



Article

# Growth of Basil (*Ocimum basilicum*) in DRF, Raft, and Grow Pipes with Effluents of African Catfish (*Clarias gariepinus*) in Decoupled Aquaponics

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**Abstract:** Basil (*Ocimum basilicum*) was cultivated in Rostock, Northern Germany, in a decoupled aquaponic system with African catfish (*Clarias gariepinus*) under intensive rearing conditions by using three hydroponic components, the dynamic root floating technique (DRF), the raft technique, and grow pipes. A 25% of the recommended feed input still allowed African catfish growth and provided adequate nitrogen and calcium levels in the process water. After 36 days, the plants were examined with respect to 16 different growth parameters. DRF performed significantly better than raft and/or grow pipes in 11 parameters. Total weight of basil was significantly higher in DRF ( $107.70 \pm 34.03$  g) compared with raft ( $82.02 \pm 22.74$  g) and grow pipes ( $77.86 \pm 23.93$  g). The economically important leaf biomass was significantly higher in wet and dry weight under DRF cultivation ( $45.36 \pm 13.53$  g;  $4.96 \pm 1.57$  g) compared with raft ( $34.94 \pm 9.44$  g;  $3.74 \pm 1.04$  g) and grow pipes ( $32.74 \pm 9.84$  g;  $3.75 \pm 1.22$  g). Two main factors limited plant growth: an unbalanced nutrient concentration ratio and high water temperatures with an average of  $28$  °C (max  $34.4$  °C), which resulted in reduced root activity in raft and grow pipes. DRF was able to maintain root activity through the 5 cm air space between the shoots and the nutrient solution and thus produced significantly more biomass. This suggests DRF to be used for basil aquaponics under glass house conditions with high-temperature scenarios. Future studies are needed to optimize nutrient loads and examine systems with the plant roots exposed to air (Aeroponics).

**Keywords:** basil; African catfish; dynamic root floating technique (DRF); floating raft; deep water culture; grow pipes; aquaponics; hydroponics

## 1. Introduction

Aquaponics is a scientific field of increasing relevance due to the possibility of sustainable, resource-friendly food production [1]. However, there are still many open questions and research areas in this young discipline, such as the growth potential of different crops in various subsystems [2]. Plant species such as basil (*Ocimum basilicum*) and spearmint (*Mentha spicata*) already show a high potential for aquaponic cultivation, and these species are economically important and should, therefore, be further investigated in aquaponics in combination with different fish species [3–5].

Especially suitable for aquaponics are plants with a high growth potential, market demand, and price, such as culinary herbs [6], while at the same time having only moderate space requirements. Plant production in aquaponics was dominated to 81% by basil (*Ocimum basilicum*) and has therefore been the most cultivated herb [3]. Basil develops a distinctive and unmistakable scent via oil glands on the leaves and is considered one

of the most versatile herbs [7]. As a medicinal herb or as an important ingredient in the kitchen, basil has become, dried or fresh, a part of almost all cultures [8–10]. The demand for basil is very high among aquaponics and hydroponics producer groups [11]. As basil is particularly suitable for soilless cultivation, it has therefore been used in various aquaponics and hydroponics experiments [12–14]. Basil can produce 1.8 kg per m<sup>2</sup> under aquaponic production [15], whereas basil in soil cultivation can produce only 0.6 kg per m<sup>2</sup> [15]. In combination with *C. gariepinus* and Nile tilapia (*Oreochromis niloticus*), basil (*O. basilicum*) showed good growth performance in an extensive coupled ebb and flood gravel substrate system [16]. However, few studies report on basil under decoupled aquaponics in different hydroponic subsystems or components [14].

African catfish (*Clarias gariepinus* Burchell, 1822) is gaining increasing scientific and economic importance, and not only in Mecklenburg Western Pomerania, Germany [17,18]. This fish is suitable for aquaculture because of its high tolerance to different rearing conditions, with a low susceptibility to disease and the ability to breathe atmospheric air with its accessory respiratory organ [19]. Furthermore, African catfish has an excellent feed conversion rate, especially at high stocking densities [20,21]. *C. gariepinus* was cultivated under aquaponic conditions with cucumber (*Cucumis sativus*) [22], water spinach (*Ipomoea aquatica*) [23], lettuce (*Lactuca sativa*), tomatoes (*Solanum lycopersicum*), and basil (*Ocimum basilicum*) [16], and has showed good growth performance. The use of the African catfish in aquaponics is possible and should be further investigated due to its consumer acceptance.

Recent aquaponics systems can use a wide range of different hydroponic subsystems or components for domestic or commercial plant cultivation [1,2]. One of these methods is the “floating raft technique (raft)” [24]. Here, the plants grow in grid pots on floating material (e.g., polystyrene), with the roots permanently submerged in the process water, also known as “deep-water culture (DWC)”. This method was already experimentally investigated several years ago and has been most frequently used [3,25]. For industrial or domestic purposes, the “nutrient film technique (NFT)” is a popular option, using closed channels or grow pipes [26] with small openings for plant cultivation. The roots are supplied with nutrients by a permanent water film and grow inside the channels. The NFT technique is a simple and cheap farming option with relatively low water consumption [24]. NFT is also a long-established aquaponics system and has been used in several experiments, with varying results regarding production and harvest potential [24,27].

A new method in aquaponics is the so-called “dynamic root floating technique (DRF)”, which is known as a suitable system for the cultivation of leafy vegetables and sweet basil [28] under tropical Asian climatic conditions in hydroponics [29,30]. DRF systems can increase the development of so-called “aero roots” or “hair roots”, which develop at the root base a few centimeters above the water level and maintain permanent contact with atmospheric oxygen. This is primarily intended to improve the plant’s oxygen supply, e.g., for nitrification to improve plant growth [31]. Nevertheless, the basal roots are in constant contact with the nutrient water [30]. Another advantage of air roots formed by DRF is the saving of electrical energy, which was described in raft aquaponics systems with an active aeration of plants [32]. A study demonstrated that the DRF technique could save up to 11.4% in electricity costs [33]. This exemplifies that DRF offers many advantages in terms of plant growth and energy costs and should be further investigated under aquaponics conditions.

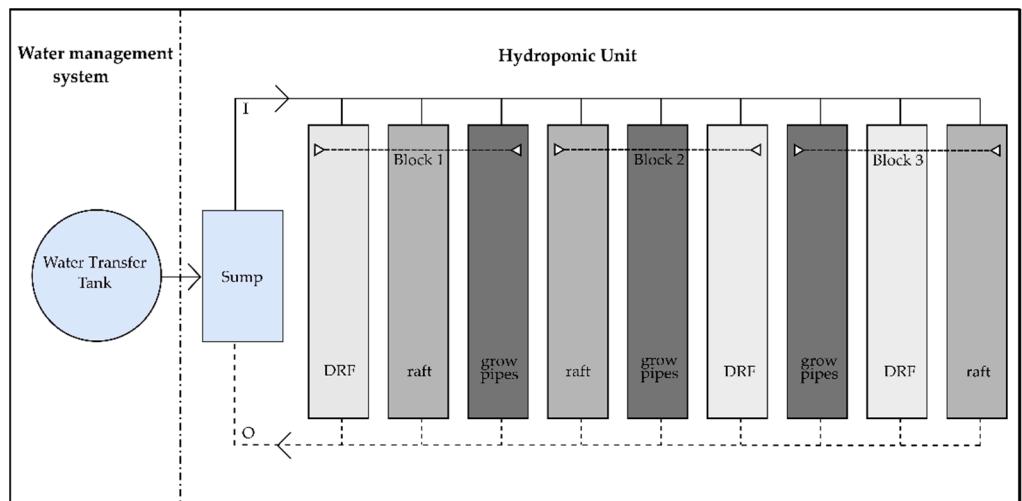
The present study was conducted in the FishGlassHouse of the University of Rostock in Northern Germany under decoupled aquaponics conditions without the use of additional fertilizer at the grow-out stage. The growth performance of basil (*Ocimum basilicum*) was compared by cultivation in three different hydroponic subsystems: dynamic root floating technique (DRF), “floating raft technique (raft), and grow pipes. For plant growth, aquaculture effluents were used from intensive *C. gariepinus* production. Fish performance and sixteen different growth parameters of basil were observed and effects of the different hydroponic subsystems on plant growth are discussed.

