International Journal of Chemical and Biochemical Sciences
(ISSN 2226-9614)
Journal Home page: www.iscientific.org/Journal.html

Development of A-Frame Hydroponic System Permitting More Growing Area and High Productivity

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Abstract

The paucity of freshwater and arable land worldwide has become a significant issue due to the growing human population. Aquaculture has become the main food production sector; it combines hydroponics and aquaculture in a closed recirculating system. A-frame design is one of many hydroponic plant-growing systems, and this study aimed to evaluate the impact of different angles for A-frame design, fish effluent depth, and tube position on the growth parameters of two leafy vegetables with different morphological features. The study examined the effects of changing the A-frame angle (30° and 60°), fish effluent depth (3 and 6 cm), and leafy plants (head lettuce and mint) on growth parameters. The results showed that changing the A-frame angle from 180° to 60° and 60° to 30° decreased the surface area by 45% and 52%, respectively. Also, changing the A-frame angle from 60° to 30° appeased the light intensity by 14.8% for head lettuce and 15.4% for mint. Changing plants from mint to lettuce reduced the light intensity by 17.7% and 21% for 30° and 60° angles, respectively. Changing the tube position from the middle to the bottom plumbed the light intensity for lettuce by 15% and 18% for 30° and 60° angles, respectively, while increasing it by 25.3% for mint with a 30° angle only. Root length and stem diameter were reduced by changing the angle from 60° to 30° and fish effluent depth from 6 to 3 cm for both mint and lettuce plants. There was no significant difference in the yield of lettuce and mint plants with 30° and 60° angles. A-frame design with a 30° angle is recommended for growing lettuce and mint since it permits 3.8 times more growing area than the unit's footprint, providing 45.8 m^2 of crop growing area in 12 m^2 of surface area.

Keywords: Aquaponics, A-Frame Design, Fish Effluent Depth, Tubes Position, Leafy Crops

Full length article **Corresponding Author*, e-mail: mohamed_rashad@agr.suez.edu.eg

1. Introduction

Aquaculture has emerged as a critical food-producing sector, and it is now an essential global industry with total annual production exceeding 171 million tons [1]. Nowadays, the scarcity of freshwater and cultivated land has become a significant problem in many countries globally due to the increase in human population. Water is a prerequisite for successful aquaculture operations. Aquaculture practices also generate lots of wastewater, which is one of major causes of environmental pollution. Aquaponics is one of solutions to both these problems. Wastewater from aquaculture system, which is nutrient-rich water, can be used to grow the plants without adding any additional chemical nutrients to be added to system. Aquaponics integrates recirculating aquaculture systems with hydroponics plant production [2]. Recirculating systems are designed in such a manner to raise large quantities of fish in relatively small volumes of water and then to reuse the wastewater after treating the water for the removal of toxic waste products. Aquaponics combines advantages for recirculating aquaculture systems (RAS) and hydroponics systems that use inorganic nutrient solutions. Hydroponics component has many designs for making the best use of floor area and serves as a bio filter, and therefore a separate bio filter is not needed as in other recirculating systems. Aquaponics systems have the only bio filter that generates income obtained from sale of hydroponics produce such as vegetables, herbs, and flowers [3].

A small proportion of ammonia is toxic to fish when nitrate is not toxic to fish. If nitrate increased over a specific limit, it will be toxic to fish eaters (human beings) and cause nitrate pollution, and the eaters will suffer from methemoglobinemia disease. The blood of the affected people became brown and will not carry oxygen to the rest of the human organs [4]. Part of the water should be discharged daily and replaced with freshwater to avoid ammonia pollution problem in aquaculture. Another solution to this problem is establishing a hydroponics system attached to aquaculture and cultivating plants in hydroponics to save discharged water and use existing nitrate [3]. Hayden [5] Reported that A-frame structure at 60° angle permitting is 1.7 times more growing area than the footprints of the unit in the greenhouse and allows the use of vertical space to provide 34 m^2 of crop growing area in 20 m^2 of greenhouse floor space. Aquaponics' benefits of aquaponics are conservation of water resources and plant nutrients, intensive production of fish protein, and reduced operating costs relative to either system in isolation. Water consumption in integrated systems, including tilapia production, is less than 1% of the pond culture required to produce equivalent yields [3]. Because of paucity of freshwater and cultivated land in line with boomed population; it is needed to conduct research, which aims to investigate a comparison between different A-frame angles, and fish effluent depth. The purpose of this study is to achieve the optimal utilization for surface area, and optimal depth for plants, and eventually make the A-frame design have more flexibility and using commercially.

