Comparative assessment of intensive tomato production in innovative non-circulating aquaponics vs. conventional hydroponics

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Abstract: New tendencies in farming techniques which include a composite agricultural production system have evolved as solutions for uninterrupted food supply. Production of high-yielding good-quality tomato (*Solanum lycopersicum* L.) is one of the leading challenges. This study aimed at evaluating the growth, yield, and fruit quality of hybrid tomato (Umagna), cultivated in non-circulating aquaponics and conventional hydroponics systems. A unique and innovative non-recirculating deep water culture aquaponics system (DWCAS) was developed as a prerequisite for high productivity comparable to current stand-alone fish/plant facilities. Including DWCAS, two other conventional hydroponics systems were compared during the study; the deep water culture hydroponics system (DWCHS) and the open bag system (OBS). The assessment of the production systems was based on the growth behavior, tomato yield, and quality. The maximum yield was observed for the DWCHS (2.81 kg/plant) followed by DWCAS (2.4 kg/plant). The least yield was observed for the OBS (2.34 kg/plant). The results demonstrated the highest average fruit weight (169.44 g/fruit) and marketable yield (2802 g) produced by DWCHS. There was no difference in plant dry matter content among production systems. The fertilizer use efficiency was increased by 11.7% and 85.86% in favor of the DWCAS and DWCHS, respectively. The total rainwater use efficiency was also increased in DWCHS.

Keywords: tomato, hydroponics, aquaponics, deep water culture

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1 Introduction

Increasing population hence increasing food demand, increases the need for efficient use of agricultural resources. Therefore, trying out alternative food production methods in agriculture is of vital importance (Saha et al., 2016). Feeding the growing population by finding more efficient and sustainable food production systems is one of the main challenges of agriculture in this century. Lack of availability of freshwater and cultivable lands are major barriers to increasing crop yields without affecting the environment (FAO, 2009). To restrain global problems such as soil degradation, water

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scarcity, climate change, and the population increase, the hydroponics and aquaponics systems perform to be alternative solutions.

Hydroponics is a gardening method that uses no soil, instead grows plants in a solution full of nutrients. It has advantages over-cultivation in soil reflecting higher yield per unit area of land. Growing crops hydroponically also reduce the risk of soil-borne plant diseases, reducing the need to apply toxic chemicals (Suhl et al., 2016).

Aquaponics is considered a combination of aquaculture (raising fish) and hydroponics (growing plants in water) that produces fish and plants together in an integrated system that is environmentally friendly while maintaining a sustainable food production system (Suhl et al., 2016). Aquaponics relies on the principle of the nitrogen cycle, where the dissolved fish waste is effectively converted to plant nutrients by Nitrosomonas and Nitrobacter bacteria. Plants utilize these nutrients for their growth (Suhl et al., 2016). Currently, the Nile tilapia (*Oreochromis niloticus*) is used for aquaponics due to its rapid growth rate, good quality flesh, disease resistance, and adaptability to a wide range of environmental conditions. According to FAO (2009), Tomato (*Solanum lycopersicum* L.) is the most cultivated vegetable in aquaponics after the potato. The high costs for implementing and maintaining the crop and the demand of the market for better quality products stimulate the research for new cultivation and management alternatives (Fernandes, 2007).

Hydroponic systems are modified and rearranged according to recycling and reuse of nutrient solutions and supporting media. Deep water culture (DWC) system is one of the prominent hydroponic techniques used for tomato cultivation in aquaponics systems. Plant nutrient deficiency is one of the major problems in DWC aquaponics system. Aquaponic systems are closed recirculating models, thus, it is not appropriate to add soluble fertilizer into the fish tank or growing bed as the recirculating water directly in contact with fish. Modified aquaponics systems are required to overcome this constraint. The present study was carried out to evaluate the growth and yield performance of tomatoes in an innovative non-circulating deep water culture aquaponics system (DWCAS), deep water culture hydroponics system (DWCHS), and conventional open bag system (OBS) under protected environmental conditions. Additionally, fruit quality parameters in tomatoes were analyzed. These investigations were important to overcome the lack of scientific information available on fruit quality parameters under aquaponics. The current study also evaluated the fertilizer efficiency and total rainwater use efficiency of hydroponic systems.

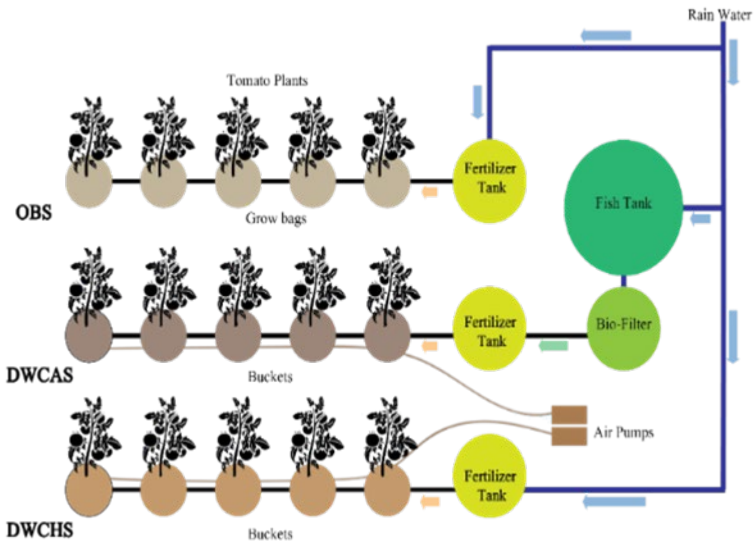

Figure 1 Schematic diagram of the experimental design

Figure 2 Experimental setup

Figure 3 Open bag system (OBS)

2 Materials and methods

2.1 Experimental design

The experiment was conducted under a non-temperature controlled polythene covered green house at the Serene International (Pvt) LTD located in Welimada (6^o.90′N, 80^o.90′ E), Sri Lanka. The experimental field belongs to the Argo-ecological zone of the up-country intermediate zone, IU3. The experimental site receives an average annual temperature of 21.1^{o}C, Climate data, 2020. Treatments were arranged in a completely random design (CRD) with five replicates as follows (Figures 1, 2). Tomatoes were grown in three systems, OBS, DWCHS, and DWCAS.