## 2. Materials and Methods

The experiment was conducted in summer 2019, from 18 June to 23 July 2019 (36 days) in the FishGlassHouse (FGH) of the University Rostock (latitude: 54.075714, longitude: 12.096591). The 100 m<sup>2</sup> greenhouse cabin (1\_05) and the 100 m<sup>2</sup> intensive aquaculture unit (IAU) were used. The IAU (PAL Anlagenbau GmbH, Germany) consists of nine fish tanks (1 m<sup>3</sup>), a sedimentation tank (1.7 m<sup>2</sup>), a pump sump (6 m<sup>3</sup>), and a trickling filter (17 m<sup>3</sup>), and had a stocking density of max 200 kg/m<sup>3</sup>, 117–130 fish/m<sup>3</sup>. The aquaponic principle was decoupled and used effluents from *C. gariepinus* production without additional fertilizer. The wastewater was pumped at regular intervals biweekly through transfer tanks to the greenhouse's hydroponic cabin.

### 2.1. Hydroponics Unit

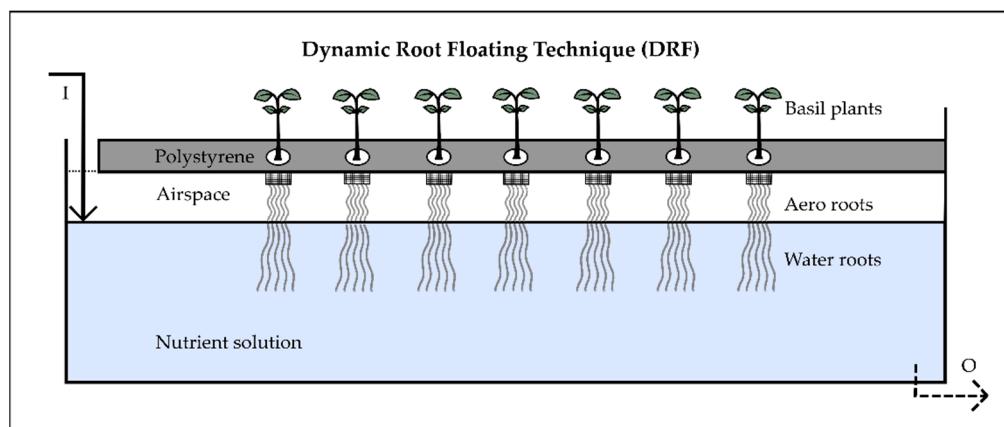
The hydroponics cabin contained a pump sump and nine individual hydroponic components with seven basil plants each. Within one system, the plants were spaced 30 cm apart [34,35]. The whole system contained 2450 L of process water. Every Tuesday and Thursday, the water of the pump sump was drained and refilled with 540 L process water from the IAU. A 780 W pump transported the water from the pump sump into the nine experimental channels. The inflows of all hydroponic subsystems were set to 4 L/min. The three techniques—DRF, raft, and grow pipes—were tested in triplicates and a completely randomized block design (CRD) (Figure 1).



**Figure 1.** Schematic illustration of the decoupled experimental hydroponics cycle with dynamic root floating (DRF), raft, and grow pipes hydroponic components in cabin 1\_05 of the FishGlassHouse. The nutrient-enriched water from the aquaculture was pumped via a transfer tank into the decoupled hydroponics cabin.

#### 2.1.1. Dynamic Root Floating Technique (DRF)

For the dynamic root floating technique (DRF), glass fiber channels were used of reinforced plastic with the dimensions of 280 cm × 40 cm × 45 cm. Each channel was filled with 317 L of water, on whose surface 40 mm-thick polystyrene rafts were placed. The rafts had holes for grid pots of 5 cm in diameter, where the seedlings were placed. Over a period of 14 days, a membrane pump (Aqua Medic Mistral 4000, AQUA MEDIC GmbH, Bissendorf, Germany) transported approximately 4000 L/h air into the system water via 4/6 mm air hoses with two air stones per tank. Two weeks after the seedlings were transplanted into the channels, the water level was continuously lowered by 1 cm daily until the total air space of 5 cm was reached via a variable escape pipe (Figure 2). The plants had the same distance from the ground and the same water surface height in all three hydroponic subsystems during the experiment.



**Figure 2.** Schematic illustration of the dynamic root floating system (DRF) with air space of 5 cm. I = Inflow, O = Outflow.

### 2.1.2. Floating Raft Culture (Raft)

For floating raft culture (raft), glass fiber channels of reinforced plastic ( $280\text{ cm} \times 40\text{ cm} \times 45\text{ cm}$ ) were used. Each channel was filled with 317 L of water, on the surface of which 40 mm-thick polystyrene rafts were placed. The rafts had holes for grid pots with a diameter of 5 cm in which the seedlings were placed. A membrane pump (Aqua Medic Mistral 4000, AQUA MEDIC GmbH, Bissendorf, Germany) transported approximately 4000 L/h of air through 4/6 mm air hoses, with two air stones per channel, into the system water over the entire period.

### 2.1.3. Grow Pipes

The grow pipes were built of unplasticized polyvinyl chloride (PVC) sewage drainage pipes [26] with the dimensions of 275 cm in length  $\times$  12 cm in diameter and a slope of 2.12%. Each tube had seven holes for the basil seedlings in the grid pots, which were fixed to the pipe with wires to ensure the same initial plant height as in the other subsystems. The roots were constantly covered by a water film of 4 L/min.

## 2.2. Fish Production and Feeding

African catfish (*C. gariepinus*) were produced in the intensive aquaculture unit (IAU) of the FishGlassHouse and reared in staggered production. The nine fish tanks were divided into three weight-size classes, with each class containing fish of the same size. At the beginning of the experiment, size class one had the largest fish with an average weight of 1310.1 g ( $\pm 29.0$ ) and 117 fish/tank. Size class two had an average weight of 623.7 g ( $\pm 14.9$ ), with 130 fish/tank. Size class three contained the smallest fish with an average weight of 297.1 g ( $\pm 6.5$ ), with 127 fish/tank. Fish were fed with SPECIAL PRO EF 4.5 mm (Alltech Coppens BV, Leende, The Netherlands) with 42% crude protein, 13% crude fat, 1.5% fiber, 7.6% ash, 1.02% phosphorus, 1.9% calcium, and 0.3% sodium. The feeding of the fish followed the protocol of PAL Anlagenbau GmbH (Abtshagen, Germany) at 25% of the recommended feed input, resulting in minimal growth rates and stable water conditions, by automatic feeders. Feeding intervals were from 9:00 pm to 5:00 am every half hour for two seconds.

## 2.3. Plant Cultivation

On 3 June 2019, the watered seeds of *O. basilicum* were sown in seed coats, with a mixed substrate of peat, perlite, and coconut fibers (Eazy Plug) and placed into seedling trays. After four days, the plants germinated and were fertilized until the start of the trial with 1 g/L Universol Orange (Everris International BV, Heerlen, The Netherlands), 6% total nitrogen (N), 5% phosphate ( $P_2O_5$ ), 25% potassium oxide ( $K_2O$ ), and 3.4% magnesium oxide ( $MgO$ ). On 18 June 2019, 63 randomly selected plants with an average height of 4 cm

and 2 leaves were transplanted to the hydroponic systems by using the grid pots. From the beginning of the experiment, the plants received only the nutrients from the process water of the fish cycle. No additional fertilizer was added.