2. Materials and Methods

The work was carried out at the roof of the Agricultural Engineering Department, Faculty of Agriculture, Suez Canal University, Ismailia, Egypt, during the 2019 season from 5th February to 5th May. The work was carried out through three stages. The first stage was conducting an aquaponics system, while the second stage was to conduct statistical analysis for plant parameters, and eventually the third stage was to conduct an economic analysis. The research's main objective is to study which depth of fish effluent in the pipe for Deep Flow Technique (DFT), the optimal angle of A-Frame design is sufficient for water use efficiency, and surface area.

2.1. System Description

The system consists of one *PVC* circular tank (1.0 m^3) was used for fish culture, with dimension (1.0 m diameter × 1.25 m height), as shown in Figure (1). The tank was provided to a particle trap consists of a small pipe for drain soft wastes, and a big one was above the smaller, which was used for removing heavy solids. The soft and heavy-waste particles are retained in the sedimentation tank at the top, and flow by gravity for further treatment. Semi-circular tank with dimension (0.25 m width and 0.8 m height) was put horizontally in this system. Water enters in the tank by the pipe which put a cross on it, and passes through a plastic panel that put with 45° angle to make the laminar flow, and save time for more sufficiently deposition.

2.1.1. Hydroponic units

The hydroponic units in this study worked as a biological filter and consisted of: one source of nutrient solution (water discharge from the fish tank), two A-frame angles 30° and 60°, two fish effluent depths 3.0 and 6.0 cm, and two types of leafy vegetables; Lettuce and Mint. Intermittent flow (15 minutes "on" and 15 minutes "off") as described previously (Fig. 2) [6]**.** Pumps model UNEE HP-8000 with high max 3.5 m and Q max 3500 Lh^{-1} was used in this system. The flow of fish effluent water through the growing channel was established between 1.5 to 2.0 L per minute, as recommended by [7] for short-cycle plants. The A-frame design at 60° angle has a dimension of 2.2 m width, 3 m length, and 1.8 m from the top joint point to the end length, permitting 1.8 times more growing area than the unit's footprint and allows the use of vertical space providing 21 m^2 of crop growing area in 12 m^2 of floor space. A-frame design at 30° angle has a dimension of 1.05 m width, 3 m length, and 2.2 m from the top joint point to the end length, permitting 3.8 times more growing area than the unit's footprint, providing 45 m^2 of crop growing area in 12 m^2 of floor space.

The A-frame was made from iron and painted with an anti-rust coating. Those make the A-frame flexible for changing head angle and taking less area for storage. The cylindrical shape of gullies was used with 0.1 m diameter, 3 m length, and zero slopes; stands on the A-frame design with a row spacing of 0.35 m. The gullies were made of *PVC* material with three layers. The outer layer has a white color to reflect the fallen rays from the sun and making the pipes cooler, which leads to a more suitable wastewater temperature for roots. The wastewater was pumped from the tank to the upper end of the gullies. Small tubes were used to supply each gully wastewater. The tank with 220 L capacity was used for collecting the drained wastewater by gravity from the end of the gullies; after that the clean water was pumped to the fish tank by the water pump. Lettuce seedlings were sown in plastic cups (7 diameter and 7 cm height) filled with gravels. The cups were irrigated daily. The plant spacing on the row was 20 cm, according to [8].

Kjeldahl desalination unit model UDK 126A was used for measuring ammonia (NH_4) and Nitrate (NO_3); root diameter was measured by Digital Micrometer, Lux meter model LX 1010BS was used for measuring light intensity. pH was measured by the pH meter model 3510, Electrical Conductivity (EC) was measured by the EC meter model AD31, the water temperature was measured by digital Thermometer, and fresh and dry weight was measured by digital Balance device. Water samples were taken at the inlet and outlet of the hydroponic units for measuring ammonia (NH_4) and nitrite (NO_2) twice weekly during the experimental period, with average values of 0.056 and 0.5 ppm for ammonia and nitrate, respectively. pH and EC were measured directly and daily in the system to keep a constant range for pH 6 - 6.5 and 2 - 2.5 ms/cm for EC. The fresh and dry weight of shoot and root was measured at the end of the experiment. After measured fresh weight, the plants were oven-dried at 70 ºC until a constant weight was reached.