The OBS consisted of five equal sizes grow bags (Figure 3). Each bag was filled with fresh coco peat (EC- < 0.5 ms cm^{-1}, pH- 5.5-6.5) and contained a tomato plant. All replicates were connected to an irrigation nozzle for the fertigation system. The DWCHS consisted of 1 × 1 L fertilizer tank and five equal-sized containers (Figure 4). The fertilizer tank had inlet and outlet facilities connected to the container system. Uniform-sized trashed paint buckets with lids were used as containers for plants. The 4 L volume buckets had a top diameter, bottom diameter, and height of 0.192 m, 0.168 m, and 0.19 m, respectively. Individual buckets were facilitated by water inlets connected to the perforated PVC (1/2) line. The water level in the bucket was adjusted at a depth of 0.118 m to maintain the water volume of 2.5 L. The desired level of water in the system was maintained by regular supplementation of water and nutrients solution. Each paint bucket was aerated with an air stone connected to an air hose powered by an air pump. The airflow rate of the pump was 3.5 L min^{-1}. Net pots were filled with coco peat and held on top of the lid as plant holders.

Figure 4 Deep water culture hydroponicssystem (left), deep water cultureaquaponics system (right)

The DWCAS is comprised of a plastic fish tank, bio-filter, mechanical filter, fertilizer tank, and container for DWC system. The fish tank was filled with 30 L of rainwater and maintained constant aeration using an aquarium air stone powered by an air pump. The airflow rate of the pump was 2.5 L min^{-1}. A polyester net was placed over the fish tank to prevent it from escaping fish. Substrates of the bio-filter consisted of 25 L of a cistern, onion bags, gravels, and PVC nets. Onion bags were used to provide a high surface area for bacteria in the bio-filter. The water level in the bio-filter was controlled by a PVC pipe placed at the outlet opening point located on top of the cistern. A mechanical filter was fixed inside the bio-filter. Nitrifying bacteria were added to the system at the initiation of the trial. The bucket system was similar to DWCHS (Figure 4). Natural lighting was used during the entire study period and all experiments were carried out in five replicates. Rainwater was used as the main irrigation source. During the production period, a combination of tilapia (*Oreochromis niloticus*) and tomatoes (*Solanum lycopersicum* L.) was produced.

2.2 Stocking and feeding of fish

The recommended fish density is based on a maximum stocking density of 20 kg per 1000 L (FAO, 2012). Uniformed-sized (29.1 g) Nile tilapia (*Oreochromis niloticus*) were stocked in the fish tank to maintain an initial stocking density at 7.76 kg m^{-3}. Fish were stocked on the same date as the sowing of tomato seeds. Fish were given a commercial feed manufactured by Skretting Nutreco company, Norway having an average protein content of 30%, and offered three times per day, one-third at 8:30 AM, one-third at 1:30 PM, and remaining at 4:30 PM at a rate of 6% of body weight (Rahmatullah et al., 2010).

2.3 Crop establishment and management

The hybrid tomato (*Solanum lycopersicum* L.)

Umagna -F1 was cultivated in three systems. Tomato seeds were sown in the nursery on the 23rd of June 2020. From the 12th day, the plants were irrigated with Albert's solution with 1.5 ms cm^{-1}. When the plants reached the stage of 4 to 6 definitive leaves, they were transplanted to the systems and maintained five seedlings under each treatment. Tomato seedlings were directly planted in OBS. Tomato seedlings were established in ten net pots before being transferred to DWCHS and DWCAS. Net pots with plants were placed on the lid of paint buckets 6 days after transplanting. The temperature inside the greenhouse was measured daily, using a thermometer, and placed at a height of 1.5m from the floor surface. During the first 6 days after transplanting, the fertigation was done manually for plants established in net pots. Potting space between two plants was 45 cm.

The plants in OBS were irrigated with nutrient solution containing Albert's solution and other fertilizer (Fertilizer ratios produced by Grow more company in the USA; 10-52-10, 20-20-20, 6-30-30, and 13-2-44) during the vegetative stage. With the appearance of bunches, the nutrient formulation was changed. Plants in DWCHS were grown in a vegetative growth solution containing Albert's solution and other fertilizer (10-52-10, 20-20-20, 6-30-30, and 13-2-44).

Tomato plants in DWCAS were irrigated with fish effluent instead of Albert's solution. Other fertilizer types (10-52-10, 20-20-20, 6-30-30, and 13-2-44) were supplied during the vegetative stage. Fertilizer application was done based on electric conductivity (EC) value. Instead of same amount of fertilizer but same EC values were maintained. Ca supplement was increased during the fruiting stage irrespective of the treatment. The loss of nutrient solution due to evapotranspiration was replenished with rainwater and nutrient solution daily, to maintain the consistent volume of 2.5 L per experimental pot. The pH of the nutrient solution was daily monitored and adjusted to the range of 5.5 to 6.5, using HCl or NaOH and, nutrient solutions in all treatments were adjusted with mineral fertilizer to an EC below 4.0 ms cm^{-1} to achieve optimal growth conditions for tomatoes.