At the end of the experiment, the following plant parameters were examined: total wet weight (g), total height (cm), leaf mass wet weight (g), number of leaves longer than 3 mm (no.), shoot axis wet weight (g), shoot axis height (cm), root wet weight (g), root length (cm), and the leaf weight (g), lengths (cm), and widths (cm) of the third upper shoot node. At the end of the experiment, the total leaf wet and dry mass (g) and the dry mass (g) of leaves, shoots, and roots of all plants were determined by drying the samples for 72 h at 60 °C and afterwards for 2 h at 120 °C in a drying oven (UF750 plus, Memmert GmbH & Co. KG, Schwabach, Germany). During the experiment, shoot height and number of leaves were taken once a week. At the end of the experiment, the chlorophyll content of the leaves of the third shoot node of each plant was examined and categorized according to the SPAD (Soil Plant Analysis Development) index (SPAD-502PLUS, Konica Minolta, Inc., Marunouchi, Japan).

#### 2.4. Physicochemical Parameters

The data of physical water parameters were collected every Monday to Friday at 1:30 pm with a HQ40d multimeter three-fold (Hach Lange GmbH, Düsseldorf, Germany). Oxygen saturation (%), oxygen concentration (mg/L), water temperature (°C), pH value, conductivity (µS/cm), redox potential (mV), and salinity (‰) were measured. Illuminance (lx ( $\times 10$ )) and photosynthetically active radiation (PPFD: photosynthetic photon flux density, µmol/m<sup>2</sup>s) were measured once a week at 1:30 pm at the same position in the center of each subsystem. Every Tuesday and Thursday, water samples were taken from the pump sump and analyzed with the Gallery™ Analyzer (Thermo Fisher Scientific, Waltham, MA USA) to determine the concentrations of the chemical parameters: ammonium (NH<sub>4</sub><sup>+</sup>), nitrite (NO<sub>2</sub><sup>-</sup>), nitrate (NO<sub>3</sub><sup>-</sup>), phosphate (PO<sub>4</sub><sup>3-</sup>), potassium (K<sup>+</sup>), magnesium (Mg<sub>2</sub><sup>+</sup>), calcium (Ca<sub>2</sub><sup>+</sup>), iron (Fe<sub>2</sub><sup>+</sup>), and sulfate (SO<sub>4</sub><sup>3-</sup>). Using the colorimetric hydrazine method (template: D08896\_01©2021 Thermo Fisher Scientific Inc., Waltham, MA USA), TON (total oxidized nitrogen) as N and nitrate (calculation: TON-nitrite) were analyzed. Using hydrazine under alkaline conditions, nitrate was reduced to nitrite. Under acidic conditions, N-1-naphthylethylenediamine dihydrochloride and sulfanilamide were used to convert the total nitrite ions to a pink azo dye. At 540 nm, the absorbance was determined and related to the TON concentration by means of a calibration curve.

#### 2.5. Mathematical and Statistical Analysis

At the beginning of the experiment on 18 June 2019, on 4 July 2019, and at the end of the experiment on 23 July 2019, the total biomass weight and the number of fish per tank, as well as three randomly selected animals per tank, were measured individually. Based on this data, the feed conversion ratio (FCR, Formula (1)), the specific growth rate (SGR, Formula (2)), the biomass increase, the condition factor (C, Formula (3)), and the percentage growth (G, Formula (4)) were calculated. The following formulae were used:

$$FCR = \text{fish feed quantity (kg)} / \text{weight gain (kg)} \quad (1)$$

$$SGR (\%/\text{day}) = (lnW_t - lnW_0) / t \times 100 \quad (2)$$

with:  $W_t$  = final biomass (kg),  $W_0$  = initial biomass (kg), and  $t$  = time in days.

$$C = (W \times 100) / L^3 \quad (3)$$

with:  $W$  = fish weight (g), and  $L$  = fish length (cm).

$$G = \text{Growth fish weight class } x (\%) = (F_x - I_x) \times 100 / I_x \quad (4)$$

with:  $F_x$  = final weight, fish weight class  $x$ , and  $I_x$  = initial weight, fish weight class  $x$ .

The following parameters of fish growth were statistically analyzed in triplicates by comparison of mean values: initial and final fish length (cm), initial and final fish weight (g), initial and final tank mass (kg), growth per tank (%), condition factor, specific growth rate (SGR), and the feed conversion ratio (FCR).

The collected datasets were processed using Microsoft Excel® [36] and statistically analyzed using the SPSS® 23 software package [37]. If the data were normally distributed, a one-way analysis of variance (ANOVA) was used. If variance homogeneity was observed, multiple mean comparisons were performed post-hoc using the Tukey HSD (Honestly Significant Difference) test. The Dunnett T3 test was used for variance-inhomogeneous datasets. If the data were not normally distributed, the nonparametric Kruskal–Wallis test was used. All tests were performed with a significance level of  $p < 0.05$ .

### 3. Results

#### 3.1. Fish Growth

At the beginning of the experiment, the fish weight classes had an initial length of 55.76 cm (class 1, large fish), 43.39 cm (class 2, medium fish), and 35.51 cm (class 3, small fish), and the final lengths were 56.90, 48.31, and 39.92 cm. The final length of fish weight class 1 was significantly different ( $p = 0.001$ ) to the final lengths of weight classes 2 and 3 (Table 1). Regarding the initial weights (1310.09, 623.74, and 297.13 g) and final weights of the fish (1395.30, 702.22, and 377.81 g), all fish showed small growth rates and the weight classes (1, 2, 3) were significantly different.

**Table 1.** Mean ( $\pm$  standard deviation (SD)) of the biological growth parameters of African catfish in different weight classes (class 1 = large fish, class 2 = medium fish, class 3 = small fish) held in the intensive aquaculture unit (IAU) during basil cultivation (36 days) under reduced feeding (25%). Different letters show different groups ( $p < 0.05$ ).

Parameters	Weight Class 1	Weight Class 2	Weight Class 3	P-I <sup>1</sup>	P-II <sup>1</sup>	P-III <sup>1</sup>
Fish initial length (cm)	55.76 $\pm$ 4.90 <sup>a,2</sup>	43.39 $\pm$ 2.99 <sup>b</sup>	35.51 $\pm$ 2.18 <sup>c</sup>	0.001	0.001	0.001
Fish final length (cm)	56.90 $\pm$ 2.54 <sup>a</sup>	48.31 $\pm$ 2.57 <sup>b</sup>	39.92 $\pm$ 2.96 <sup>b</sup>	0.001	0.038	0.078
Fish initial weight (g)	1310.09 $\pm$ 29.00 <sup>a</sup>	623.74 $\pm$ 14.90 <sup>b</sup>	297.13 $\pm$ 6.52 <sup>c</sup>	0.001	0.001	0.001
Fish final weight (g)	1395.30 $\pm$ 15.32 <sup>a</sup>	702.22 $\pm$ 12.54 <sup>b</sup>	377.81 $\pm$ 7.73 <sup>c</sup>	0.001	0.001	0.001
Tank initial mass (kg)	152.83 $\pm$ 2.64 <sup>a</sup>	81.27 $\pm$ 0.37 <sup>b</sup>	37.63 $\pm$ 0.87 <sup>c</sup>	0.001	0.001	0.001
Tank final mass (kg)	161.66 $\pm$ 1.80 <sup>a</sup>	90.45 $\pm$ 2.55 <sup>b</sup>	46.34 $\pm$ 0.44 <sup>c</sup>	0.001	0.001	0.001
Growth per tank (kg)	8.83 $\pm$ 3.48 <sup>a</sup>	9.18 $\pm$ 2.53 <sup>a</sup>	8.71 $\pm$ 0.62 <sup>a</sup>	0.984	0.998	0.973
Growth per tank (%)	5.80 $\pm$ 2.37 <sup>b</sup>	11.29 $\pm$ 3.11 <sup>b</sup>	23.19 $\pm$ 2.10 <sup>a</sup>	0.087	0.003	0.001
Feed conversion ratio (FCR) <sup>3</sup>	2.40 $\pm$ 0.85 <sup>a</sup>	1.43 $\pm$ 0.45 <sup>ab</sup>	0.94 $\pm$ 0.07 <sup>b</sup>	0.161	0.042	0.561
Specific growth rate (%/day) <sup>3</sup>	0.16 $\pm$ 0.06 <sup>b</sup>	0.30 $\pm$ 0.08 <sup>b</sup>	0.58 $\pm$ 0.05 <sup>a</sup>	0.080	0.001	0.004
Condition factor (C)	0.70 $\pm$ 0.09 <sup>a</sup>	0.69 $\pm$ 0.09 <sup>a</sup>	0.67 $\pm$ 0.15 <sup>a</sup>	0.977	0.977	0.977

<sup>1</sup> Significances, with P-I = between fish weight class 1 and 2, P-II = between weight class 1 and 3, P-III = between weight class 2 and 3,

<sup>2</sup> Means in each row followed by the same superscript letters indicate no significant differences among the fish growth parameters. Means with different letters are statistically different, in that the mean with the lower alphabetical order letter (e.g., a > c) has a mean statistically greater than the mean it is compared to,<sup>3</sup> FCR and specific growth rate based on tank biomasses:  $n = 3$ .