2.2. Statistical analysis

Mean growth parameters (n = 4) of lettuce and mint plants were compared using multifactorial and two-way factorial analysis of variance and Tukey's honestly significant differences tests at a significance level of $P < 0.05$. Data analyzed using IBM SPSS Statistics Software version 21. Standard error of means calculated from four replicates for each variable (growth parameter: root length (cm) and stem diameter (mm)). Interactive effects of A-frame angels (30° and 60°) and positions of hydroponic tube (top, center, and bottom) on measured variables were also determined.

2.3. Economics analysis

Cost analysis was carried out using the current prices for the equipment and installation according to 2019 price level, and the production cost of head lettuce and mint.

The effect of A-frame angle, and fish effluent depth on total cost and net returns of head lettuce and mint production was then evaluated. The total cost per one-hectare area is divided into fixed costs and variable or operating costs. The estimated fixed costs were depreciation, interest on investment, taxes, and insurance costs. Meanwhile, estimated variable costs were repair and maintenance, energy, and other costs. The following equations were used to calculate the cost analysis, as shown in Table (1). A list of necessary components and approximate seasonal costs of aquaponic system for calculating cost economics shown in Table (2). The suggested scenario for cost analysis considers the effect of the changes in input and output prices of head lettuce yield in next years if the inflation rate (*Inf.*) increases by 5 or 10 %. The plant yield was calculated for A-frame systems (60°and 30°) in this experiment for hectare area.

3. Results and Discussion

This chapter presents the engineering design effect of A-frame hydroponic design for deep flow technique (*DFT*) on two different leafy crops (head lettuce and mint) plants growth. The work was divided into two categories; first off, evaluate optimal angle of A-frame design, which influences light intensity, fish effluent temperature, and growth parameters. Secondly, study the effect of fish effluent depth in pipe on its temperature, and plant growth parameters. The results will be showing effect of each factor clearly by making each factor a variable with fixing others. A-Frame Angle: Effect of A-frame angle (30° and 60°) on surface area, light intensity, fish effluent temperature, and the growth parameter for the head lettuce and mint plants, under following titles.

3.2. Surface area

The occupied surface area by plants was dipped by using an A-frame angle and influenced by changing its angle. Fig. (3) Shows the comparison between A-frame angle (60° and 30°) for floor surface area (m^2). The surface area was plummeted by decreasing the angle from 180° (datum level) to 60° and 30° A-frame angle as (12 to 6.6 m^2 by 45%) and (12 to 3.15 m^2 by 73.75%), respectively. Similarly, the surface area declined from 6.6 to 3.15 m^2 by 52.2% with decreasing the A-frame angle from 60° to 30°.

3.3. Light intensity

The light intensity was influenced by the A-frame angle, plant type, and tube position in all tubes except the top. The light intensity was relatively went up by increasing the A-frame angle for both lettuce and mint plants. Fig. (4) and Table (3) show that the average values for intensity were raised by increasing the A-frame angle from (30° to 60°) for the maximum growth of lettuce plant as (1325 to 1536 LUX) on middle and from (1118 to 1330 LUX) on bottom pipe position, respectively due to highest exposure of sunlight that falls on the ample width. The intensity values boomed from (1348 to 1934 LUX) for mint plants in the middle and from (1690 to 1700 LUX) on bottom pipe position, respectively.