2.4 Determination of plant yield and plant growth

Tomatoes were harvested 86 days after the sowing date. To compare the total yield, the harvested tomatoes of each plant were weighed and counted. Evaluating the weight, fruits were categorized as marketable (>50 g) and non-marketable (<50 g). The plant height of each plant per treatment was measured and recorded from the fourth week after transplanting and thereafter on a fortnightly basis until the plants reached nearly 2 m in height. The plant height was measured from the plant stem crown to the growing point of the plant using a 3 m measuring tape. The number of leaves was also counted on each plant on a fortnightly basis. The number of days taken from sowing until 50% of plants having the most flowers was recorded as days to flowering.

2.5 Fruit physical parameters

The fruit length of five randomly selected fruits from the replicates was measured from the base to the tip of the fruit. The width of the same fruits was measured as per the equation (1) given below (Jahanbakhshi et al., 2019).

$$Width\ of\ the\ fruit\,(mm) = \frac{Circumference\ of\ each\ fruit\,(mm)}{2} \quad (1)$$

The fruit diameter of the same selected fruits was measured and expressed. All measurements were expressed in millimeters. Fruit firmness was determined on three fruits per treatment per replication at the red stage using a hand penetrometer [Fruit pressure tester, Model: FT 327 (200 g-20 kg), with 0.7 × 0.92 mm of probe's size].

2.6 Soluble solids, fruit pH, and EC

The total soluble solids content was measured using a hand-held refractometer [Model SKU: MT-032 (Brix, 0%-32%)]. The pH and EC contents of fruit juice were measured using an EC/pH meter [Model: PCTEST-35]. The average TSS, pH, and EC were determined by selecting three fruits per treatment for each replicate. The final values were obtained by calculating the average of the replicate for each treatment.

2.7 Water and fertilizer use

The freshwater and fish wastewater volumes consumed by the systems during the entire study period were measured. To estimate the fertilizer use, the amount of each nutrient added to each treatment was weighed and summed throughout the experiments. However, the loss of nutrients caused by regularly discarded volumes of nutrient solution used to prevent EC fluctuation was not considered in these calculations. The total fertilizer use is expressed in kilograms (kg). Fertilizer savings by DWCAS were calculated by using the number of nutrient requirements in aquaponics concerning that used in hydroponics and considered as 100%. The total rainwater use efficiency (RWUE) was calculated for each treatment. In terms of the OBS and DWCHS systems, the RWUE was calculated as the ratio between yield and total rainwater use. The results were expressed as kg tomatoes per m^3 of rainwater ($kg\ m^{-3}$). The RWUE regarding the DWCAS system was calculated in the same manner, however, under the assumption of total utilization of rainwater for fish production in fish tanks and fish wastewater used for tomato production. As such, the quantity (in kg) of fish and tomatoes that can be produced with the same volume of rainwater was tested. The mean total fertilizer use efficiency (FUE) in terms of all fertilizer types for all treatments was calculated as a ratio between the total yield and the total fertilizer use. The results are expressed in kg of fruit yield per kg of fertilizer supplied ($kg\ kg^{-1}$).

2.8 Biomass production

The fresh matter content of the plant was measured at the end of the cropping cycle. Fresh leaves, fresh stems, and fresh roots were weighed using a weighing balance scale (SF-400, 10000 g × 1g). The dry matter content of the plant was determined by drying samples in an oven at 60 ºC until a constant weight is obtained.

2.9 Statistical analysis

The data obtained were subjected to Analysis of Variance (ANOVA) using Minitab version 2019. Significant means were separated by mean differences Tukey method at $p \leq 0.05$.

3 Results

3.1 Plant yield and plant growth

The number of fruits recognized as the marketable yield was statically identical in all treatments (OBS=14, DWCHS=16, DWCAS=14). The highest average weight of fruit (169.44 g/fruit) was reported by DWCHS while the lowest was reported from OBS (139.96 g/fruit) which was statically significant (Figure 5). The total weight of tomato fruits harvested per plant in DWCHS was 2817 g, marking the highest (p <0.05) among the other treatments. The use of fish wastewater with mineral fertilizer in DWCAS yielded a total weight of 2400 g/plant, while OBS was 2344 g/plant, with no significant difference. When the marketable yield is considered, the plants grown in DWCHS produced a significantly higher (p<0.001) marketable yield per plant (2802.0 g/plant) than those grown in OBS (2250.0 g/plant) and DWCAS (2239.0 g/plant). In this study, the maximum and the minimum plant height were recorded in DWCHS (175.20 cm) and OBS (150.40 cm), respectively (Table 1). Although the total number of leaves differed among the treatments, (OBS=18, DWCHS=19, DWCAS=17) it was not statically significant. As illustrated in Table 1, the OBS had taken 48 days from sowing to flowering, whereas the DWCAS recorded the lowest number of days (40) to first flowering (p<0.001), marking the efficiency of the system. The variation among treatments for the average girth of the stem with the mean values ranging from 38.400 mm to 41.000 mm. In this study, the maximum girth of the stem was recorded in OBS (41.000 mm), while DWCAS showed the minimum girth (38.400 mm), and was recorded to be the least when compared with other treatments (Table 1).

