Aquaponics (s.l.) Production of Spearmint (Mentha spicata) with African Catfish (Clarias gariepinus) in Northern Germany

Ulrich Knaus 1,* , Lisa Carolina Wenzel 2, Samuel Appelbaum 3 and Harry Wilhelm Palm 1

1 Department of Aquaculture and Sea-Ranching, Faculty of Agricultural and Environmental Science, University of Rostock, D-18059 Rostock, Germany; harry.palm@uni-rostock.de
2 Fischzucht Abtshagen GmbH & Co. KG, D-18510 Wittenhagen OT Abtshagen, Germany; lisa.wenzel@fischzucht-abtshagen.de
3 French Associates Institute for Agriculture and Biotechnology of Drylands, Jacob Blaustein Institutes for Desert Research, Ben-Gurion University of the Negev, Sede Boqer Campus, Midreshet Ben-Gurion 8499000, Israel; sappi@bgu.ac.il

* Correspondence: ulrich.knaus@uni-rostock.de; Tel.: +49-381-498-3744

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Abstract: Aquaponics production of spearmint (Mentha spicata) was evaluated under commercial grow-out conditions of African catfish (Clarias gariepinus) in Northern Germany (Mecklenburg-Western Pomerania). Fish batch production under different stocking densities in an extensive aquacultural unit (EAU) and an intensive aquacultural unit (IAU) was connected to conventional plant cultivation on ebb-and-flood planting tables and compared to a liquid fertilizer control. The best growth parameters of M. spicata were found under the intensive stocking density of C. gariepinus (IAU), resulting in a plant leaf area of 10.9 ± 2.5 cm², leaf length of 8.6 ± 1.6 cm, and a cut fresh biomass from aboveground of 31.8 ± 13.8 g/plant, compared to the EAU (5.6 ± 2.1 cm²; 5.4 ± 1.4 cm; 17.4 ± 4.7 g/plant) and the control (5.7 ± 2.2 cm²; 5.5 ± 1.4 cm; 11.2 ± 5.3 g/plant). The fresh biomass of the whole plants was not significantly different between the EAU (165.5 ± 71.7 g/plant) and the IAU (190.7 ± 105.6 g/plant), though the latter gained more weight. The initial fish number ratio between the EAU and the IAU of 1/4 increased the M. spicata leaf area by twofold in the IAU. Our results demonstrate that aquaponics (s.l.) production of M. spicata is possible under the direct use of effluent waters from intensive African catfish cultivation without the addition of any liquid fertilizer.

Keywords: aquaponics; Mentha spicata; leaf area; African catfish; FishGlassHouse

1. Introduction

Plant cultivation in aquaponics comprises a wide variety of species, from vegetables and herbs to medicinal and ornamental plants [1]. In recent years, the production of fast-growing culinary herbs has been emphasized, and mint (Mentha spp.) was described as a plant with a high economic potential [2,3]. The economic effectiveness of plant cultivation under coupled aquaponics conditions is still under dispute, and feasibility studies with low nutrient crops, including herbs and medicinal plants, are still needed.

Species of the genus Mentha (Lamiaceae) are, in general, popular due to their high content of essential oils for medical and culinary purposes. Spearmint’s (Mentha spicata) essential oil is rich in carvone (60-70%), monoterpenes, which is responsible for the typical spearmint odor and, to a lesser extent, the fragrance limonene (about 10%) from the same biochemical group [4]. Other ingredients of mint’s essential oils possess interesting characteristics, such as pulegone, with a strong insecticidal
activity, and menthone, with mutagenic and/or genotoxic activity [5]; in general, oils from *M. spicata* are known to be antimicrobial [6].

The essential oils of *Mentha* spp. are used for a wide range of industrial and pharmaceutical products, such as chewing gum, toothpaste, cosmetics, and tea [7]. The proportion of global production of *Mentha* spp. in 2016 was dominated by Morocco (92.7%, 98.45 k ton), followed by Argentina (6.7%), Mexico (0.3%), Bulgaria (0.2%), and Spain (0.3%) [8]. In the United States, the mean value of spearmint (*M. spicata*) oil production was relatively stable at 51,459 k $ (±5372 k $) between 2015 and 2017 [9]. In Europe, the demand for mint as a fresh herb or for use as tea is increasing, especially in the United Kingdom, the Netherlands, Sweden, and Germany [10]. In *M. spicata*, a significant amount of essential oil substances are formed on the leaf surfaces [11]. For this reason, the leaf number and the leaf surface area are the most important factors to evaluate the performance and economic potential of *Mentha* spp. [12]. The combination of *M. spicata* cultivation with a high plant growth performance and the production of *Clarias gariepinus* under aquaponic conditions has great potential for industrial production in the context of the widespread use of *M. spicata* as a culinary and medicinal herb.

Investigations of *Mentha* spp. in aquaponics are limited, though mint has been characterized as a plant with relatively low nutrient requirements and good growth potential [1]. Low-nutrient-level aquaponics systems with extensive fish stocking seemed to be ideal for its cultivation. The yield of peppermint (*Mentha piperita*) was 1.8-fold better when using Nile tilapia (*Oreochromis niloticus*), compared with common carp (*Cyprinus carpio*) under summer–autumn conditions in northern Germany in a low nutrient backyard aquaponics system [13]. The growth parameters for *Mentha piperita* and *M. sativa* were better in hydroponics, but the essential oil content was higher in *Mentha piperita* under aquaponics [14]. Good mint yields, with a 26.7% higher growth rate of field mint (*Mentha arvensis*), were described in combination with *O. niloticus* under aquaponics conditions compared to a system without fish [15]. *Mentha arvensis* was successfully cultivated in a gravel substrate aquaponics [16] with common carp (*Cyprinus carpio*) and a mean plant yield of 1.146 kg at two m$^2$ (three replicates) over an experimental duration of two months, as well as in crushed stone media beds with a mean harvest of 1.076 kg at about 2 m$^2$ surface area with a volume of 1000 L [17]. Excellent growth of *Mentha* species was described in brackish water aquaponics, with only slight chlorosis under freshwater aquaponics in the desert [18]. Herbs can also be used for biological filters (hydroponics subsystem). *Mentha piperita* and *M. spicata* were successfully tested in *O. niloticus* intensive aquaponics, where herbs removed significant concentrations of nitrogen and phosphate [19]. These studies demonstrate that *Mentha* spp. has already been successfully cultivated in smaller scale aquaponics; however, so far, there has been no information in the context of large-scale commercial fish production.