With an initial tank mass of 81.27 kg and a final tank mass of 90.45 kg, weight class 2 (medium fish) achieved the highest growth per tank with 9.18 kg. Weight class 1 (large fish) had an increase of 8.83 kg and reached 161.66 kg (initial mass: 152.38 kg, Table 1). Weight class 3 (small fish) had an average increase of 8.71 kg and reached 46.34 kg (initial mass: 37.63 kg). Overall, there were no significant differences between the three weight classes in growth per tank. In terms of percentage growth per tank, weight class 1 (5.80%) and class 2 (11.29%) differed significantly from weight class 3 (23.19%).

The feed conversion ratio achieved the best value for the small fish (0.94), thus differing significantly from large fish (FCR: 2.40, Table 1). The medium fish (FCR: 1.43) showed no statistical difference to the other groups. For the specific growth rate, the small fish again showed the best performance with 0.58%/day and differed significantly from the large (0.16%/day) and medium fish (0.30%/day). The condition factor was not significantly different between the weight classes ( $p = 0.977$ ) (class 1: 0.70, class 2: 0.69, and class 3: 0.67).

### 3.2. Plant Growth

The plants showed a typical exponential growth over the entire experiment. During the experiment, there were no mortality losses among the plants. In the third week, individual plants from the grow pipes and raft systems showed slight deficiency symptoms and lesions or necrosis on the lower leaf pairs. Table 2 shows the growth parameters of the three subsystems.

**Table 2.** *Ocimum basilicum* growth parameters of wet and dry weights (means  $\pm$  SD) and total weight parameters (sum of all individual plant weights) of the three experimental groups (dynamic root floating technique (DRF), floating raft culture (raft), grow pipes) at the end of the experiment (36 days). Different letters show different groups ( $p < 0.05$ ,  $n = 21$ ). Last part of the table shows total and leaf mass of *Ocimum basilicum* (wet and dry) produced by one system over the entire experiment period.

Growth Parameters	DRF	Raft	Grow Pipes	P-I <sup>1</sup>	P-II <sup>1</sup>	P-III <sup>1</sup>
Total wet weight (g)	107.70 $\pm$ 34.03 <sup>a,2</sup>	82.02 $\pm$ 22.74 <sup>b</sup>	77.86 $\pm$ 23.93 <sup>b</sup>	0.006	0.002	0.755
Total height <sup>3</sup> (cm)	108.41 $\pm$ 13.45 <sup>a</sup>	99.66 $\pm$ 10.80 <sup>a</sup>	106.20 $\pm$ 18.94 <sup>a</sup>	0.142	0.879	0.330
Leaf mass wet weight (g)	45.36 $\pm$ 13.53 <sup>a</sup>	34.94 $\pm$ 9.44 <sup>b</sup>	32.74 $\pm$ 9.84 <sup>b</sup>	0.010	0.001	0.796
Leaves (No.)	108.05 $\pm$ 47.43 <sup>a</sup>	83.81 $\pm$ 19.64 <sup>a</sup>	89.90 $\pm$ 26.84 <sup>a</sup>	0.152	0.152	0.152
Shoot axis wet weight (g)	27.33 $\pm$ 10.11 <sup>a</sup>	18.42 $\pm$ 6.73 <sup>b</sup>	20.01 $\pm$ 7.29 <sup>b</sup>	0.002	0.022	0.424
Shoot axis height (cm)	54.09 $\pm$ 8.86 <sup>a</sup>	46.78 $\pm$ 7.22 <sup>b</sup>	55.75 $\pm$ 10.65 <sup>a</sup>	0.010	0.520	0.001
Root wet weight (g)	35.00 $\pm$ 12.03 <sup>a</sup>	28.65 $\pm$ 7.69 <sup>a,b</sup>	25.11 $\pm$ 8.40 <sup>b</sup>	0.178	0.005	0.629
Root length (cm)	54.32 $\pm$ 8.53 <sup>a</sup>	53.60 $\pm$ 10.00 <sup>a</sup>	50.46 $\pm$ 11.77 <sup>a</sup>	0.971	0.440	0.581
Leaf wet weight <sup>4</sup> (g)	1.84 $\pm$ 0.49 <sup>a</sup>	1.83 $\pm$ 0.38 <sup>a</sup>	1.53 $\pm$ 0.28 <sup>b</sup>	0.995	0.039	0.049
Leaf length <sup>4</sup> (cm)	14.29 $\pm$ 1.62 <sup>a</sup>	13.12 $\pm$ 1.72 <sup>b</sup>	12.77 $\pm$ 1.25 <sup>b</sup>	0.043	0.006	0.744
Leaf width <sup>4</sup> (cm)	9.18 $\pm$ 1.33 <sup>a</sup>	8.50 $\pm$ 1.08 <sup>ab</sup>	8.31 $\pm$ 1.06 <sup>b</sup>	0.147	0.049	0.869
Leaf SPAD-Value <sup>3</sup>	29.76 $\pm$ 2.61 <sup>a</sup>	29.09 $\pm$ 2.67 <sup>a</sup>	28.63 $\pm$ 2.23 <sup>a</sup>	0.659	0.316	0.826
Dry Weight Parameters	DRF	Raft	Grow Pipes	P-I <sup>1</sup>	P-II <sup>1</sup>	P-III <sup>1</sup>
Total dry weight (g)	10.38 $\pm$ 3.44 <sup>a</sup>	8.07 $\pm$ 1.92 <sup>b</sup>	8.21 $\pm$ 2.35 <sup>a,b</sup>	0.034	0.064	0.996
Leaf dry weight (g)	4.96 $\pm$ 1.57 <sup>a</sup>	3.74 $\pm$ 1.04 <sup>b</sup>	3.75 $\pm$ 1.22 <sup>b</sup>	0.009	0.009	0.999
Shoot axis dry weight (g)	3.03 $\pm$ 1.33 <sup>a</sup>	1.90 $\pm$ 0.69 <sup>b</sup>	2.04 $\pm$ 0.80 <sup>b</sup>	0.019	0.033	0.833
Root dry weight (g)	2.39 $\pm$ 0.81 <sup>a</sup>	2.44 $\pm$ 0.41 <sup>a</sup>	2.43 $\pm$ 0.44 <sup>a</sup>	0.994	0.997	0.999
Total Weight Parameters <sup>5</sup>	DRF	Raft	Grow Pipes	-	-	-
Total wet weight (g)	2261.68	1722.31	1635.04	-	-	-
Total leaf wet weight (g)	952.66	733.77	687.50	-	-	-
Total dry weight (g)	218.06	169.55	172.36	-	-	-
Total leaf dry weight (g)	104.23	78.45	78.65	-	-	-