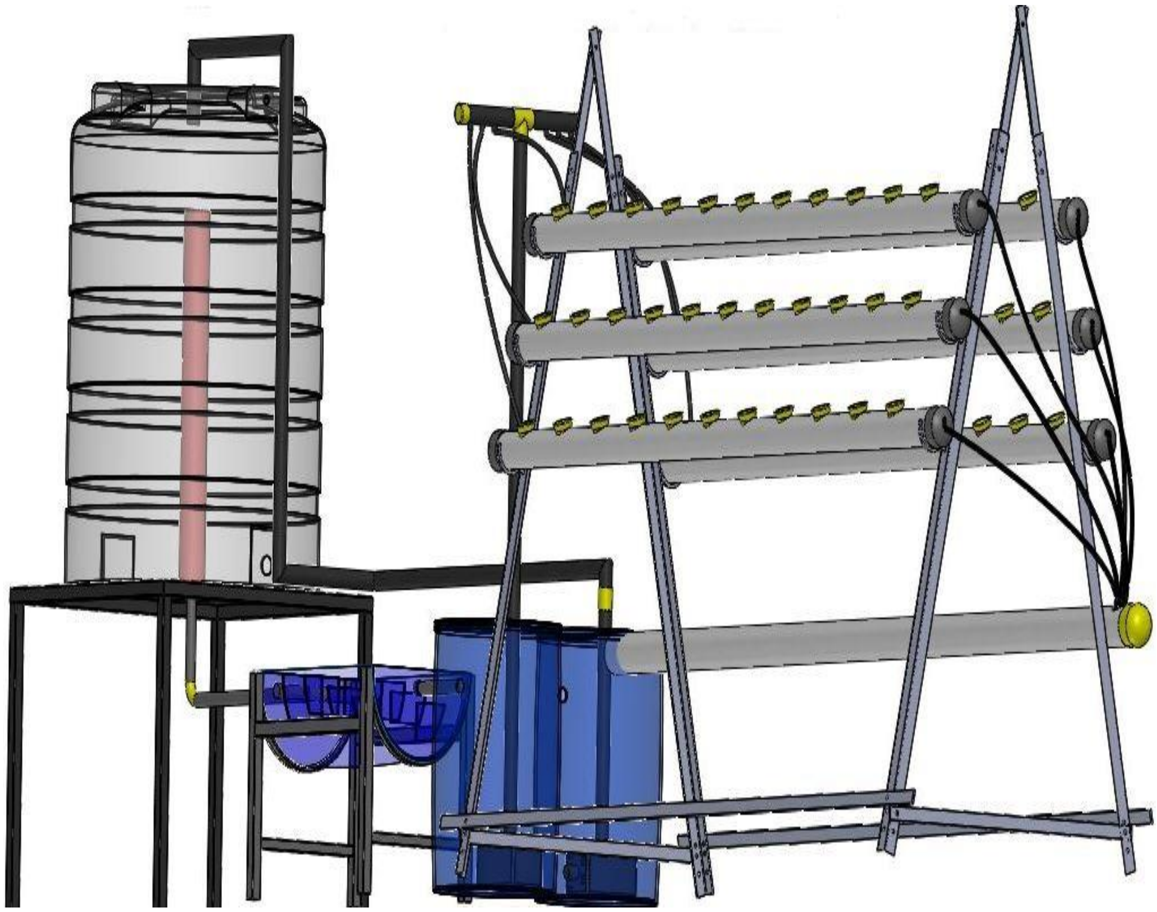

Fig. 1: 3-D design illustrates the developed aquaponic system with A-Frame hydroponic design