African catfish (*Clarias gariepinus*) is a new species to be produced in aquaponics with a very good growth potential [20–23]. Due to its well-known flesh quality and uncomplicated fish-rearing management requirements, global aquacultural production of *C. gariepinus* increased, from 1992 to 2015, by 243,195 t [24]. In aquaponics, good growth of *C. gariepinus* was described in combination with water spinach (*Ipomoea aquatica*, [25]), basil (*Ocimum basilicum*, [20,26]), lettuce (*Lactuca sativa*), cucumber (*Cucumis sativus*), and tomato (*Solanum lycopersicum*) [20]. However, the growth of basil and parsley (*Petroselinum crispum*) was reduced in combination with *C. gariepinus* compared with Nile tilapia (*O. niloticus*) [22]. Thus, the choice of fish species influences plant growth. The combination of spearmint (*M. spicata*) and African catfish (*C. gariepinus*) seems especially promising under commercial aquaponics conditions.

We compared the growth of *M. spicata* with process waters from extensive and intensive batch cultivation of *C. gariepinus* under semi-coupled aquaponics conditions. The spearmint was cultivated in triplicates on ebb-and-flood tables in standard starter fertilized commercial pots and using nutrient-enriched water with a fertilizer from a gardening company (Grönfingers Rostocks Gartenfachmarkt GmbH, Germany) as a control. The production principle followed aquaponics farming (sensu lato: s.l.) with garden plants [27]. The study was conducted in the “FishGlassHouse,” a modern experimental aquaponics facility in northern Germany (Mecklenburg-Western Pomerania),
and mint was cultivated during a short period of the entire fish production cycle. The main purpose of this study was to demonstrate commercial aquaponics (s.l.) production of *M. spicata* by using standard plant cultivation methods and extensive and intensive process waters from *C. gariepinus* aquaculture without conventional liquid fertilizer. The most relevant water parameters for successful decoupled spearmint aquaponics gardening are discussed.

2. Materials and Methods

2.1. Experimental Facility and System Design

The experiment was carried out in late summer to autumn from 27 August 2015 to 4 November 2015 (70 days) in the FishGlassHouse, Faculty of Agricultural and Environmental Sciences, University of Rostock (UoR, Mecklenburg-Western Pomerania, Germany). The experiment was integrated into the commercial batch production of *C. gariepinus* with a mean grow-out phase of 156.3 days (total 257 days between stocking the first batch and harvesting the final batch).

The FishGlassHouse has a total production area of 1000 m² [28]. The aquaculture unit, with a total area of 300 m², consists of three separate recirculating aquaculture systems (RAS, each 100 m²) with different stocking densities (extensive, semi-intensive, and intensive) of African catfish (*C. gariepinus*), constructed in the same manner as commercial production systems in Mecklenburg-Western Pomerania, northern Germany (PAL Anlagenbau GmbH, Germany). A water management system (100 m²) enabled the transfer of the aquaponics process water between the fish and plant units. The hydroponics unit (600-m² total production area), a VENLO greenhouse (GTW Gewächshaustechnik Werder GmbH, Germany), was equipped with automatic climate control (Hempel & Rülcker, Gesellschaft für elektronische Klimaregelsysteme GmbH, Dresden, Germany). This production system is classified as aquaponics of “intermediate/large-scale commercial for business and industry” [27].

The aquaculture effluents from the extensive (EAU) and intensive (IAU) aquaculture units (Figure 1) were connected to the 100 m² hydroponics system for cultivation of spearmint (*M. spicata*). The two aquaponics test groups were established as garden plants in peat pots with a 50% reduced amount of conventional dried fertilizer on ebb-and-flood tables (n = 9) in triplicates [27] and compared with a liquid fertilizer control group. The fish process water was semi-continuously pumped via the water management system into temporary water storage tanks (EAU: WT–E–1; IAU: WT–I–1) and subsequently into the hydroponics cabin with corresponding aquaculture effluent water storage tanks without the addition of fertilizer (EAU: AET–E; IAU: AET–I). The hydroponics control group was autonomous (NT–Control) and filled repeatedly with a mineral fertilizer solution. Each water storage tank (AET–E; AET–I; NT–Control) was connected to one hydroponics water recirculating system that pumped aquaculture effluents and nutrient-enriched water (NT-Control) to the plant cultivation tables with the mint pots and back into the tanks (Fackler Gewächshaustechnik, Munningen-Laub, Germany).

2.2. Fish Production and Feeding

The schematic view of the FishGlassHouse operating extensive (EAU, total volume 13.9 m³) and intensive (IAU, total volume 16.9 m³) aquaculture units are given in Figure 1. Both units consisted of nine fish tanks of 1.26 m³ (F 1–9, volume 1 m³), one solids separation unit (EAU: Se–E with 1.1 × 1.2 × 0.9 m and 1.2 m³; IAU: Se–I with 1.5 × 1.3 × 0.9 m and 1.7 m³) with a filter material (FAP 627, tube size 54 mm) and total filter volumes of 0.66 m³ (EAU) and 1.03 m³ (IAU), and a nitrifying trickling filter (EAU: TF–E with 2.9 m³ = 368.55 m²; IAU: TF–I with 11.8 m³ = 1474.20 m²), and corresponding sumps (EAU: S–E with 1.6 m³; IAU: S–I with 4.0 m³). The process water was transferred from the EAU and IAU solids separation units to a hydroponics cabin, purified from coarse particulate substances.
with an initial mean weight of 275 g, and each fish tank was stocked with 35 (EAU) and 140 (IAU) ± feed conversion ratios (PAL Anlagenbau GmbH, Abtshagen, Germany) six times per day per tank of 153.7 ± S Sustainability 0.3% copper sulfate, and 18.9 MJ digestible energy. during the run of the experiment). Fish were fed by automated feeding and protocol based on actual and on 28 September 2015 for fish tanks 1, 4, and 7 (tanks 1, 4, and 7 remained unstocked for 32 days EAU and IAU on 17 July 2015 for fish tanks 3, 6, and 9; on 17 August 2015 for fish tanks 2, 5, and 8; and on 28 September 2015 for fish tanks 1, 4, and 7 (tanks 1, 4, and 7 remained unstocked for 32 days during the run of the experiment). Fish in tanks 3, 6, 8, and 9 were measured on 24 November 2015; in tanks 2, 5, and 8 on 26 January 2016; and in tanks 1, 4, and 7 on 29 March 2016 (Figure 2).