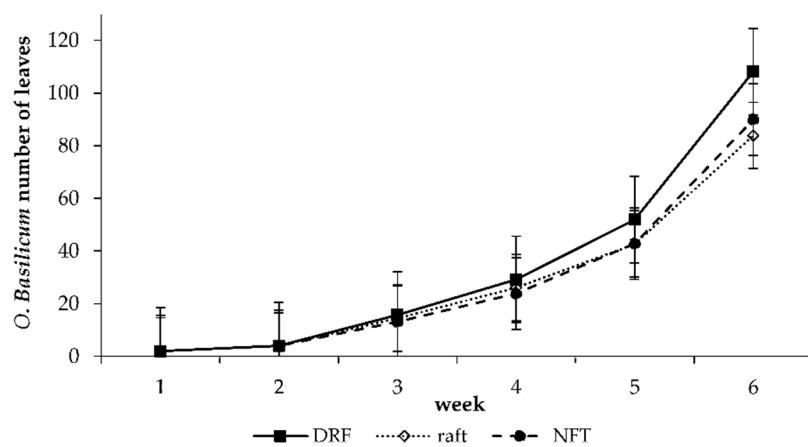
<sup>1</sup> Significances, with P-I = between DRF and raft, P-II = between DRF and grow pipes, P-III = between raft and grow pipes, <sup>2</sup> Means in each row followed by the same superscript letters indicate no significant differences among the plant growth parameters. Means with different letters are statistically different, in that the mean with the lower alphabetical order letter (e.g., a > b) has a mean statistically greater than the mean it is compared to, <sup>3</sup> Total height (cm) = Shoot axis height (cm) + Root length (cm), <sup>4</sup> Measured on the leaf of the third upper shoot node, <sup>5</sup> Total weight parameters calculated as the sum of all individual plants of the respective experimental group.

The basil total wet weight of the DRF with 107.70 g was significantly higher than that of the plants in the other two subsystems ( $p < 0.05$ , Table 2). No statistical differences were found in plants between the raft (82.02 g) and the grow pipes (77.86 g). Total height was not significantly different between plants of the DRF (108.41 cm), grow pipes (106.20 cm), and raft hydroponic subsystems (99.66 cm). Leaf mass wet weight was significantly different between the basil of the DRF with 45.36 g, and the raft (34.94 g) and grow pipes (32.74 g). No significant differences were found in the number of leaves (no.) between the subsystems. The shoot axis wet weight was significantly higher in the DRF system (27.33 g) compared with raft (18.42 g) and grow pipes (20.01 g), which were not statistically different ( $p = 0.424$ ). In the height of the shoot axis, the plants of the raft (46.78 cm) system were significantly shorter than in the DRF (54.09 cm) and grow pipes (55.75 cm). Plants of the DRF developed the highest root wet weight, although only slight rudiments of so-called “hair roots”, and in grow pipes, a slight brown coloring was visible (Figure 3).



**Figure 3.** Examples of basil plants at the end of the experiment from DRF (left), raft (middle), and grow pipes (right).

At 35.00 g, the root wet weight in the DRF was significantly higher than in grow pipes (25.11 g), but without a statistical difference to raft (28.65 g). Although the systems showed significant differences in the root wet weights, there were no differences in root length. The roots of the respective plants in the three hydroponic subsystems measured, on average, 50.46–54.32 cm. The leaf wet weight was similar for DRF (1.84 g) and raft (1.83 g) and each was significantly higher than grow pipes (1.53 g). Significance was also found between the leaf length in DRF (14.29 cm) compared to raft (13.12 cm) and grow pipes (12.77 cm). In leaf width, the DRF and raft systems performed best (9.18 and 8.50 cm), in contrast to the grow pipes (8.32 cm). SPAD values were not significantly different among experimental groups. Figure 4 illustrates the evolution of basil leaf development with, on average, higher leaf number increase in plants in DRF.



**Figure 4.** *Ocimum basilicum* leaf number development per week in hydroponic subsystems DRF, raft, and grow pipes during the experiment over a period of 36 days.

The total dry weight was significantly higher in DRF and grow pipes (10.38 and 8.21 g) compared with that of the raft plants (8.07 g), which was equal to the basil of the grow pipes (Table 2). Leaf dry weight was highest in the DRF system (4.96 g), one third higher (each  $p = 0.009$ ) than in raft (3.74 g) and grow pipes (3.75 g). Shoot axis weight was significantly

heavier in DRF plants (3.03 g) compared with raft (1.90 g) and grow pipes (2.04 g). Root dry weight was not significantly different between the experimental groups.

Total wet weight of basil plants (sum of individual plant weights) was highest in DRF (2261.68 g, Table 2), followed by raft (1722.31 g) and grow pipes (1635.04 g), and total dry weight was greater in DRF (218.06 g), followed by grow pipes (172.36 g) and raft (169.55 g). Total leaf wet weight was highest in plants of the DRF (952.66 g), followed by raft (733.77 g) and grow pipes (687.50 g), and total leaf dry weight was best in DRF (104.23 g), followed by grow pipes (78.65 g) and raft (78.45 g).

### 3.3. Physicochemical Parameters

Photosynthetic photon flux density (PPFD) was highest above the grow pipes (173.10  $\mu\text{m}/\text{m}^2\text{s}$ , Table 3) and significantly different to raft (157.92  $\mu\text{m}/\text{m}^2\text{s}$ ) and DRF (155.83  $\mu\text{m}/\text{m}^2\text{s}$ ). The illuminance showed no statistical differences and varied in the systems from 985.00 to 1024.00 ( $\text{lx } (\times 10)$ ).

**Table 3.** Means ( $\pm \text{SD}$ ) of photosynthetic photon flux density (PPFD), illumination intensity ( $\text{lx}$ ), and physico-chemical water parameters of the three subsystems measured in the sump of the three hydroponic subsystems during basil cultivation (36 days).

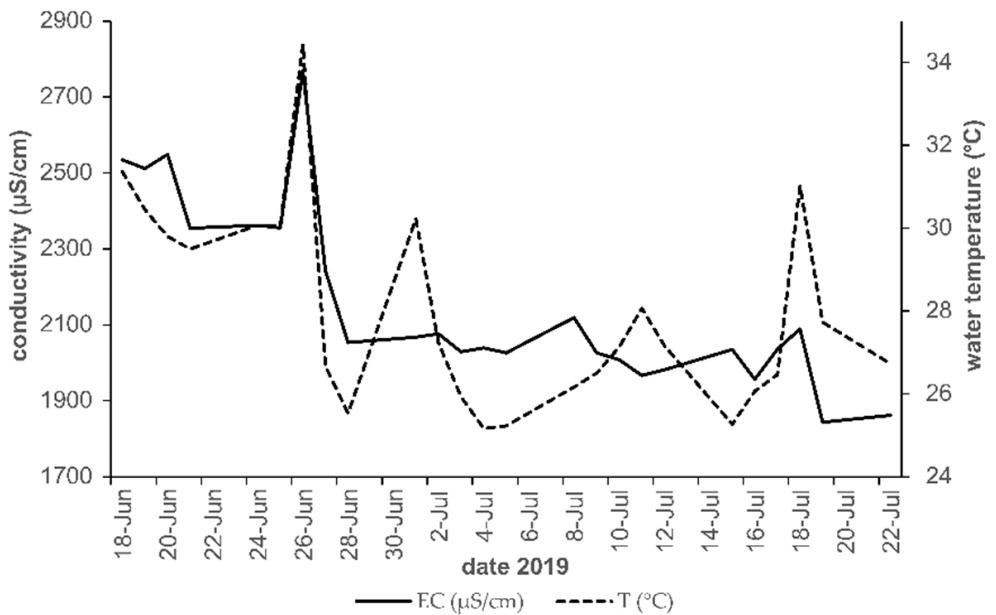
Light Parameters	DRF	Raft	Grow Pipes	P-I <sup>1</sup>	P-II <sup>1</sup>	P-III <sup>1</sup>
PPFD <sup>2</sup> ( $\mu\text{m}/\text{m}^2\text{s}$ )	155.83 $\pm$ 32.29 <sup>b,3</sup>	157.92 $\pm$ 32.14 <sup>b</sup>	173.10 $\pm$ 22.40 <sup>a</sup>	0.404	0.001	0.002
Light ( $\text{lx } (\times 10)$ )	985.00 $\pm$ 116.70 <sup>a</sup>	1013.00 $\pm$ 93.40 <sup>a</sup>	1024.00 $\pm$ 161.30 <sup>a</sup>	0.063	0.063	0.063

<sup>1</sup> Significances, with P-I = between DRF and raft, P-II = between DRF and grow pipes, P-III = between raft and grow pipes, <sup>2</sup> PPFD = photosynthetic photon flux density, <sup>3</sup> Means in each row followed by the same superscript letters indicate no significant differences among the light parameters. Means with different letters are statistically different, in that the mean with the lower alphabetical order letter (e.g., a > b) has a mean statistically greater than the mean it is compared to.