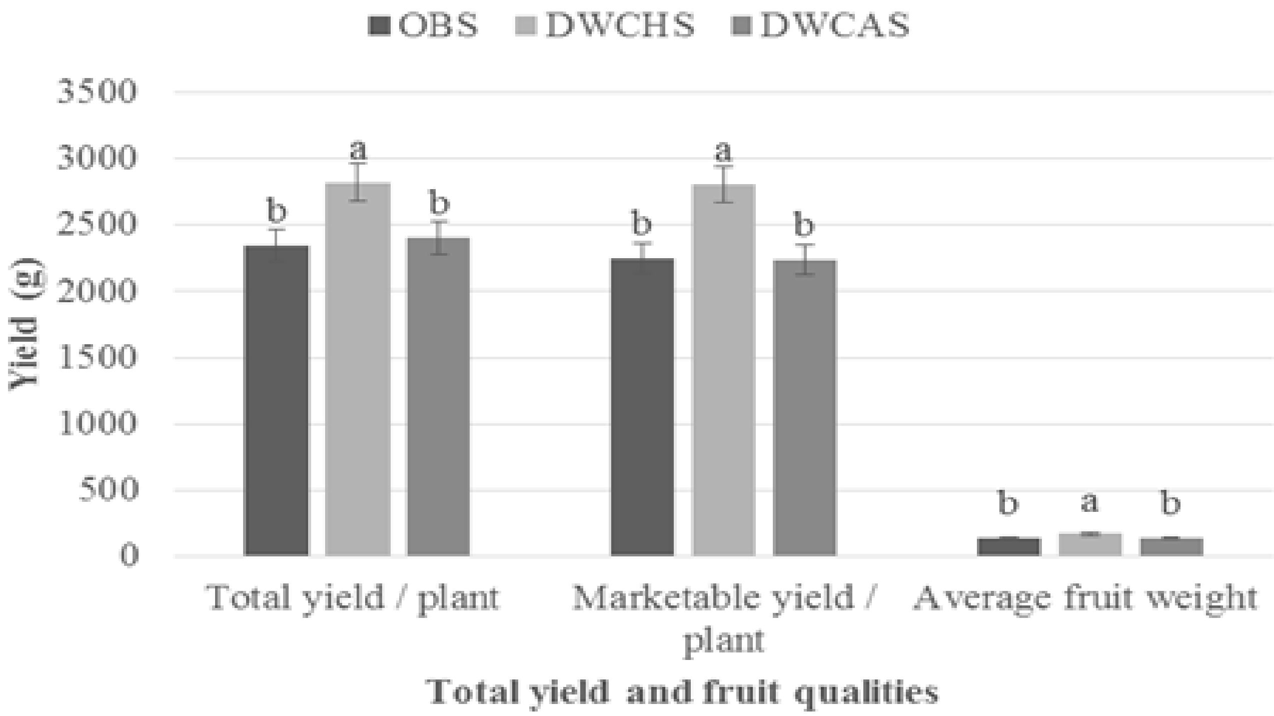

Figure 5 Effects of growing methods on fruit yield and quality

Note: The values represent the mean value of total tomato yield per plant, marketable yield per plant and fruit weight. The small letters indicate significant differences

Table 1 Effects of growing methods on plant growth parameters

Treatment	Plant height (cm)	Number of leaves	Days to flowering	Girth of stem (mm)
OBS	150.40 [b]	18	48 [a]	41.000 [a]
DWCHS	175.20 [a]	19	43 [b]	40.800 [a]
DWCAS	163.40 [ab]	17	40 [c]	38.400 [b]
LSD	0.007	ns	<0.001	0.014

Note: ns = non-significant, LSD = Least significant difference

Values bearing different letters within the same column were significantly different at (p<0.05)

3.2 Fruit quality

The highest levels of fruit's total soluble solids (TSS) were observed in fruits from OBS (3.85). However, the TSS showed no significant difference among treatments (Table 2). The pH value of DWCHS (4.86) was significantly less (p<0.05) than OBS (5.02) and DWCAS (5.04). Interestingly, the type of treatment demonstrated a significant effect on fruit juice EC (Table 2). The DWCHS (10.84 ms cm^{-1}) and DWCAS (10.72 ms cm^{-1}) were statically identical, while the EC of OBS (10.33 ms cm^{-1}) was significantly less than other systems. The highest fruit length (106.2 mm) was recorded in DWCHS whereas the minimum (97.6 mm) fruit length was in OBS (Figure 6). Except for the fruit width, significant differences were not noted between the treatments regarding the fruit diameter. The highest average fruit width was observed in the OBS (118.4 mm) (Figure 6). The DWCHS and DWCAS produced fruits with an average width of 118.0 mm and 109.0 mm, respectively. To test the influence of growing methods on fruit's physical properties, the firmness of the fruit was tested. The results demonstrated a non-significant increase in the firmness of fruits from DWCHS (2.02 kg f^{-1}) than fruits from other treatments (OBS= 1.88 kg f^{-1}, DWCAS= 1.8 kg f^{-1}).