**Figure 1.** Schematic view of the FishGlassHouse operating units. Intensive Aquaculture Unit (IAU) with fish tanks 1–9 (F1–F9), solids separation unit, sedimentor (Se–I), and sump (S–I) with trickling filter (TF–I); Extensive Aquaculture Unit (EAU) with fish tanks 1–9 (F1–F9), solids separation unit, sedimentor (Se–E), and sump (S–E) with trickling filter (TF–E). The aquaculture units were connected to hydroponics via the water management system tanks, with the inflow from the IAU and EAU into the water tanks (WT–I–1/WT–E–1) and the backflow tanks (WT–I–2/WT–E–2). Process water from aquaculture was stored in the aquaculture effluent tanks (AET) of the IAU (AET–I) and EAU (AET–E) and an autonomous fertilizer control tank (NT–Control) and distributed to triplicate groups of planting tables with intensive (T–I–1/3) and extensive (T–E–1/3) fish production water, and the liquid fertilizer control group (T–C–1/3). Continuous lines mark inflows and dotted lines return flows.

The fish (C. gariepinus) were supplied by Fischgut Nord eG (Wittenhagen OT Abtshagen, Germany) with an initial mean weight of 275 g, and each fish tank was stocked with 35 (EAU) and 140 (IAU) fish (total fish growth phase of 257 days, Figure 2). Three tanks were stocked consecutively in the EAU and IAU on 17 July 2015 for fish tanks 3, 6, and 9; on 17 August 2015 for fish tanks 2, 5, and 8; and on 28 September 2015 for fish tanks 1, 4, and 7 (tanks 1, 4, and 7 remained unstocked for 32 days during the run of the experiment). Fish were fed by automated feeding and protocol based on actual C. gariepinus feed conversion ratios (PAL Anlagenbau GmbH, Abtshagen, Germany) six times per day (from 18:00 pm to 06:00 am) with a single feeding amount in EAU per tank of 41.9 ± 15.8 g, and in IAU per tank of 153.7 ± 55.2 g. A high-protein diet ME–4.5 44–14 Meerval (Skretting, France) was used with 44% crude protein, 14% crude lipid, 22.3% NFE, 10.5% ash, 1.2% crude fiber, 1.6% phosphorus, 0.3% copper sulfate, and 18.9 MJ digestible energy.

**Figure 2.** Experimental overview of the fish stocking principle (grey), total time (257 days), and the mint growth phase (green, days 42–111) with fish stocked in tanks 3, 6, and 9 from days 1 to 131, in tanks 2, 5, and 8 from days 32 to 194, and in tanks 1, 4, and 7 from days 74 to 257.
Fish growth parameters were taken at the beginning and the end of the grow-out phase using a scale (Kern SFB 100K10HIP, Kern & Sohn GmbH, Balingen-Frommern, Germany). Fish in tanks 3, 6, and 9 were measured on 24 November 2015; in tanks 2, 5, and 8 on 26 January 2016; and in tanks 1, 4, and 7 on 29 March 2016 (Figure 2).

2.3. Plant Production

A total of 1260 spearmint plants (*M. spicata*) were supplied by the local company Grönfingers GmbH (Germany) in conventional garden pots (white peat 80%: 0–10 mm and clay 20%, pH 5.5–6.5, EE-Typ 0 “Nullerde”, Einheitserdewerk, Werner Tantau GmbH & Co. KG, Uetersen, Germany, with 50% commercial plant starter fertilizer) as seedlings and distributed on nine (3 × 3) hydroponics ebb-and-flood tables (3.05 × 1.01 m/table, Otte Metallbau GmbH & Co. KG, Germany, slope: 1.68 ± 0.89%, n = 3) for the EAU (Table T–E–1/3), the IAU (Table T–I–1/3), and the control (T–C–1/3; Figure 1). First, 140 mint pots were placed at a distance of about 10 cm on each ebb-and-flood table. The tables were arranged from north (T-E-1) to south (T-I-3) inside the greenhouse with windows towards the west (natural light) and were connected to aquaculture effluent tanks (EAU: AET–E; IAU: AET–I) and the fertilizer nutrient tank (control: NT–Control), each approx. 1000 L in volume (Fackler Gewächshaustechnik, Germany). The control nutrient tank (NT–Control) operated independently and was filled with a commercial hydroponics fertilizer solution with a nutrient composition of 1.12 mg/L NH₄⁺–N, 9.61 mg/L NO₃⁻–N, and 5.54 mg/L PO₄³⁻–P originating from a local commercial plant producer (Grönfingers GmbH, Germany). The plant tables were flooded four times a day, controlled by an automatic clock timer in one direction (4 min flooding, 4 min outflow by gravity, 8 min total irrigation time). The process water from the extensive (AET–E) and the intensive (AET–I) aquaculture effluent tanks was refilled three times a week (Monday, Wednesday, Friday) and returned from the tanks to the specific aquaculture units in a semi-coupled aquaponics system design.

Plant biomass and growth parameters were taken at the beginning of the experiment (n = 9), after 42 days (day 1), and at the end of the experiment (day 111, plant growth duration 70 days), randomly with n = 11 plants per table (n = 33 per treatment group) and measured with a hand ruler [29–31]; leaf area (cm²) was analyzed and calculated by picture [32]. The dry mass of the mint plants was determined using a drying oven (Memmert UN750, Memmert GmbH & Co. KG, Schwabach, Germany) after drying for 3 days at 60 °C and 2 h at 100 °C.

2.4. Physical and Chemical Water Parameters

The physical water parameters of temperature (°C), dissolved oxygen (DO, mg/L), oxygen saturation (%), conductivity (EC, µS/cm), pH, and redox potential (mv) were measured daily (except on weekends) in triplicates at approx. 09:00 a.m. inside the aquaculture units and the hydroponics tanks (AET–E, AET–I, NT–Control) with an HQ40D multimeter (Hach Lange GmbH, Düsseldorf, Germany). Daylight was measured automatically by a digital lux-meter probe on the top of the FishGlassHouse.