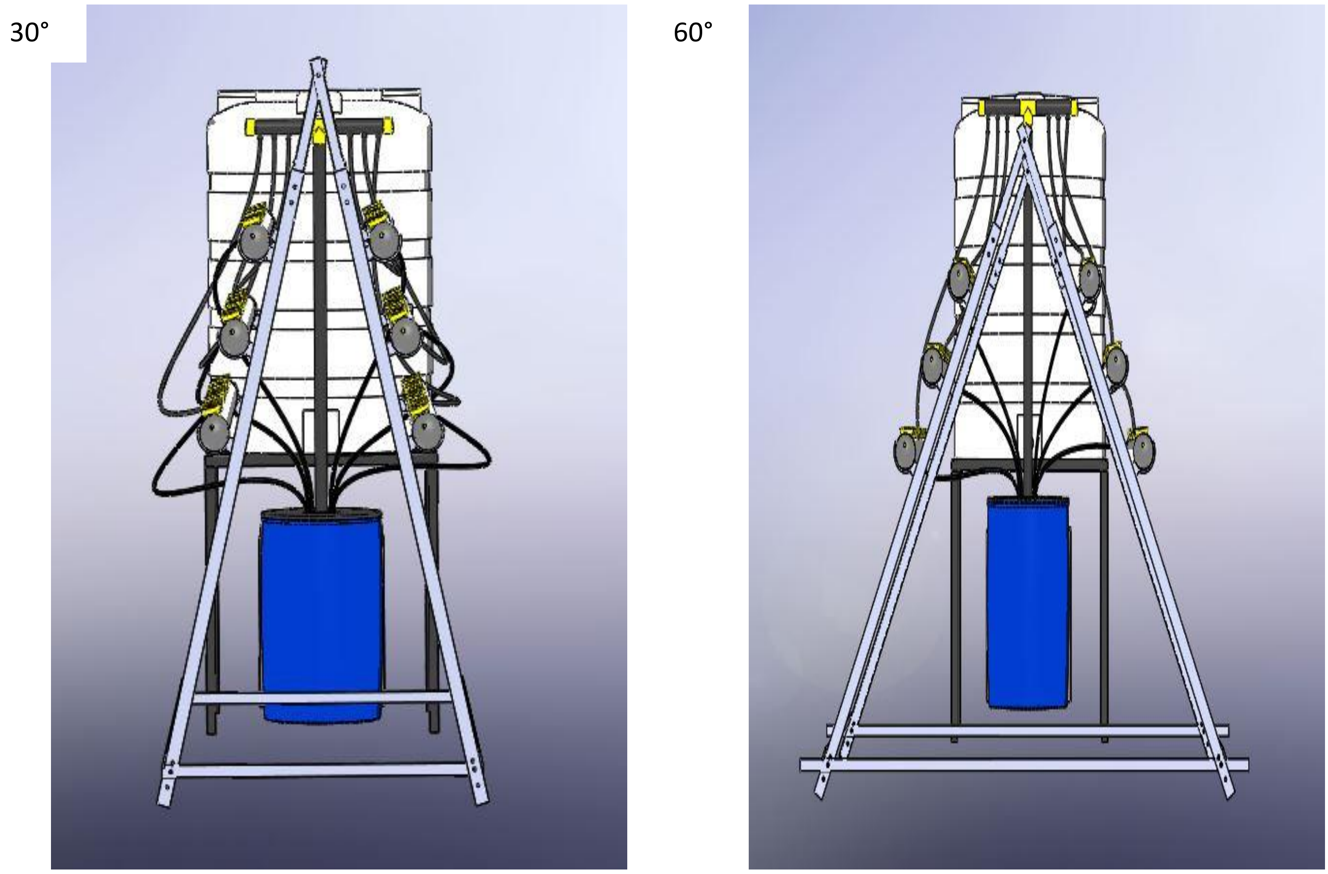

Fig. 2: 3-D-Design of A-frame hydroponic system with two angles of 30° and 60°.