Table 2 Effects of growing methods on fruit quality parameters

Treatment	TSS%	pH	EC (mS/cm)	Firmness (kg/f)
OBS	3.85	5.02 [a]	10.33 [b]	1.88
DWCHS	3.70	4.86 [b]	10.84 [a]	2.02
DWCAS	3.6	5.04 [a]	10.72 [a]	1.80
LSD	ns	0.003	<0.001	ns

Note: ns = non-significant, LSD = Least significant difference

Values bearing different letters within the same column were significantly different at (p<0.05)

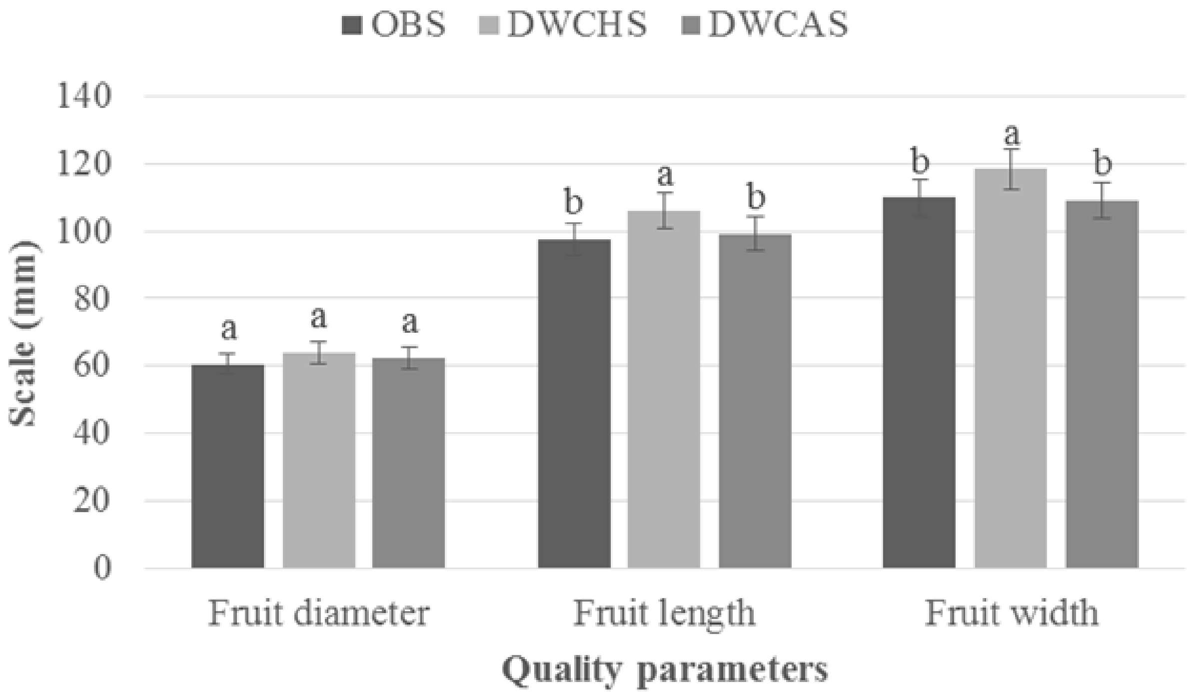

Figure 6 Effects of growing methods on fruit quality parameters

Note: Influence of growing methods on fruit diameter, length and width. The data represent mean values and small letters indicate significant differences (p < 0.05)

3.3 Rainwater consumption and total rainwater use efficiency

From initial fish stocking until the last day of tomato harvest (118 days) the total rainwater consumption of 5 plants under OBS was 0.0636 m^3. The DWCHS, with a total of 5 plants, consumed 0.0455 m^3, whereas the DWCAS consumed 0.0455 m^3 (Figure 7). However, we observed 0.065 m^3 rainwater consumption by the fish tank during the plant growth period. Thus, to investigate the RWUE, total mean yields of OBS (2.34 kg $plant^{-1}$), DWCHS (2.81 kg $plant^{-1}$), and DWCAS (2.4 kg $plant^{-1}$) were calculated. This resulted in a total fruit yield of 11.72 kg (OBS), 14.08 kg (DWCHS) and 12.0 kg (DWCAS) achieved.

The RWUE reached a value of 184.2 kg m^{-3} in the OBS system, with a total fruit yield of 11.72 kg and a 00636 m^3 rainwater consumption. However, the RWUE in DWCHS was 309.45 kg m^{-3}, yielding 14.08 kg of fruit, while the rainwater consumption was 0.0455 m^3. Surprisingly, the DWCAS achieved a total fish yield of only 0.42 kg. Based on the study conditions and results of tomato yield and water consumption of the DWCAS, the present study revealed a theoretical possibility of obtaining 6.46 kg tilapia and 263 kg tomato fruit produced with one m^3 rainwater applied to the fish tank.

3.4 Fertilizer use and fertilizer use efficiency

The addition of total fertilizer into the DWCAS was reduced by 23.0% compared to that delivered to plants grown in the DWCHS. Based on the total tomato yields and the fertilizer use as shown in Table 3, the FUE was calculated under each treatment. The FUE was improved by 11.7% in favor of the DWCAS. In other words, the DWCAS showed that 4.11 kg more tomatoes can be produced with the application of one-kilogram fertilizer into the system compared to the DWCHS. The FUE was improved by 85.86% in DWCHS. Therefore, 16.1 kg more tomatoes can be produced with the application of one-kilogram fertilizer into this system compared to the OBS. Further, compared to OBS, the FUE was improved by 107.78% in favor of the DWCAS. According to this result, 20.21 kg more tomatoes can be produced with the application of one-kilogram fertilizer into this system compared to the OBS.