The chemical water parameters were taken twice a week (Monday and Wednesday) in the process water tanks of the hydroponics cabin (AET–E, AET–I, NT–Control) before and after replacement of the fish effluent waters; means were created and analyzed. Data of NH₄⁺–N (mg/L), NO₂⁻–N (mg/L), and PO₄³⁻–P (mg/L) were analyzed three times a week with a Gallery™ Automated Photometric Analyzer (Thermo Fisher Scientific, Waltham, MA, USA) and standard protocol NH₄⁺: ISO 7150–1 (DIN 38406–5:1983–10), NO₂⁻: ISO 6777:1984 (DIN EN 26777:1993–04), PO₄³⁻: EN ISO 6878–1–1986 (DIN 38405 D11–4). TON (total oxidized nitrogen) as N and nitrate by calculation (TON-nitrate) was analyzed by colorimetric hydrazine method (Template: D08896_01 © 2020 Thermo Fisher Scientific, Waltham, MA, USA). Nitrate was reduced to nitrite by hydrazine under alkaline conditions. The total nitrite ions were reacted with sulphanilamide and N-1-naphthylethenediamine dihydrochloride under acidic conditions to form a pink azo-dye. The absorbance was measured at 540 nm and was
related to the TON concentration by means of a calibration curve. Nitrate (as N) value was obtained by calculating TON (as N) – nitrite (as N).

2.5. Mathematical and Statistical Analysis

Fish growth parameters (specific growth rate, Equation (1); feed conversion ratio, Equation (2)) were calculated from the biomass of the fish production units (tanks 1, 4, 7; tanks 2, 5, 8; tanks 3, 6, 9) in the EAU and IAU for 257 days. The fish biomass per unit \( m_U \) at the beginning of the experiment, before and after stocking (tank 1, 4, 7) on day 74 (all tanks stocked), and at the end of the experiment was calculated according to Equation (3).

\[
\text{SGR} \left( \% \text{ d}^{-1} \right) = \frac{\ln W_t - \ln W_0}{t} \times 100
\]

with \( W_t = \) final biomass, \( W_0 = \) initial biomass, \( t = \) time in days.

\[
\text{FCR} = \frac{\text{fish feed quantity (g)}}{\text{weight gain (g)}}
\]

\[
m_U = (m_{stock\ 3,6,9} + \frac{m_{feed\ 3,6,9}}{FCR}) + (m_{stock\ 2,5,8} + \frac{m_{feed\ 2,5,8}}{FCR}) + (m_{stock\ 1,4,7} + \frac{m_{feed\ 1,4,7}}{FCR})
\]

with \( m_U \): fish biomass per unit at a specific time; \( m_{stock} \): total fish biomass at stocking in tanks 3, 6, 9, tanks 2, 5, 8, and tanks 1, 4, 7; \( m_{feed} \): feed input into the tanks 3, 6, 9, tanks 2, 5, 8, and tanks 1, 4, 7 until a specific time since stocking.

Significant differences \((p < 0.05)\) were calculated from the means of fish and plant growth and water parameters of the hydroponic aquaculture effluent and nutrient tanks. For normally distributed data, a One-Way Analysis of Variance (ANOVA) was used to determine significant differences between the three subgroups (control, EAU, IAU), and a post hoc Tukey-HSD-test was used at variance homogeneity. Otherwise, the Dunnett-T3 test for variance inhomogeneity was used. Non-normalized data were analyzed after Kruskal–Wallis (non-parametric ANOVA) with a Bonferroni adjustment. For two experimental groups, a \( t \)-test and the Mann-Whitney test were used. All data were calculated using Microsoft Excel (2010) and SPSS 25 statistical software package (IBM).

3. Results

3.1. Fish and Plant Production

The duration of grow-out was identical in both aquacultural units (156.3 days, Table 1). The individual initial (275 g) and final fish weight was comparable (EAU: 1526.6 ± 284.0 g; IAU: 1458.8 ± 222.5 g), as were the feed conversion and specific growth rates (EAU: 0.94 ± 0.04, 1.09 ± 0.06% d\(^{-1}\); IAU: 0.96 ± 0.04, 1.07 ± 0.08% d\(^{-1}\)), and the fish reached commercial marketing sizes.

Under extensive fish rearing, survival was higher (96.2 ± 6.4%) than in the intensive production (89.8 ± 5.3%). In accordance with the final stocking density, total weight per tank (at harvest) and feed input were 3.6, 3.5, and 3.7 times higher, respectively, in the IAU (146.8 ± 20.6 kg/m\(^3\), 146.4 ± 25.9 kg, 141.2 ± 27.1 kg) than in the EAU (40.6 ± 6.6 kg/m\(^3\), 41.5 ± 8.3 kg, 38.6 ± 6.9 kg). The calculated fish biomasses at the beginning of the experiment, before and after stocking the tanks 1, 4, and 7 on day 74 and at the end of the experiment are given in Table 2.

In late summer to autumn conditions, the spearmint growth was relatively good (Figure 3). The best results were achieved in the intensive subgroup with the highest total fresh biomass (80.1 kg), plant height (51.0 ± 16.9 cm), shoot number (2.3 ± 1.2), leaf area (10.9 ± 2.5 cm\(^2\)), leaf length (8.6 ± 1.6 cm), fresh biomass (190.7 ± 105.6 g/plant), and cut fresh biomass (31.8 ± 13.8 g/plant; Table 3).
Table 1. *Clarias gariepinus* commercial production tank parameters (in means ± SD) in the FishGlassHouse [21] during the grow-out phase (257 days) in the extensive (EAU) and intensive (IAU) aquacultural units.

| Parameters          | Extensive (EAU) | Intensive (IAU) | p   |
|---------------------|-----------------|-----------------|-----|
| **Initial Parameters** |                 |                 |     |
| Tanks               | 1, 4, 7         | 2, 5, 8         | 3, 6, 9 |
| Date of Stocking    | 28 September    | 17 August       | 17 July |
| Day of Grow Out (d) | 74              | 32              | 1    |
| Individual Weight (g) | 275.0          | 275.0           | 275.0 |
| Fish Number (no)    | 105             | 105             | 105  |
| Biomass Weight (kg) | 28.9            | 28.9            | 28.9 |
| Stocking Density (kg/m³) | 7.6          | 7.6             | 7.6  |
| **Final Parameters** |                 |                 |     |
| Date of Harvest     | 29 March        | 26 January      | 24 November |
| Day of Grow Out (d) | 257             | 194             | 131  |
| Duration Grow Out (d) | 156.3 ± 23.0 a | 156.3 ± 23.0 a  | 1.000 |
| Individual Weight (g) | 1356.8 ± 294.0 a  | 1498.8 ± 222.5 a | 0.436 |
| Mean Fish Number (no) | 33.7 ± 2.2 a   | 127 ± 8.8 a     | 0.001 |
| Survival (%)        | 96.2 ± 6.4 a    | 89.8 ± 5.3 b    | 0.024 |
| Stocking Density (kg/m³) | 40.6 ± 6.6 b  | 146.8 ± 20.6 a | 0.001 |
| Total Weight (kg/tank) | 41.5 ± 8.3 b    | 146.4 ± 25.9 a | 0.001 |
| Feed Input (kg/tank) | 38.6 ± 8.9 b    | 141.2 ± 27.1 a | 0.001 |
| SGR (% d⁻¹)         | 1.09 ± 0.06 a   | 1.07 ± 0.08 a   | 0.545 |

1 Start day of fish grow out between day 1 and 257; 2 End day of fish grow out between day 1 and 257; Different letters(a, b) show statistically significant differences (p < 0.05).