In the sump, the dissolved oxygen averaged  $7.8 \pm 0.4 \text{ mg/L}$  and the oxygen saturation  $100.5\% \pm 1.1\%$ . The averaged pH-value of  $6.5 \pm 0.1$  remained constant during the experimental period. Temperature was relatively high at  $28.0 \pm 2.4^\circ\text{C}$ , and the average conductivity was  $2155.9 \pm 238.5 \mu\text{s/cm}$ , redox potential  $183.3 \pm 20.1 \text{ mV}$ , and salinity  $1.0 \pm 0.1\%$ .

At the beginning of the experiment, the conductivity was above  $2500 \mu\text{s/cm}$ : it increased to over  $2700 \mu\text{s/cm}$  in the second week, and then slowly decreased to  $1862 \mu\text{s/cm}$  (Figure 5). The initial water temperature was  $31.3^\circ\text{C}$  and reached the maximum value of  $34.4^\circ\text{C}$  in the first third of the experiment, and then decreased constantly to about  $26^\circ\text{C}$  until the end of the study, with a mean of  $28 \pm 2.4^\circ\text{C}$  (Figure 5). The room temperature averaged  $23.8^\circ\text{C}$  (min  $18.2^\circ\text{C}$ , max  $40.0^\circ\text{C}$ ), and the average room humidity was 52.8% (min 15.6%, max 79.7%).

The chemical water parameters were measured in the middle of the pump sump from which the process water was transferred into specific hydroponic subsystems to maintain homogeneous nutrient conditions. The mean concentration of nitrate-nitrogen ( $\text{NO}_3^-$ -N) was  $204.47 \pm 47.98 \text{ mg/L}$  and nitrite-nitrogen ( $\text{NO}_2^-$ -N) was  $0.06 \pm 0.08 \text{ mg/L}$ , resulting in a total of  $204.53 \pm 47.97 \text{ mg/L}$  total oxidized nitrogen (TON) in the process water. The ammonium nitrogen ( $\text{NH}_4^+$ -N) had an average concentration of  $0.19 \pm 0.12 \text{ mg/L}$ , resulting in an average concentration of  $204.72 \pm 48.02 \text{ mg/L}$  of total dissolved nitrogen (TDN). The remaining average concentrations were as follows: orthophosphate ( $\text{PO}_4^{3-}$ -P)  $4.71 \pm 2.88 \text{ mg/L}$ , potassium ( $\text{K}^+$ )  $14.67 \pm 3.20 \text{ mg/L}$ , magnesium ( $\text{Mg}^{2+}$ )  $24.93 \pm 3.79 \text{ mg/L}$ , calcium ( $\text{Ca}^{2+}$ )  $291.69 \pm 56.66 \text{ mg/L}$ , iron ( $\text{Fe}^{2+}$ )  $0.02 \pm 0.01 \text{ mg/L}$ , and sulphate ( $\text{SO}_4^{2-}$ )  $42.60 \pm 7.13 \text{ mg/L}$ .



**Figure 5.** Electrical conductivity ( $\mu\text{S}/\text{cm}$ ) and water temperature ( $^{\circ}\text{C}$ ) over the experimental period.

#### 4. Discussion

##### 4.1. Fish Growth

The growth performance of *C. gariepinus* was satisfactory over the entire experimental period, and the FCR values of 0.94, 1.43, and 2.40 (small, medium, and large fish) were as expected, under consideration of the reduced feeding rate of 25%. Depending on the weight of fish, stocking density, feed quantity, and feed composition, FCR values of 0.61–2.69 were recorded in previous studies, with younger fish regularly performing better [38–40]. A similar study achieved FCR values of 0.97, 1.23, and 2.69, where also 25% of the recommended amount of a commercial feed was fed, and thus a large part of the feed energy was used for basal metabolism and not for growth [40]. High feed conversion ratios of the African catfish, such as FCR 0.74, 0.84, and 0.91 [14], and 0.72, 0.87, and 0.97 [41], have been reached at 80% of the maximum recommended feed amount. However, the 25% feeding was sufficient in this experiment to produce stable water conditions for the aquaponics plant production and an EC (Electric Conductivity) value of over 2000  $\mu\text{S}/\text{cm}$ . Feed restriction resulted in a deterioration in FCR, particularly in large fish, since larger catfish require much more energy for their basal metabolism, in relative terms, than small fish [16].

The same explanation can be used for the specific growth rate. At 0.58%, 0.30%, and 0.16%/day (small, medium, and large fish), the results showed the expected values based on the limited feeding rate. At 80% feeding, SGR values of 3.23%, 1.50%, and 0.90%/day can be expected [14]. The small- and medium-sized fish had, on average, five times and the large fish three times the daily growth rate, with 80% and 25% feeding, respectively. An SGR of 1.80%/day was recorded over a total production period of 204 days under intensive production conditions [38]. If an aquaponic farm aims to succeed economically mainly through plant production, it is reasonable, as can be seen in the present experiment, to reduce the feed input to 25% of the recommended feed rate and still provide the fish with sufficient feed to produce adequate EC values for the plants. However, if the aquaponics is also designed to operate profitably in its aquaculture section, it is still advised not to use too low feeding rates or stocking densities that prohibit adequate fish growth.

#### 4.2. Physio-Chemical Parameters

The physical and chemical water parameters were sufficient for adequate growth of *O. basilicum* at recommended levels of pH of 5.5–6.5 [26]. The mean photosynthetic photon flux density (PPFD) of  $162.3 \pm 9.4 \text{ } \mu\text{mol/m}^2\text{s}$  was suboptimal and 67.5% lower than the recommended  $500 \text{ } \mu\text{mol/m}^2\text{s}$  [42] for highest edible biomass production of sweet basil. The highest radiation measured was above the grow pipe system, with the  $173.2 \text{ } \mu\text{mol/m}^2\text{s}$  obviously influenced by local weather variations of light incidence. However, since the grow pipes had the lowest total fresh mass and no statistical differences were found in the light intensity (lx), the slightly differing light parameters were not the decisive factors for the observed growth differences of the basil plants.

The water temperature of  $28^\circ\text{C}$  was higher than the recommended  $20\text{--}25^\circ\text{C}$  for basil cultivation [12,26,43]. In the first third of the experiment, the temperature increased to the maximum value of  $34.4^\circ\text{C}$ , which is significantly above the recommended maximum of  $30^\circ\text{C}$  [26]. This might have negatively influenced the growth of basil in all three subsystems. However, the “dynamic root floating technique (DRF)” was developed for hydroponic cultivation under tropical conditions with very high temperatures and humidity in Taiwan [30]. At a lower temperature of  $25^\circ\text{C}$ , no significant differences were found in vegetable fresh weight between DRF, Nutrient Film Technique (NFT), and Deep Flow Technique (DFT); however, with an increase in water temperature to almost  $35^\circ\text{C}$ , a significant decrease of root activity in NFT and DFT was observed, in contrast to the relatively higher fresh biomass in the DRF system [30]. In the present study, the significantly better weight of basil in the DRF system might be explained by the high water temperatures during the summer season and the presence of the specific DRF-aero-space. The oxygen concentration of the nutrient solution decreases with increasing water temperatures [44], and the respiration rate of the roots and the uptake of water and mineral nutrients decreases [45], resulting in reduced plant growth. In the nutrient solution, oxygen stress caused by high temperatures can produce a brown discoloration of the roots [30]. The oxygen content in our study was generally high with a saturation level of 100.5% ( $7.8 \text{ mg/L}$ ), with the expectation of uniform plant growth in all subsystems. However, the color of the roots was different with a lighter shade in DRF (Figure 3). In contrast, the coloration inside the grow pipes was brown, and they had a lower wet weight. DRF seemed to promote plant growth through the specific air space, as well as the increase in humidity inside the channel to form aero roots. At the higher temperatures of the present study, the DRF subsystem still provides enough oxygen supply, resulting in improved plant growth.