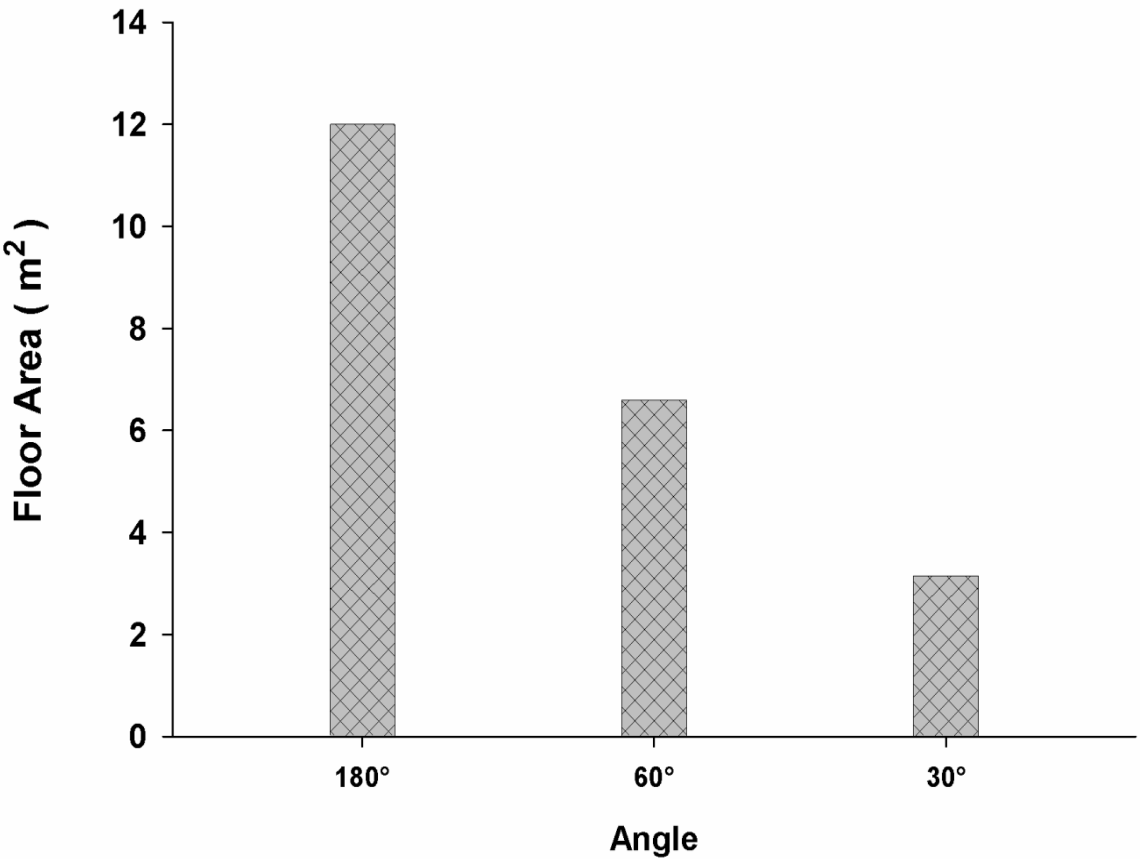

Fig. 3: The comparison between A-frame angle (60° and 30°) for floor surface area (m^2).