Table 2. Calculated values of the fish biomasses in the different fish tanks of the extensive (EAU) and intensive (IAU) aquaculture units in the FishGlassHouse during the experiment, showing the biomasses at the beginning of the experiment and at day 74 (all tanks stocked) before and after stocking tanks 1, 4, and 7.

| Extensive (EAU) | Intensive (IAU) | p |
|-----------------|-----------------|---|
| Tanks           |                 |   |
| 1, 4, 7         | 2, 5, 8         | 3, 6, 9 |
| Total Fish Biomass (kg) |                 |     |
| Beginning of the Experiment | 0 | 37 | 43 | 0 | 146 | 174 |
| Day 74 before Stocking Tanks 1, 4, 7 | 0 | 68 | 75 | 0 | 242 | 270 |
| Day 74 after Stocking Tanks 1, 4, 7 | 29 | 68 | 75 | 116 | 242 | 270 |

Table 3. *Mentha spicata* growth parameters (mean ± SD, total values) of the control, extensive (EAU), and intensive (IAU) aquaculture units.

| Parameters                  | Fertilizer (Control) | Extensive (EAU) | Intensive (IAU) | p-I ¹ | p-II ¹ | p-III ¹ |
|-----------------------------|----------------------|-----------------|-----------------|-------|-------|--------|
| Initial Parameters          |                      |                 |                 |       |       |        |
| Initial Biomass (g/plant)   | 2.7 ± 1.0 a          | 2.3 ± 0.6 a     | 2.8 ± 0.8 a     | 0.831 | 0.979 | 0.725  |
| Plant Height (cm)           | 8.5 ± 1.7 a          | 9.7 ± 2.0 a     | 11.2 ± 2.4 a    | 0.558 | 0.558 | 0.558  |
| Leaf Length (cm)            | 3.4 ± 0.6 a          | 4.0 ± 0.5 a     | 3.7 ± 1.5 a     | 0.773 | 0.956 | 0.912  |
| Leaf Width (cm)             | 2.2 ± 0.3 a          | 2.3 ± 0.3 a     | 2.4 ± 0.7 a     | 0.961 | 0.812 | 0.933  |
with 50.7 kg total fresh biomass; however, some plant growth parameters were comparable in both
control and EAU in shoot number (control: 1.6 ± 0.7; EAU: 1.6 ± 0.6), leaf area (control: 5.5 ± 2.2 cm²; EAU: 5.6 ± 2.1 cm²), and leaf length (control: 5.5 ± 1.4 cm; EAU: 5.4 ± 1.4 cm); mint dry biomasses were not significantly different between all groups (control: 18.3 ± 7.4 g/plant; EAU: 23.6 ± 12.4 g/plant; IAU: 21.3 ± 14.2 g/plant).

Compared to the EAU subgroup, leaf area in the IAU was 1.9 times higher, leaf length 1.6×, and cut fresh biomass 1.8×. The lowest plant growth parameters were found in the fertilizer control group with 50.7 kg total fresh biomass; however, some plant growth parameters were comparable in both the fertilizer control group and the EAU in shoot number (control: 1.6 ± 0.7; EAU: 1.6 ± 0.6), leaf area (control: 5.7 ± 2.2 cm²; EAU: 5.6 ± 2.1 cm²), and leaf length (control: 5.5 ± 1.4 cm; EAU: 5.4 ± 1.4 cm); mint dry biomasses were not significantly different between all groups (control: 18.3 ± 7.4 g/plant; EAU: 23.6 ± 12.4 g/plant; IAU: 21.3 ± 14.2 g/plant).

**Table 3. Cont.**

| Parameters                   | Fertilizer (Control) | Extensive (EAU) | Intensive (IAU) | p-I ¹ | p-II ¹ | p-III ¹ |
|------------------------------|----------------------|-----------------|-----------------|-------|-------|--------|
| **Final Parameters**         |                      |                 |                 |       |       |        |
| Plant Height (cm)            | 38.4 ± 8.2 b         | 45.2 ± 11.5 a   | 51.0 ± 16.9 a   | 0.009 | 0.001 | 0.109  |
| Shoot Number (no)            | 1.6 ± 0.7 b          | 1.6 ± 0.6 b     | 2.3 ± 1.2 a     | 0.848 | 0.004 | 0.002  |
| Leaf Area (cm²)              | 5.7 ± 2.2 b          | 5.6 ± 2.1 b     | 10.9 ± 2.5 a    | 0.977 | 0.001 | 0.001  |
| Leaf Length (cm)             | 5.5 ± 1.4 b          | 5.4 ± 1.4 b     | 8.6 ± 1.6 a     | 0.997 | 0.001 | 0.001  |
| Fresh Biomass (g/plant)      | 120.6 ± 51.8 b       | 165.5 ± 71.7 a  | 190.7 ± 105.6 a | 0.034 | 0.003 | 0.621  |
| Total Fresh Biomass (kg) *   | 50.7                 | 69.5            | 80.1            | -     | -     | -      |
| Fresh Cut Biomass (g/plant) **| 11.2 ± 5.3 c       | 17.4 ± 4.7 b   | 31.8 ± 13.8 a   | 0.006 | 0.001 | 0.005  |
| Total Fresh Cut Biomass (kg) *| 4.7                | 7.3             | 13.4            | -     | -     | -      |
| Dry Biomass (g/plant)        | 18.3 ± 7.4 a         | 23.6 ± 12.4 a   | 21.3 ± 14.2 a   | 0.375 | 0.375 | 0.375  |

* calculated with total number of cultured plants (420) per experimental group and mean of (g/plant); ** represents the aboveground. biomass section (cut–green–biomass) of the plants; Different letters (a, b, c) show statistically significant differences (p < 0.05); ¹ Significance (p) with: p-I = control/extensive, p-II = control/intensive, p-III = extensive/intensive.