The mean conductivity level of  $2155.9 \pm 238.5 \text{ } \mu\text{S/cm}$  was much higher than already reported for aquaponic plant production, from 300 to  $600 \text{ } \mu\text{S/cm}$  [46]. Optimum EC levels for basil cultivation in hydroponics under use of mineral fertilizer also differs, ranging from 1000 to  $1600 \text{ } \mu\text{S/cm}$  [47], and 2800 to  $3100 \text{ } \mu\text{S/cm}$  [48]. With the same experimental design and a lower mean EC level ( $1619.4 \pm 205.6 \text{ } \mu\text{S/cm}$ ), basil shoot axis height (plant height above ground after 35 days) was higher and leaf numbers were substantially greater in growth pipes, raft, and gravel substrate ebb-and-flood hydro-components [14]. The lower number of leaves and lower root weights in the present study could be influenced by the type of feed (Coppens Special Pro EF) and specific nutrient/mineral composition, as well as by the decreasing EC value, which in the previous study steadily increased when fed with an alternative feed (Skretting ME-4.5 Meerval 44-14 [14]).

The proportions of nitrogen corresponded to hydroponic nutrient solutions for basil production [11], while phosphate and potassium were also lower in comparison to aquaponic nutrient solutions [49]. Hydroponics nutrient solutions usually contain six essential nutrients, N, P, K, Ca, Mg, and S, which must be available in the correct ion ratios for optimal plant growth [50]. In hydroponic sciences, there are several formulations of nutrient solutions, which range in mg/L: N 170–235, P 30–60, K 150–300, Ca 160–185, Mg 35–50, and S 50–335 [50]. For basil cultivation with soil, a wide range is given for N (104–200 kg/ha), P (12–100 kg/ha), and K (73–120 kg/ha); in some areas in the USA, even an NPK ratio of 1:1:1 is given [51]. Assuming an optimum of  $2800 \text{ } \mu\text{S/cm}$  for hydroponic basil cultivation,

the chemical composition of this nutrient solution should be as follows (rounded): nitrogen 220 mg/L, phosphorus 62 mg/L, potassium 262 mg/L, calcium 192 mg/L, magnesium 73 mg/L, sulfur 106 mg/L, and iron 1.95 mg/L [48]. The average concentrations measured in the present study at a 25% feeding rate were: Total Dissolved Nitrogen (TDN) 204.53 mg/L, phosphorus 4.71 mg/L, potassium 14.67 mg/L, calcium 291.69 mg/L, magnesium 24.93 mg/L, sulfur 14.22 mg/L, and iron 0.02 mg/L. Thus, only nitrogen was close to the optimal range and calcium was approximately 50% higher. The magnesium concentration was about 37%, sulfur about 16%, phosphorus and potassium were less than 8%, and iron was only about 1% of the optimal concentration. Yellow coloring of the leaves (while the leaf-veins remained green), which is typical due to the strong iron deficiency, and even necrosis were observed early in this experiment. The process water produced by the fish production was sufficient for plant growth, but it can be assumed that the overall growth performance of the plants in all three subsystems was negatively affected by nutrient deficiencies [52].

#### 4.3. Plant Growth

During the experimental period from 18 June to 23 July 2019, the plants from three subsystems showed several differences in their growth parameters, implying that growth and development were strongly influenced by the hydroponic components. A total of 16 growth parameters were compared. The DRF subsystem performed best in 14 of them. Eleven of these sixteen parameters differed significantly from raft and/or grow pipes ( $p < 0.05$ ).

##### 4.3.1. Leaf Development

The leaf numbers between 83.81 and 108.05 were not significantly different between the hydroponic subsystems (DRF = raft = grow pipes, Table 2). This is in accordance with a former study of basil cultivation with no significant differences in the number of leaves between grow pipes and raft hydroponics and the production of *C. gariepinus* under decoupled aquaponic conditions [14]. In hydroponics, a seven-week trial produced the most leaves (119.41 leaves/plant), highest leaf fresh weight (64.09 g), and dry weight (6.03 g) at an N:P:K ratio of 10:1:10 mol/m<sup>3</sup>, with an NO<sub>3</sub><sup>-</sup>/NH<sub>4</sub><sup>+</sup> molar ratio of 1:0 [53]. A similar growth performance would have been expected with a two-week longer growth period in this experiment. In another study with different algal extract treatments, the best treatments only produced 91.3 leaves/plant in 12 weeks [54]. These plants, grown in culture substrates, were fertilized with Osmocote Plus (14:13:13 N, P, K +microelements) (2 g/L substrates) and grew at a photosynthetically active radiation of 1000 µmol/m<sup>2</sup>s [54]. In contrast, an aquaponic 42-day experiment produced an average of 508.93 ± 13.27 leaves/plant, which is significantly higher than the results of the earlier studies [14]. A N:P:K ratio of 106.8:9.4:60.6 mg/L, combined with the advantages of the beneficial bacterial communities in aquaponic systems, may have led to this extraordinary growth performance [14,55].

With the same experimental design and the cultivation of spearmint (*Mentha spicata*), the grow pipes and raft showed higher numbers of leaves (grow pipes: 639.7, raft: 532.2) in contrast to the lowest leaf number in the DRF system (482.3) [41]. These contrasting results from the present study might have been influenced by the different cultivation temperatures: the DRF system was originally designed for tropical regions in Asia and higher temperatures, where oxygen saturation and root activity in raft and NFT systems decrease [30]. The water temperature of the experiment with *M. spicata* was 3.3 °C lower (24.7 ± 0.1 °C [41]), and the benefits of oxygen saturation were still present in grow pipes and raft. At temperatures below 28 °C, as seen in the present study, the DRF system does not seem to be advantageous for plant cultivation due to lower leaf numbers in the production of *M. spicata* [41]. In northern regions such as Germany (Mecklenburg-Vorpommern), the DRF should only be used in summer to avoid temperature fluctuations and low humidity in the aerospace of the DRF system. The application of only one cropping cycle for the DRF system, from June to September, is recommended, in contrast to the two

cropping cycles in tropical regions of Asia from April to October and October to March [30]. Under semi-natural cultivation conditions, a summer cropping period seems to be ideal. However, the adaptation of DRF use in tropical greenhouses under aquaponic conditions worldwide is a future challenge.

The DRF system showed a significantly higher leaf wet ( $45.36 \pm 13.53$  g) and dry weight ( $4.96 \pm 1.57$  g) than raft ( $34.94 \pm 9.44$  g;  $3.74 \pm 1.04$  g) and grow pipes ( $32.74 \pm 9.84$  g,  $3.75 \pm 1.22$  g; DRF > raft = grow pipes, Table 2), and the leaf length was highest in DRF ( $14.29 \pm 1.62$  cm; DRF > raft = grow pipes). Leaf width was also highest ( $9.18 \pm 1.33$  cm) and comparable to raft ( $8.50 \pm 1.08$  cm; DRF > grow pipes, Table 2). Under the same environmental conditions, DRF appears economically attractive as it produced about 30% more leaf fresh and dry biomass. Consequently, the dynamic root floating technique (DRF) must not be omitted from aquaponics gardening production methods in northern latitudes [38].

