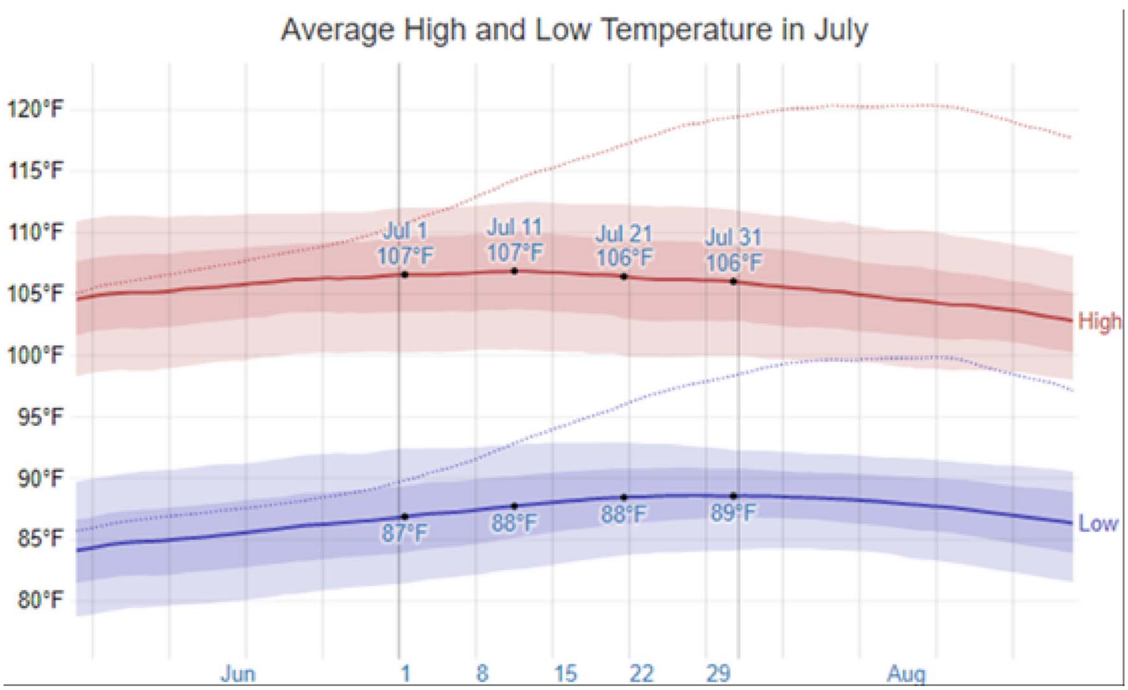

Figure 7. *Simulated summer temperature profile in Doha, Qatar.*

the project with an AC-capacity of 124.4 kW and DC 153 kW. Five inverters were needed using ABB's 27.6 kWp inverter. Each inverter has two MPPTs. Each Maximum Power Point Tracker carries three strings each with 17 solar panels.

Table 2. *Simulated humidity profile in Doha, Qatar, for a typical day in July.*

Time	Wind direction	Wind speed	Temperature	Humidity
3:00	NNW	36/66 km/h	37/44°C	43%
9:00	N	39/51 km/h	39/45°C	38%
15:00	NNW	49/73 km/h	41/44°C	26%
21:00	NNW	6/8 km/h	38/53°C	55%

3.3 Comparing the two cooling methods

Two cooling methods were compared; those methods were conventional AC-split units and water-chiller based HVAC system based on humidity control criteria.

When air temperature was lowered, the air's ability to hold moisture was also lowered. Usually, when relative humidity is also taken into account and is needed to be around a specified range of values, decentralized systems like AC-split unit's/heat pumps are not used because they do not take humidity and ventilation rate into account, they just reduce the temperature. It is often the fluctuation in the humidity's rage that causes more damage than having a constantly high or low relative humidity. Therefore, an HVAC system is needed that would cool and dehumidify the air. An advantage of HVAC that outweigh other cooling methods is humidity control. Humidity and temperature control are two critical factors in healthy plant growth.