**Figure 3.** Mint plant garden pots of different experimental groups in the hydroponics cabin of the FishGlassHouse.
3.2. Physical and Chemical Water Parameters

The analysis of the physicochemical water parameters in the aquaculture units during mint cultivation (70 days) showed differences between the EAU and IAU (Table 4). Extensive African catfish production showed higher levels of dissolved oxygen (7.1 ± 0.6 mg/L), saturation level (88.6 ± 7.9%), and pH (7.2 ± 0.5). With intensive fish production, higher values were found in salinity (0.6 ± 0.1%), conductivity (1247.7 ± 128.9 µS/cm), NH$_4^+$–N (16.69 ± 5.11 mg/L), TON (76.50 ± 12.53 mg/L), NO$_3^−$–N (76.02 ± 12.37 mg/L), TDN (93.19 ± 14.04 mg/L), and PO$_4^{3−}$–P (7.06 ± 1.11 mg/L). No significant differences between the EAU and IAU were found in redox potential (122.6 ± 32.4 mV; 131.0 ± 26.7 mV) and NO$_2^−$–N (0.29 ± 0.17 mg/L; 0.48 ± 0.54 mg/L).

**Table 4.** Physicochemical water parameters of the extensive (EAU) and intensive (IAU) aquaculture units with *Clarias gariepinus* production in means (±SD) during mint cultivation (70 days).

| Parameters          | Extensive (EAU)          | Intensive (IAU)          | p-Value  |
|---------------------|--------------------------|--------------------------|----------|
| O$_2$ (mg/L)        | 7.1 ± 0.6$^a$            | 4.9 ± 1.7$^b$            | 0.001    |
| O$_2$ (%)           | 88.6 ± 7.9$^a$           | 60.1 ± 20.4$^b$          | 0.001    |
| Temperature (°C)    | 26.7 ± 0.2$^a$           | 25.8 ± 0.8$^b$           | 0.001    |
| pH                  | 7.2 ± 0.5$^a$            | 6.6 ± 0.2$^b$            | 0.001    |
| Salinity (%o)       | 0.5 ± 0.1$^b$            | 0.6 ± 0.1$^a$            | 0.001    |
| Conductivity (µS/cm)| 952.3 ± 87.2$^b$         | 1247.7 ± 128.9$^a$       | 0.001    |
| Redox Potential (mV)| 122.6 ± 32.4$^a$         | 131.0 ± 26.7$^a$         | 0.241    |
| NH$_4^+$–N (mg/L)   | 0.38 ± 0.23$^b$          | 16.69 ± 5.11$^a$         | 0.001    |
| NO$_2^-–N$ (mg/L)   | 0.29 ± 0.17$^a$          | 0.48 ± 0.54$^a$          | 0.842    |
| TON (mg/L)          | 44.49 ± 8.73$^b$         | 76.50 ± 12.53$^a$        | 0.001    |
| NO$_3^−$–N (mg/L)   | 44.20 ± 8.69$^b$         | 76.02 ± 12.37$^a$        | 0.001    |
| TDN (mg/L)          | 44.87 ± 8.82$^b$         | 93.19 ± 14.04$^a$        | 0.001    |
| PO$_4^{3−}$–P (mg/L)| 3.06 ± 1.20$^b$          | 7.06 ± 1.11$^a$          | 0.001    |

Different letters ($^a$, $^b$) show statistically significant differences ($p < 0.05$).

Water parameters in the hydroponics aquaculture effluent and nutrient tanks (AET–E, AET–I, NT–Control) showed differences (Table 5). Between all groups, differences in dissolved oxygen concentration (DO) and oxygen saturation were significant, with the lowest values in the intensive group (AET–I) with 2.8 mg/L (±1.7) and 31.2% (±18.6), respectively. The highest DO and saturation levels were found in the fertilizer control group with 8.3 mg/L (±0.8) and 87.4% (±2.1). Temperature was relatively stable between the groups; the extensive and intensive subgroups showed slightly higher values at 20 °C. The process water in the fertilizer group was more alkaline (pH 8.1 ± 0.2) than in the EAU group (pH 7.3 ± 0.3) and the IAU group (pH 7.4 ± 0.3). Salinity was higher in the aquaponics groups and significant (IAU: 0.6 ± 0.1%; EAU: 0.5 ± 0.1%) compared with the control (0.4 ± 0.0%).

Conductivity was highest in the IAU (1095.2 ± 122.4 µS/cm), followed by the EAU (821.0 ± 149.3 µS/cm) and control group (673.7 ± 120.1 µS/cm). In contrast, the redox potential was lowest in the IAU (100.6 ± 46.1 mV), followed by the control (117.1 ± 102.4 mV) and EAU (142.1 ± 136.9 mV). Light intensity was highly variable and dropped from 70,300 lx (day 7) to 10,900 lx (day 70) during the experiment ($y = -274.32x + 45,157$, $R^2 = 0.07$) under late summer to autumn conditions with a mean of 35,418.6 lx and a minimum of 3,200.0 lx (Figure 4), as well as an air temperature (outside) from 30.2 °C (day 5 = maximum) to 5.1 °C (day 70 = minimum) with a mean of 17.0 °C ($y = -0.2039x + 24.202$, $R^2 = 0.51$, Figure 4).
Table 5. Physicochemical nutrient water parameters (mean ± SD), nutrient ratios (N/P; leaf area/N; leaf area/P), and biomass relations (fresh biomass/leaf area) of the experimental aquaculture effluent and nutrient tanks (Fertilizer control: NT-Control; extensive EAU: AET-E; intensive IAU: AET-I) with nutrients for Mentha spicata cultivation in hydroponics (70 days).