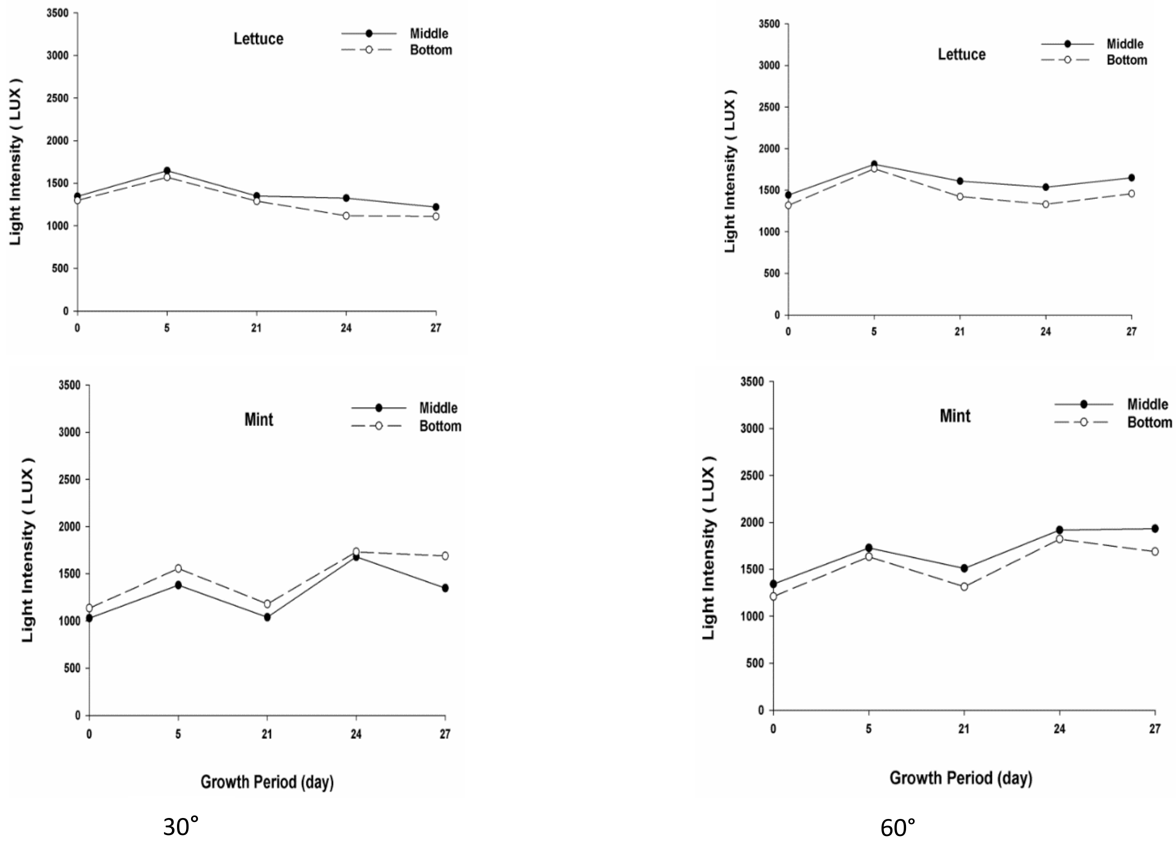

Fig. 4: The effect of A-frame angle on Light intensity for different plants and positions.

Table 1: The used equations in cost analysis

Cost type	Equation	Parameters
Depreciation costs, *D*, USD/hec/season	* $D = \frac{P_m - S}{L_m}$	P_m: the cost new (USD), *S*: salvage value price (0.1 P_m) (USD). L_m: total expected life (year)
Interest on the investment costs, *I*, USD/hec/season	* $I = \frac{P_m - S}{2} \times i$	*i*: interest rate as compounded annually 10 % (decimal)
Fixed costs, *F.C*, USD/hec/season	* $F.C = D + I + T_i$	T_i: taxes and insurance costs were assumed to be 1.5 % of the purchase price of the unit (P_m)
Repair and maintenance costs, R_m	* $R_m = (3\%\ new\cos t)$	
Energy cost, *E.C*, USD/hec/season	** $E.C = Bp \times T \times P_r$ ** $Bp = \frac{Q \times TDH}{C \times E_{overall}}$	*Bp*: the brake power (kW), *T*: the annual operating time (*hr.*), P_r: cost of electrical power (0.125 LE/kW), *Q*: the total discharge rate (*L/s*), *TDH*: the dynamic head (m) *C*: the conversion coefficient (C = 102 according to Jensen, 1981); $E_{overall}$: overall efficiency (67.5 % for pump derived by electric motor)
Variable costs, *V.C*, USD/hec/season	* $V.C = R_m + E.C + O$	*O*: the other costs (mechanization, lettuce seeds, fertilization per hectare, pesticides, labor, harvesting and transportation)
Total costs, *T.C*, USD/hec/season	* $T.C = F.C + V.C$	
The economical net seasonal income, *NSI*, USD/hec	*** $NSI = (Y \times Y_p) - T.C$	*Y* : the total yield (plant/hec), Y_d : the yield price (USD/plant);

[9-12]

Table 2: List of the required materials and other approximate seasonal costs of aquaponic system, supposed for an area of one hectare of head lettuce crop for calculating cost economics.

Fixed cost		Technical specification	Unit cost (USD[a])	Total cost of treatments (USD) Different A-frame angle		Useful life (years)
A)	New aquaponic system cost			60º	30º	
1-	Fish tank	1000 L (PE)	22.47	18,247	25,797	10
2-	Sedimentation tank	200 L (PE)	6.74	5,474	7,739	5
3-	Pumping unit	H max 3m	11.23	9,123	12,898	7
4-	Air pump	-	3.37	2,737	3,869	5
5-	Timer	-	1.68	1,368	1,934	7
6-	Heater	-	250	11,404	16,123	7
7-	A-frame materials	-	12	9,807	13,866	15
8-	Cultivated pipes	12 pipes with 4-inch PVC 3m	42.47	34,487	48,757	10
9-	Cups	7×7cm	7.86	6,386	9,029	5
10-	Fittings and accessories	–	6.17	5,017	7,094	5
11-	Transportation and installation	–	–	280	365	–
B)	Others					
12-	Head lettuce	–	–	2,335	3,114	–
13-	Fingerlings	–	–	6,320	8,426	–
14-	Labor	–	–	280	365	–
15-	Harvesting and transportation	–	–	112	168	–

a = United States Dollar

Hectare = 812 aquaponic system with 60° A-frame angle Hectare = 1148 aquaponic system with 30° A-frame angle