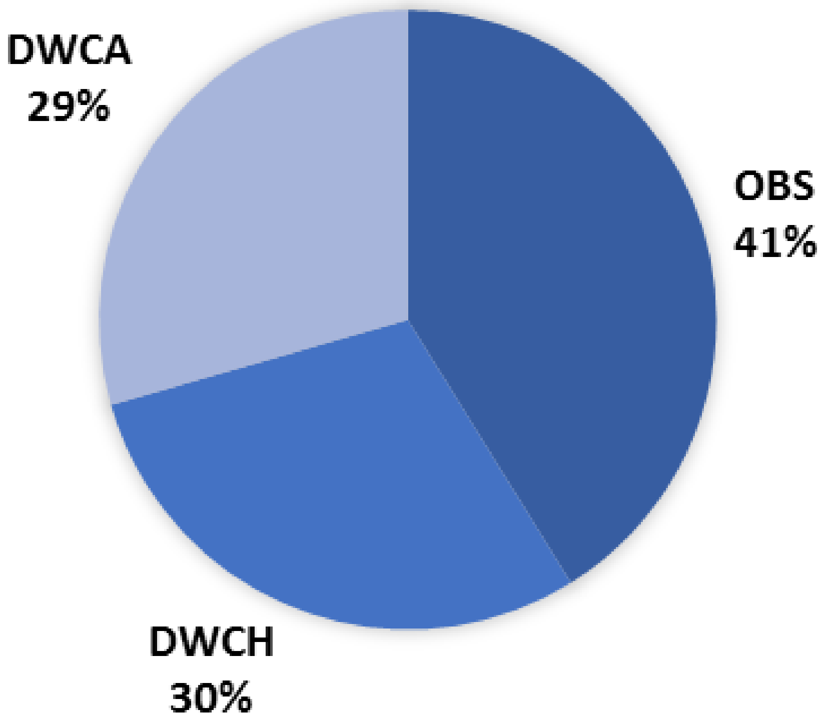

Figure 7 Water usage of treatments during experiment

Table 3 Total yield, total fertilizer addition, and fertilizer use efficiency (FUE) caused by growing methods

	OBS	DWCHS	DWCAS
Total yield per treatment (kg)	11.72	14.08	12.0
Mineral fertilizer addition (kg)	0.625	0.404	0.308
		(100%) *	(23%) *
	(100%) **	(35.36%) **	
	(100%) ***		(50.72%) ***
FUE (kg kg^{-1})[a]	18.75	34.85	38.96

Note: *The percentages in the brackets represent the reduced fertilizer addition in DWCAS compared to DWCHS (100%)

**The percentages in the brackets represent the reduced fertilizer addition in DWCHS compared to OBS (100%)

***The percentages in the brackets represent the reduced fertilizer addition in DWCAS compared to OBS (100%)

[a] The FUE is calculated in kg produced tomatoes per kg mineral fertilizer addition

Table 4 Effects of growing methods on plant biomass production

Treatment	Fresh weight of plant (g)				Dry weight of plant (g)			
	Leaves	Stem	Root	Total	Leaves	Stem	Root	Total
OBS	140.0 [b]	169.0	56.0	365.0 [b]	20.8 [b]	27.4	8.6	56.8
DWCHS	218.0 [a]	177.0	57.0	452.0 [a]	30.0 [a]	30.0	9.4	69.4
DWCAS	195.0 [a]	157.0	61.0	413.0 [ab]	29.8 [a]	27.4	9.8	67.0
LSD	0.002	ns	ns	0.035	0.009	ns	ns	ns

Note: ns = non-significant, LSD = Least significant difference

Values bearing different letters within the same column were significantly different at (p<0.05)

3.5 Biomass production

The maximum total fresh weight of the plant was noted in the DWCHS (452.0 g) followed by DWCAS (413.0 g) (Table 4). The minimum total fresh weight of the plant was recorded in OBS (365.0 g). Although there was no significant difference in average total dry matter content per plant within treatments, maximum (69.4 g) and minimum (56.8 g) total dry weight were observed among the DWCHS and OBS, respectively.

4 Discussion

The aim to reach comparable yields with the innovative DWCAS as produced in the conventional hydroponics way was accomplished. A yield of 2400 g per plant was gained using fish wastewater, enabling the new system to compete with conventional OBS. However, at the harvesting stage, the highest yield per plant (2817.0 g/plant) was obtained from DWCHS which is not commonly used on a commercial scale. Wortman (2015) found that the relative vegetative growth rates of basil, kale, tomato, and pepper in recirculated aquaponics (low EC + high pH) did not differ from plants grown in conventional hydroponics (high EC + low pH). However, the marketable yields of all species were significantly reduced in aquaponics. In agreement with them, the current study demonstrated that DWCAS produced a lower yield than DWCHS. Moreover, Suhl et al. (2016) reported that the rate of marketable tomato on total yield was nearly the same in both treatments (hydroponics = 99.1%, aquaponics = 99.5%). Concordantly, our study demonstrated a nearly similar contribution toward marketable yield obtained from DWCAS (30.70%) and OBS (30.86%). The results of this research agree with those of Castro et al. (2006) found that irrigation with fish effluent enhanced tomato fruit number and productivity in the first three analyzed harvest periods. However, the increase in fruit number in treatments that received fish wastewater resulted in lower mean fruit weight. They found that even with a reduction in average fruit weight, the increase in fruit number was enough to raise the total productivity. Logendra et al. (2001) observed an increased number of leaves which in most instances tends to increase fruit weight and not the fruit number. The result of this study is tally with that finding, due to DWCHS having a higher number of leaves (19) and fruit weight (169.44 g/fruit) as well.