| Parameters | Fertilizer (Control) | Extensive (EAU) | Intensive (IAU) | p-I * | p-II * | p-III * |
|------------|----------------------|-----------------|-----------------|-------|--------|--------|
| O2 (mg/L)  | 8.3 ± 0.8 a           | 5.1 ± 1.2 b     | 2.8 ± 1.7 c     | 0.001 | 0.001  | 0.001  |
| O2 (%)     | 87.4 ± 12.1 a         | 56.1 ± 13.0 b   | 31.2 ± 18.6 c   | 0.001 | 0.001  | 0.001  |
| Temperature (°C) | 18.9 ± 2.0 b     | 20.9 ± 2.6 a    | 20.8 ± 2.7 a    | 0.001 | 0.001  | 0.900  |
| pH         | 8.1 ± 0.2 a           | 7.3 ± 0.3 b     | 7.4 ± 0.3 b     | 0.001 | 0.001  | 0.622  |
| Salinity (%) | 0.4 ± 0.0 c          | 0.5 ± 0.1 b     | 0.6 ± 0.1 a     | 0.001 | 0.001  | 0.001  |
| Conductivity (µS/cm) | 673.7 ± 120.1 c     | 821.0 ± 149.3 b | 1095.2 ± 122.4 a | 0.001 | 0.001  | 0.001  |
| Redox Potential (mV) | 117.1 ± 102.4 a,b   | 142.1 ± 136.9 a | 100.6 ± 46.1 b  | 0.130 | 1.000  | 0.042  |
| NH4+−N (mg/L) | 0.24 ± 0.31 c        | 2.11 ± 3.44 b   | 20.46 ± 6.53 a  | 0.001 | 0.001  | 0.001  |
| NO2−−N (mg/L) | 0.52 ± 1.11 b        | 0.55 ± 0.30 a   | 0.60 ± 0.49 a   | 0.001 | 0.001  | 0.843  |
| TON (mg/L)  | 7.55 ± 2.12 b        | 40.59 ± 12.40 a | 43.99 ± 17.94 a | 0.001 | 0.001  | 0.469  |
| NO3−−N (mg/L) | 7.03 ± 1.95 b        | 40.04 ± 12.38 a | 43.38 ± 17.85 a | 0.001 | 0.001  | 0.444  |
| TDN (mg/L)  | 7.79 ± 2.14 c        | 42.70 ± 13.92 b | 64.45 ± 20.55 a | 0.001 | 0.001  | 0.001  |
| PO43−−P (mg/L) | 3.44 ± 1.05 b       | 3.30 ± 1.16 b   | 7.98 ± 1.69 a   | 0.392 | 0.001  | 0.001  |
| N1/P2  | 2.4 ± 0.7 c          | 13.4 ± 3.1 a    | 8.2 ± 2.3 b     | 0.001 | 0.001  | 0.001  |
| Leaf Area/N | 0.7 ± 0.3 a          | 0.2 ± 0.1 b     | 0.2 ± 0.1 b     | 0.001 | 0.001  | 0.356  |
| Leaf Area/P | 1.6 ± 0.8 a          | 2.2 ± 1.5 a     | 1.6 ± 0.7 a     | 0.148 | 0.148  | 0.148  |
| Fresh Biomass/Leaf Area | 23.0 ± 10.5 ab    | 29.2 ± 19.8 a   | 16.9 ± 11.6 b   | 0.313 | 0.069  | 0.009  |

1 N = TDN (mg/L), 2 P = PO43−−P (mg/L); Different letters (a, b, c) show statistically significant differences (p < 0.05).
* Significance (p) with: p-I = control/extensive, p-II = control/intensive, p-III = extensive/intensive.

Figure 4. Light intensity (lx) and air temperature (°C) during the experiment outside the FishGlassHouse at 12:06 for 70 consecutive days.

Chemical water parameters of the aquaculture effluent and nutrient tanks (Table 5) were highest in the IAU for NH4+−N (20.46 ± 6.53 mg/L) by 85-fold compared to the control group and 9.7-fold compared to the EAU. Levels of TON were approx. 5–6 times greater in the EAU (40.59 ± 12.40 mg/L) and also in the IAU (43.99 ± 17.94 mg/L) compared to the control (7.55 ± 2.12 mg/L), nearly the same was found for NO3−−N values. The TDN value was highest in the IAU (64.45 ± 20.55 mg/L) by 1.5-fold compared to the EAU (42.70 ± 13.92 mg/L) and 8.3-fold compared to the control (7.79 ± 2.14 mg/L). Phosphorus (PO43−−P) was generally low in all groups and not significantly different between the control (3.44 ± 1.05 mg/L) and the EAU (3.30 ± 1.16 mg/L), with the highest level in the IAU (7.98 ± 1.69 mg/L).
The levels of NO$_3^-$–N were variable with comparable developments in both IAU and EAU aquaponic subgroups (Figure 5), with highest values in the IAU ($y = 0.5163x + 28.191$, $R^2 = 0.29$) followed by the EAU ($y = 0.4829x + 24.158$, $R^2 = 0.60$). In contrast, NO$_3^-$–N levels in the fertilizer group (control) were lower; they never reached the values of the aquaponics systems and decreased over the duration of the experiment ($y = -0.0281x + 7.8937$, $R^2 = 0.08$).

The phosphorus levels showed a strong difference between the IAU ($y = 0.0299x + 7.0957$, $R^2 = 0.11$, Figure 6) and both other groups. P levels in the EAU nearly reached the intensive $p$ values (days 13, 23), but were generally at lower levels ($y = 0.0273x + 2.4013$, $R^2 = 0.21$), nearly parallel to the control. In contrast, the PO$_4^{3-}$–P levels of the fertilizer group (control) were in the range of the EAU and decreased during the experiment ($y = -0.0193x + 4.017$, $R^2 = 0.13$).

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3.3. Nutrient Ratios and Biomass Relations

Between the subgroups, the N/P ratio was highest in the extensive group (EAU: 13.4 ± 3.1, Table 5), followed by the intensive (IAU: 8.2 ± 2.3) and fertilizer group (control: 2.4 ± 0.7). The ratio of leaf area to N was 3.5 times larger in the control than in the other groups. In contrast, differences in the leaf area to P ratio were generally insignificant between all groups. The relation of fresh biomass (uncut) to leaf area was highest and significant between the EAU (29.2 ± 19.8) and IAU (16.9 ± 11.0); however, there were no significant differences from the control group (23.0 ± 10.5, Table 5).

TDN and leaf area values were positively correlated in the experimental groups with the aquaponics process water from C. gariepinus effluents (EAU, IAU; Figure 7). The highest correlation was found in the EAU group, with the highest m value of 0.98 (y = 30.49 + 0.98x, R² = 0.033), followed by the IAU (y = 48.22 + 0.82x, R² = 0.013) and the control group with a very low negative correlation (y = 8.81–0.02x, R² = 0.002). In contrast, PO₄³⁻–P and leaf area values were not correlated in the fertilizer and EAU groups (Figure 8). Only the IAU group showed a slightly positive correlation (y = 6.79 + 0.08x, R² = 0.009).