#### 4.3.2. Plant Biomass Development

*O. basilicum* biomass development was significantly higher in DRF in total wet ( $107.70 \pm 34.03$  g) and dry weight ( $10.38 \pm 3.44$  g), as well as in shoot axis wet and dry weight ( $27.33 \pm 10.11$  g,  $3.03 \pm 1.33$  g), compared with raft ( $82.02 \pm 22.74$  g,  $8.07 \pm 1.92$  g,  $18.42 \pm 6.73$  g,  $1.90 \pm 0.69$  g) and grow pipes ( $77.86 \pm 23.93$  g,  $8.21 \pm 2.35$  g,  $20.01 \pm 7.29$  g,  $2.04 \pm 0.80$  g; DRF > raft = grow pipes, Table 2). With  $2261.68$  g total mass and  $952.66$  g leaf mass, DRF performed 30% better than raft and grow pipes. With  $218.06$  g total dry mass, the DRF system produced about a quarter more mass than the other two systems, and with  $104.23$  g dry leaf mass, about a third more (Table 2). Literature on comparative studies with hydroponic subsystems and DRF are scarce. An aquaponic comparison with Nile tilapia and Pak choi (*Brassica rapa chinensis*) in raft and DRF showed no significant differences for plant yield, under a pH of 8.7 (DRF) to 8.8 (raft) and a conductivity ( $\mu\text{S}/\text{cm}$ ) of 1005 and 975, not suitable for Pak choi cultivation [33]. In hydroponics, a better basil growth performance (fresh weight, dry weight, and height) was reported in raft (or DFT) compared with a conventional NFT system with a rectangular profile [43]. In a former experiment under decoupled aquaponics in grow pipes and raft, basil wet ( $382.8$  g,  $360.8$  g) and dry weight ( $36.6$  g,  $35.7$  g) were also not significantly different. However, wet weight values for grow pipes were 4.92-fold higher and raft values 4.40-fold higher than in the present study (dry weights grow pipes: 4.46-fold higher, raft: 4.42-fold higher) [14]. With the use of an alternative fish feed (Skretting ME-4.5 Meerval [14]) and different nutrient ratios, basil developed a higher biomass. This was despite a lower EC value of  $1619.4 \mu\text{S}/\text{cm}$ , twice as much phosphorus, and four times as much potassium inside the process water. This resulted in an N:P:K ratio that was significantly closer to the proposed ratios for hydroponic cultivation [48,50]. A deficiency of essential nutrients may have resulted in deterioration in the development of leaves and biomass [56].

Better biomass development of basil [14] might have been influenced by the method of plant transplantation during the first stages of development. High growth performance of *O. basilicum* was observed after plants were brought into the system three weeks after sowing, with 6–8 leaves and 4 cm shoot axis height ([57], Pribbernow, pers. comm., 2020). Most studies indicate that basil seedlings are transplanted into the experimental systems 2–3 weeks after sowing, or with 1–3 true, fully expanded leaf pairs [12,58,59]. Young basil plants in the present study were planted in hydroponic subsystems with equal 4 cm shoot heights. However, only one pair of true leaves occurred, and thus, a lower leaf mass as the most relevant photosynthetic organ was present. This might have been caused by contamination of the seed material but also by adaptation of light [60] and heat [61]. The further development of the plants was thus inhibited and delayed, which could explain the basil's relatively low biomass and leaf development.

#### 4.3.3. Root Development

The wet weight of the roots was best in DRF (35.00 g) and raft (28.65 g), whereas the wet weight between the roots of the grow pipes (25.11 g) was not significantly different compared with raft (DRF = raft, raft = grow pipes; Table 2). The dry weight of the roots showed no differences between the hydroponic subsystems (DRF = raft = grow pipes) and exhibited comparable root development. In general, the DRF system was developed to stabilize the production of leafy vegetables during the monsoon season, when plant growth in NFT and raft deteriorated, and root activity was significantly reduced by oxygen depletion at higher temperatures [30]. In the DRF system, root activity is maintained at high temperatures by the development of additional hair roots or “aero roots” that occupy the air space above the water [30]. The two root types, aero roots and nutrient roots [30], were beneficial in the DRF system and promoted biomass development compared with plant culture in the raft system and growth pipes. In contrast, mint (*Mentha spicata*) production in decoupled aquaponics at lower temperatures ( $25.64 \pm 1.91^\circ\text{C}$ ) and humidity showed a lignification of aerial roots with a brown coloration [41]. The growth performance of mint was significantly lower in DRF compared with grow pipes, and root dry weights were not significantly different between DRF, raft, and grow pipes [41]. Thus, advantageous DRF hydroponics was seen only at high temperatures above  $30^\circ\text{C}$  and should be used at northern latitudes only during the hot summer season when the oxygen content in the process water of comparable systems, such as raft and grow pipes, becomes suboptimal.

#### 4.3.4. Plant Height Development

Total plant height was comparable between the hydroponic subsystems and not significantly different (DRF = raft = grow pipes; Table 2). However, height of the shoot axis was significantly higher in the plants in both DRF ( $54.09 \pm 8.86\text{ cm}$ ) and grow pipes ( $55.75 \pm 10.65\text{ cm}$ ), followed by raft ( $46.78 \pm 7.22\text{ cm}$ ; DRF = grow pipes > raft). With the same experimental design, basil showed higher shoot axis heights above-ground in grow pipes ( $79.7 \pm 8.1\text{ cm}$ ) and raft ( $84.9 \pm 10.3\text{ cm}$ ) after 35 days [14]. In contrast to our study, the potassium availability was four-fold higher [14], the plants were transplanted into the system one week later with a higher leaf development, and artificial lighting was used during the growth period [14,57]. Compared to conventional basil cultivation, plant height (shoot axis) in the present study was lower, as described with heights ranging between 75 and 95 cm, but at a growing period of 120 days from sowing to transplanting to the fields (30 days) to maturity (85–90 days) [62]. In hydroponics, the shoot axis height was higher by about 74 cm, after 70 days and an EC value of  $640\text{ }\mu\text{S/cm}$  [63]. In contrast, basil plants were only 46.4–49.2 cm tall after 12 weeks when algae extracts were provided as fertilizer [54]. At a comparable growth time of 8 weeks (3 weeks from sowing until transplanting + 5 weeks of growth), plant heights of approximately 45 cm were determined in an aquaponic raft system during an interim evaluation, while basil grown in a hydroponic raft system only reached about 28 cm at this time (calculated from original data of Figure 2) [12]. At high EC values of 5000 and  $10,000\text{ }\mu\text{S/cm}$  and a growth time of 70 days, shoot heights of approximately 62 and 49 cm were measured, also in hydroponics with arbuscular mycorrhizal fungi inoculations [63]. Summarizing the above and under consideration that the plant height during the present study was assessed after a short growth period (15 days sowing to transplanting + 36 days growth), basil growth, especially inside the DRF and grow pipes, performed moderately.

## 5. Conclusions

*O. basilicum* showed adequate growth performance in a decoupled aquaponic system design, by using aquaculture effluents of *C. gariepinus* cultivation under 25% of the recommended feed input. High water temperatures of  $28 \pm 2.4$  °C and nutrient concentrations at a mean conductivity level of  $2155.9 \pm 238.5$  µS/cm were not optimal for basil production, limiting the plant growth. The dynamic root floating technique performed significantly better in 11 (total wet weight, leaf mass wet weight, shoot axis wet weight, shoot axis height, root wet weight, leaf wet weight, leaf length, leaf width, total dry weight, leaf dry weight, and shoot axis dry weight) of 16 *O. basilicum* growth parameters than raft or grow pipes (DRF > raft = grow pipes). Total biomass production was highest in plants cultured in DRF in wet and dry weight (2261.68 g, 218.06 g) compared with raft (1722.31 g, 169.55 g) and grow pipes (1635.04 g, 172.36 g). In comparison to earlier studies, the nutrient concentration ratio in the process water was suboptimal. In particular, the lack of potassium, phosphorus, and iron must have reduced plant growth. For better plant performance under low feed input and high water temperatures, partial fertilization or a feed with a different nutrient composition should be considered. The high water temperatures of up to 34.4 °C resulted in reduced root activity in raft and grow pipes and thus, reduced biomass. Aero roots in the DRF were also poorly developed, but still better than in both other sampled subsystems. Consequently, the DRF can be recommended for summer basil production in northern latitudes under glasshouse conditions when the water temperatures reach above 28 °C.

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