There was a wide range of variation among the growing methods for plant height with the mean values ranging from 175.20 cm (DWCHS) to 150.40 cm (OBS) possibly due to several factors, such as planting season, crop growing methods, number of branches left per plant, number of fruit left per plant and material used to cover the Poly- tunnel (Papadopoulos and Hão, 1997; Manju and Sreel, 2004). Since DWCAS recorded the lowest days to first flowering, it will be a most economically important factor for commercial fruit production. But the very first harvest was obtained from DWCHS, three days earlier than DWCAS. Imais (1987) studied that the reduction of the vegetative growth period, and survival of the plants in adverse conditions resulted in a delay in flowering and fruit development in the open bag system. Nevertheless, the days to first flowering remained within the range of reference values found in previous studies (Logendra, 2001; Wortman, 2015).

The TSS (ºBrix) content is one of the important quality attributes during the ripening stage for various fresh fruits, including tomatoes (Siddiqui et al., 2015). In the nutritional market, high-quality tomato fruits should possess percentages of ºBrix above 3 (Schwarz , 2013). This study demonstrated higher values (>3.5) for TSS than the suggested levels. It means tomatoes in all treatments have higher sugar content. Furthermore, the amount of sugars in tomato fruits is the main constituent of post-harvest quality, being directly related to its flavor. As for pH, foods are classified into three categories: low acidity (pH 4.5), acid (pH 4.0 - 4.5) and very acid (pH < 4.0). Tomato fruits have a pH below 4.6 and are considered acidic foods (Suhl et al., 2016; Peixoto , 2018). Contradictorily, the fruits in our study presented pH values above 4.6, possibly due to the harvesting stage. The acidity of fresh tomatoes can be thoroughly associated with their degree of ripeness. The more mature and ripe, the lower the acidity, with pH approaching the 4.9 ends of the range. Further investigations will be required in this regard. The EC of the tomato fruit juice was not significantly different in tomato cultivation with the same substrates (Water culture), which is by Islam et al. (2002). Although significant differences were not noted between the treatments regarding the fruit diameter, there was a 5.3% and 2.5% reduction in the fruit diameter of OBS and DWCAS compared to DWCHS. The growing method may have influenced fruit width in three treatments as was observed in the study of Seran and Iqram (2016) where the tomato irrigated with Albert's solution enhanced tomato width. In this study, increased fruit diameter, fruit width, and fruit length were recorded DWCHS over other treatments agreeing with the previous evidence of changes in fruit physical parameters along with the type of fertilizer (Maatjie, 2015). The present study indicated an increased fruit length in both water culture systems. Types of growing methods had not significantly influenced fruit firmness. Suhl et al. (2016) reported that fruit firmness was not differed within the same cultivar due to the growing method which is in agreement with the present findings.

It is noteworthy, that the OBS used 41% of rainwater out of the total water consumption during the plant production period. Both of the other treatments used equal amounts of rainwater. However, considering the yields and the water consumption, the present study showed the ability to produce 6.46 kg tilapia and 263 kg tomato fruit with one m^3 of rainwater applied to the fish tank in DWCAS. The higher tomato yield production in our study can be described by better control and an accurate fertilizer strategy followed, where the stock nutrient solution for the plants was adjusted regularly to maintain uniformity. A further advantage of the small-sized, protected house would be that the limitation of ventilation results in higher CO_2 levels and an associated faster vegetative crop growth, higher yields, and an increased accumulation of primary and secondary plant metabolites in fruit. Furthermore, the water uptake of the plants can be reduced which resulted in a better water use efficiency (Suhl et al., 2016).

The addition of total fertilizer into the DWCHS was reduced by 35.36.0% (Table 3) compared to plants grown in the OBS system. The addition of total fertilizer into the DWCAS was reduced by 50.72% compared to that OBS system. In the present study, it has been successfully demonstrated that the total yield produced in aquaponics is comparable to that in OBS and the FUE was increased by approximately 20.21%. Applying 1 kg of mineral fertilizer led to a fruit production of 38.96 kg in DWCAS, whereas only 18.75 kg in OBS and 34.85 kg of tomatoes were produced in DWCHS. Confirming this statement, previously it has been found that the FUE was also improved by 23.6% in aquaponics systems compared to hydroponics systems (Suhl et al., 2016).

Feed conversion ratio (FCR) is one of the most important parameters in terms of the economy of an aquaponics system which should be optimized together with fish density and feeding ratio. Previous evidence showed an average FCR of 1.2 to 1.3 in an aquaponics system with 40 kg fish m^{-3} and recommended positive for commercial aquaculture (Monsees et al., 2017). The present study demonstrated an FCR of 1.11 for DWCAS. Thus, this finding is in agreement with Monsees et al's finding.

To our surprise, although a significant difference was observed in fresh matter content among treatments, there was no significant difference in the average total dry matter content of plants. This result is similar to the findings by Islam et al. (2002), in protected tomato cultivation, indicating that, under hydroponic cultivation, no significant differences in the total dry matter content of plants were observed between the treatments.

The DWCAS had a relatively high cost of production due to the initial construction of the structure. The maximum gross return (Rs.449600.00) and net return (Rs.325440.00) were obtained for the

DWCHS. Similarly, the highest benefit-cost ratio (B/C) (3.62) was also obtained for the same treatment. The reason to obtain such high value may be due to the low cost of media, fertilizer, and the high yield of tomatoes. The OBS exhibited the lowest B/C ratio (2.66) though the gross return was Rs.374400.00. However, all the treatments showed a B/C ratio of more than 2.5. Thus, the DWCAS can be a potential technology for hydroponics tomato cultivation as previously described where >3.0 B/C is considered favorable for hydroponics tomato cultivation in aggregate methods (Joseph and Muthuchamy, 2014).