Table 3: The effect of A-frame angle (A°) on light intensity (L), fish effluent temperature (T), Root Length (RL), Stem diameter (SD), fresh (Fr) and dry mass of shoot (Sh) and root (R) at different fish effluent depth (D) and tubes position (Pos.) for head lettuce and mint plants at the end of the experiment.

A.°	D. (cm)	Plant	Pos.	L. (LUX)	T.°C	Growth		R. mass(g)		Sh. mass (g)	
						RL (cm)	SD (mm)	Fr.	Dry	Fr.	Dry
30°	3	Lettuce	Top	1659	24.5	26.3	15.3	48	5.3	189.8	15.5
			Mid	1325	24	24.2	12.9	46	4	155.5	13.5
			Bot	1118	23.8	18.2	11.7	44.3	3.5	144.3	11.8
		Mint	Top	1831	24.5	30.6	3.4	40.1	9.8	137.6	11.3
			Mid	1348	24	26.3	2.3	29.8	6.8	91.8	8.2
			Bot	1690	23.8	28.4	3.2	32	7.8	107.2	9.7
	6	Lettuce	Top	1659	25.2	28.6	16.1	48.9	5.6	191.3	18.2
			Mid	1325	24.9	26.8	14.2	46.5	4.3	156.9	13.9
			Bot	1118	24.2	21.2	12.2	45.2	3.8	146.3	12.1
		Mint	Top	1831	25.2	32.2	3.6	45.1	12.6	140.3	13.2
			Mid	1348	24.9	28	2.4	35.6	8.8	96.7	9.2
			Bot	1690	24.2	30	3.5	38.3	9.3	119.7	11.2
60°	3	Lettuce	Top	1800	25.8	30.5	7.5	78.8	7.5	199.3	20.3
			Mid	1536	25.3	27.4	5.7	51.7	6.3	162.3	17.5
			Bot	1330	24.7	22.4	4.6	50.2	6.1	152.6	13.8
		Mint	Top	2120	25.8	34.2	3.9	50.3	14.8	146	16.8
			Mid	1934	25.6	31.2	3.3	42.3	11.8	130.7	13.9
			Bot	1700	24.6	30.5	2.6	37.6	9.3	125.7	12
	6	Lettuce	Top	1800	26.5	33.5	8.9	80.8	8	225.6	27
			Mid	1536	25.8	30.2	16.1	53.6	6.4	165	18.2
			Bot	1330	25	26.4	14.9	51.7	6.2	156.4	14.8
		Mint	Top	2120	26.5	34.8	3.9	65.5	16.6	166.5	19
			Mid	1934	25.8	32	3.7	57	13.5	147.5	15.3
			Bot	1700	25	30.9	2.8	46.6	11.3	132.7	13.2

Mid = (Middle), Bot = (Bottom)

4. Conclusions

The surface area used in plant cultivation and light intensity is influenced by changing the A-frame design angel. The intensity values were declined by decreasing the A-frame angle. Furthermore, the light intensity which falls on lettuce was lower than mint in A-frame with both angles of 30° and 60°; This is mainly due to the increasing in the width of lettuce shoot than the mint plant. The fresh and dry mass of shoot and root for lettuce was decreased by changing the A-frame angle from 60° to 30°, fish effluent depth from 6 to 3cm, and the tube's position from the middle to bottom. The fresh and dry mass of shoot and root increased for mint in the bottom than middle pipe position with 30°angle. Optimal yields of lettuce and mint plants grown in A-frame hydroponics system with 30° angle was like those grown in A-frame hydroponic system with 60° angle, indicating no significant differences in plant biomasses of lettuce and mint plants. The economic analysis of variance indicated that the profit had increased by 42.2% by using an A-frame design with 30° than an A-frame design with 60°.

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