When the relative humidity levels are very high i.e. there is low air circulation, plants are not able to evaporate water; plant

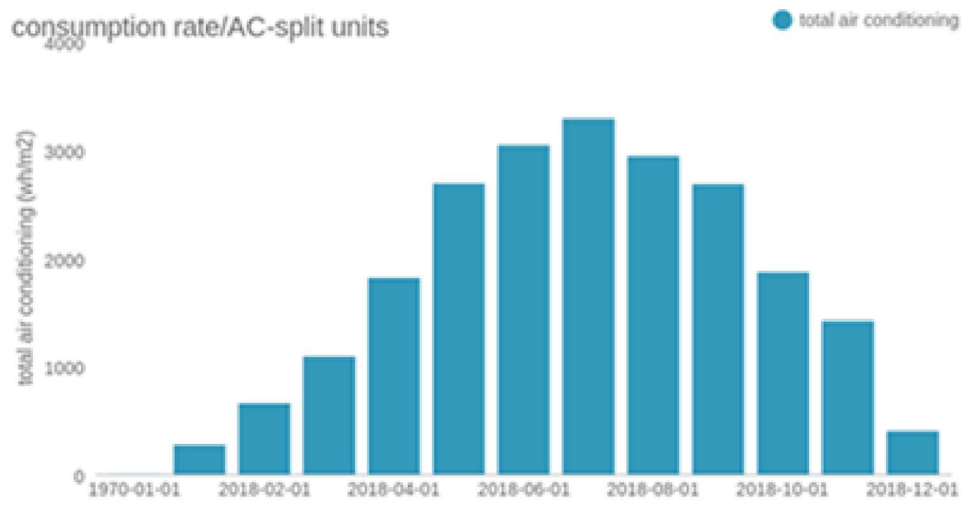

Figure 8. *Monthly AC consumption rate.*

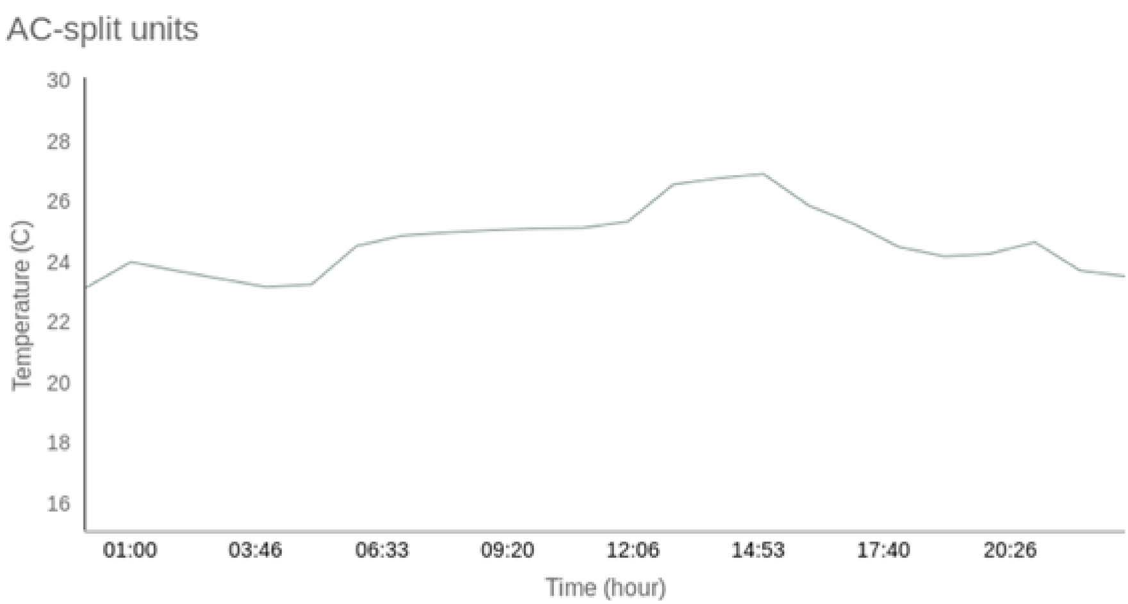

Figure 9. *Temperature profile after installing an AC-split unit.*

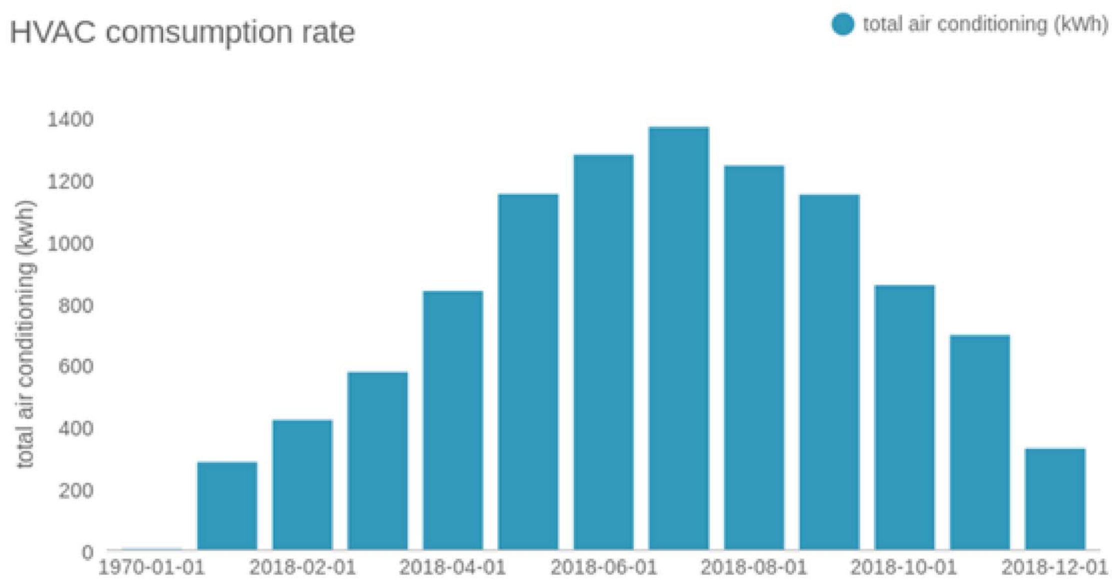

Figure 10. *HVAC consumption rate.*

evaporation is part of the transpiration process. This makes the plant unable to draw nutrients from the media. Either can do dehumidification: i) DECs (DX coil). It operates under the same principle of condensation where a coil containing a refrigerant is cooler than the incoming air and thus condensation takes place. A drain is connected to it to absorb the water attained, and ii) absorption of moisture using dehydrating agents like silica gels.

The total land area needed to mount the system was 1919.18 m^2. This would be for a small to medium aquaponics integrated greenhouse that is almost 360 m^2. This result discourages investors who plan for the future extension as more land would be needed and dedicated to the PV system.

4 CONCLUSION

For 'Khodra'-Jordan, a combination of good ventilation rate with 50% green color shading was sufficient to reduce the temperature down by almost 10 degrees. The knitted range starts from 30% to 90% at 10% increments. Microgreens only need ambient light to grow especially when during long daylight hours in the summer. The reason why the color green was chosen over black and beige was because black absorbs unwanted heat into the greenhouse and beige, on the contrary, lets too much sunlight in. 'Khodra'-Qatar, however, has a major challenge due to high humidity. This can be solved by an HVAC water-chiller based HVAC system to get more steady state-like of rate. In this paper, AC split units were cheaper to utilize due to the small total area of the greenhouse of ∼360 m^2. However, a larger scale aquaponics greenhouse is desired; budgeting for an HVAC system is crucial.

Moreover, since the electricity rate in Qatar is cheaper than that in Jordan, the payback period it requires for the installed PV system would be quite long. For future work, 'Khodra'-Qatar is planning, with the help of an automation company, to regulate the greenhouse fully with sensors that would automatically open and close vents based on the readings by the sensors. Another critical point that would dramatically lower heat loss from the greenhouse's envelope is the material used. Low-density polyethylene has a very high U-value, 5 $W/m^2{\cdot}K$. If a different material with better material *U*-value is utilized, the cooling load demand would be dramatically lowered.

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