5 Conclusion

It was shown that the DWCHS and DWCAS provide the opportunity to produce higher tomato yields compared to those obtained by the conventionally used hydroponic system (OBS). Moreover, it was demonstrated that even with considerable fish production a good plant growth and fruit yield can be produced using DWCAS. The yield of tomatoes indicated that DWCHS recorded the highest values for total yield per plant, average weight of fruit, and marketable yield per plant. Although DWCHS recorded the highest yield per treatment, the DWCAS allows more sustainable food production. The FUE was also improved in DWCHS and DWCAS compared to OBS. To the best of our knowledge, this is the first study to demonstrate a non-circulating deep water culture crop growing method.

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Conflicts of Interest

The authors declare no conflict of interest.

References

Castro, R. S., C. M. S. A. Borges, and F. Bezerra-Neto. 2006. Increasing cherry tomato yield using fish effluent as irrigation water in northeast Brazil. *Scientia Horti-Culturae*, 110(1): 44-50

FAO. 2009. Global Agriculture Towards 2050. Available at: https://www.fao.org. Accessed 20 February 2021.

FAO. 2012. Food and Agricultural Organization of the United Nations, the State of World Fisheries and Aquaculture. Available at: https://www.fao.org. Accessed 20 February 2021.

Fernandes, A. A. 2007. Cultivo sucessivo de plantas de tomate oriundas de sementes e propagação vegetativa em sistema hidropônico. *Pesquisa Agropecuária Brasileira*, 42(7): 1013-1019.

Imais, H. 1987. Non-circulating hydroponics system. In *Proc. Symp. on Hort. Prod. Under structures*, 18-19 Feb,1987, Tai-Chung, Taiwan, R.O.C.

Islam, S., S. Khan, T. Ito, T. Maruo, and Y. Shinohara. 2002. Characterization of the physico-chemical properties of environmentally friendly organic substrates in relation to rock-wool. *Journal of Horticultural Science and Biotechnology*, 72(2): 143–148.

Jahanbakhshi, A., V. Rasooli, S. Kobra, M. Kaveh, and E. Taghinezhad. 2019. Evaluation of engineering properties for waste control of tomato during harvesting and postharvesting. *Food Science and Nutrition*, 7(4): 1473-1481.

Joseph, A., and I. Muthuchamy. 2014. Productivity, quality and economics of tomato (Lycopersicon esculentum Mill.) cultivation in aggregate hydroponics – a case study from coimbatore region of Tamil Nadu. *Indian Journal of Science and Technology*, 7(8): 1078–1086.

Logendra, L. S., J. Thomas, T. J. Gianfagna, R. David, D. R. Specca, W. Harry, and H. W. Janes. 2001. Greenhouse tomato limited cluster production systems: crop management practices affect yield. *HortiScience*, 36(5): 893–896.

Maatjie, M. A. 2015. Growth, yield and quality of hydroponically grown tomatoes as affected by different particle sizes of sawdust. M.S. thesis, University of South Africa.

Manju, P. R., and A. Sreel. 2004. Genetic divergence in hot chili (*Capsicum Chinesejacq.*) *Capsicum and Eggplant Newsletter*, 23(1): 69-72.

Monsees, H., W. Kloas, and S. Wuertz. 2017. Decoupled systems on trial: Eliminating bottlenecks to improve aquaponics processes. *PLoS ONE*, 12(9): 1-18.

Papadopoulos, A. P., and X. Hão. 1997. Effects of three greenhouse cover materials on tomato growth, productivity, and energy use. *Scientia Horticulturae*, 70(2): 165-178.

Peixoto, A. 2018. Post-harvest evaluation of tomato genotypes with dual purpose. *Food Science and Technology*, 38(2): 255-262.

Rahmatullah, R., M. Das, and S. M. Rahmatullah. 2010. Sustainable stocking density of tilapia in aquaponics system. *Bangladesh Journal of Fisheries Research*, 14(3): 29-35.

Saha, S., A. Monroe, and M. R. Day. 2016. Growth, yield, plant quality and nutrition of basil (*Ocimum basilicum* L.) under soilless agricultural systems. *Annals of Agricultural Sciences*, 61(2): 181-186

Schwarz, K. 2013. Desempenho agronômico e qualidade físico-química de híbridos de tomateiro em cultivo rasteiro. *Horticultura Brasileira*, 31(3): 410-418

Seran, T. H., and A. M. M. Iqram. 2016. Effect of foliar application of Albert solution on growth and yield of tomato (*Lycopersicon esculentum*). *Journal of Advance Research in Food, Agriculture and Environmental Science*, 3(4): 17-22

Siddiqui, M. W., J. F. Ayala-zavala, and R. S. Dhua. 2015. genotypic variation in tomatoes affecting processing and antioxidant properties. *Critical Reviews in Food Science and Nutrition*, 55(13): 1819-1835

Suhl, J., D. Dannehl, W. Kloas, D. Baganz, S. Jobs, G. Scheibe, and U. Schmidt. 2016. Advanced aquaponics: Evaluation of intensive tomato production in aquaponics vs. conventional hydroponics. *Agricultural Water Management*, 178(1): 335–344.

Wortman, S. E. 2015. Crop physiological response to nutrient solution electrical conductivity and pH in an ebb-and-flow hydroponic system. *Scientia Horticulturae*, 194(1):34–42.

Abbreviations

Abbreviations	
DWCAS	Deep water culture aquaponics system
DWCHS	Deep water culture hydroponics system
FCR	Feed conversion ratio
FUE	Fertilizer use efficiency
OBS	Open bag system
RWUE	Rainwater use efficiency
BC	Benefit-cost ratio