4. Discussion

4.1. Fish Production

Fish production of C. gariepinus followed the “run–in” and “batch production” phases in the FishGlassHouse [21]. Even though the final stocking density was 3.6 times higher in the intensive aquaculture unit, no differences in final individual weight, feed conversion, or specific growth were observed, and the fish growth was generally good in both aquacultural units. This is not in accordance with [33], who recorded a positive influence of an increasing stocking density for 67–133 fish/m³.

Commercial African catfish indoor production with a slightly higher stocking density of 166 fish/m³ showed a significantly lower feed conversion and final weight (FCR: 1.373 ± 0.01; final weight:
787 ± 6.31 g), starting with juveniles of 12 g and a shorter cultivation period of 154 days (OFF-Farm, Nigeria, [34]). Fish in the present study were much older (275 g initial weight), had a lower stocking density (140 fish/m³), and a longer cultivation period (40% more total time), suggesting highly beneficial cultivation conditions under semi-coupled aquaponics. Feed conversion was more comparable to younger fish (e.g., 190.9 g and 193.0 g), and FCRs were between 0.90 and 0.99 [35]. Moreover, 2.7-times younger fish (growth phase from 102.1 ± 3.49 g to 275.12 g) showed a better FCR of 0.81 with stocking of 133 fish/m³ than older fish [33]. With nearly the same initial fish weight of 254.7 g in a nearly closed RAS, a comparable FCR of 0.97 was reported [36], indicating that our feed conversion and C. gariepinus production was generally similar to earlier experiments under intensive production conditions.

The specific growth of C. gariepinus of 1.07–1.09% d⁻¹ was relatively low due to the higher fish size. Better growth of 1.4% d⁻¹ was reported with slightly younger African catfish of 200 g at slightly higher temperatures from 27–28 °C [37], with 2.05% d⁻¹ from 102.1–275.12 g production [33] and 2.73% d⁻¹ with fish meal protein substitution by winged bean (Psophocarpus tetragonolobus) protein in fish feed [38]. Different specific growth rates have also been reported under aquaponics conditions. With an initial body weight of 480.23 g, a specific growth rate of 0.65% d⁻¹ was reported with the production of lettuce (Lactuca sativa), cucumber (Cucumis sativus), tomatoes (Solanum lycopersicum), and basil (Ocimum basilicum) [20]. In contrast, younger fish (30–40 g) grew better with a specific growth of 1.68–1.83% d⁻¹ in a gravel substrate aquaponics system [25]. The reduced specific growth during the present study might be explained by the restrictive feeding protocol (based on actual FCRs and did not correspond to feeding “to saturation”) that was used to prevent nutrient overload inside the catfish RAS.

The physical and chemical water parameters for C. gariepinus production were mainly close to or in their optimal range. The mean dissolved oxygen concentration under intensive production was above 3 mg/L (and 40%) when young C. gariepinus can change to atmospheric air breathing [39]. The temperatures were below the optimum (~25–26 °C), where the optimal temperature range for C. gariepinus juveniles (1.1 ± 0.4 g) was suggested to be 28–30 °C [39]. C. gariepinus is tolerant to poor water quality [40], though the data are still contradictory. Reports of the high maximum NH₄⁺–N levels of 16.69 mg/L in the present study are scarce, and recommended NH₄–N levels reached only 0.34 mg/L [41]. For juvenile C. gariepinus (5 g), a 96 h LC₅₀ level of 2.3 mg/L NH₃ was found [40]. However, toxic levels for African catfish are much higher under real production conditions, where the systems run at a very low pH, suggesting no negative effects of the observed NH₄⁺–N levels for our aquaponics fish. Nitrite levels were at the maximum in the IAU at 0.48 mg/L, below the toxic level of 0.6 mg/L NO₂⁻ [42], and nitrate was below 140 mg/L without a negative impact on fish growth [43]. Interestingly, the NO₂⁻–N parameters were comparable between the extensive and intensive catfish production, indicating good functionality of the used biofilters, including their dimension and material.

Under intensive production, the maximum stocking level for African catfish was not reached. This species is tolerant to very high stocking densities (180.7 kg per 900 L), particularly with their air-breathing physiology and lethargic behavior, which results in lower maintenance requirements of recirculating systems [44]. The highest density of up to 1067 fish/m³ (growth range 102.1–295.20 g) with good specific growth (2.14% d⁻¹) and feed conversion (0.81) was reported by van de Nieuwegiessen et al. [33]. Under commercial production, a final stocking density of 500 kg/m³ seems to be possible [33], 3.4-fold of the final stocking density in our study.

4.2. Mint Production

The best growth of mint was observed in combination with the effluents of intensive C. gariepinus aquaponics production. Compared with the extensive rearing of African catfish and the fertilizer control group, the use of intensive aquaponics process water resulted in more fresh plant biomasses of 13.21% compared to the EAU and 36.76% in the control, and in higher plant heights of 11.37% (EAU) and 24.7% (control). The leaf area, an important parameter for commercial mint production, was highest under intensive catfish production and nearly twofold better compared with the extensive
C. gariepinus effluents and fertilizer control group. Our results of the leaf area under intensive rearing of African catfish are in agreement with M. spicata cultivation in garden soil (leaf area = 9.6 ± 0.5 cm² [45]), demonstrating that culture conditions inside the FishGlassHouse were adequate and the observed differences in mint growth between the three treatment groups were mainly influenced by the increased nutrient supply from the intensive fish cultivation in the IAU.

The dry biomass of M. spicata showed no differences between the aquaponics experimental groups and the fertilizer control. This demonstrates the generally good adaptation of mint to wet habitats, low nutrient concentrations, and good cultivation conditions in aquaponics. Earlier investigations showed the advantages of aquaponics compared to the use of commercial fertilizers. Plants grown in aquaponics consumed nutrients faster than in hydroponics with a higher accumulation of biomass [46]. Lettuce started flowering one week earlier and cucumber and tomatoes 5–10 days earlier compared to plant cultivation in a hydroponics system. Obviously, there is a yet unknown component in the aquaponics solution that increases plant growth versus the exclusive use of conventional hydroponics fertilizer. It was suggested that certain bacteria can promote plant growth in aquaponics, known as plant-growth-promoting rhizobacteria (PGPR) [46]. A better root fresh weight, leaf area, and leaf color were described in Batavian lettuce (Lactuca sativa var. capitata) and also in iceberg lettuce (Lactuca sativa spp.) with the use of aquaponics process water from C. gariepinus production combined with a fertilizer in contrast to the use of the fertilizer alone and separate aquaponics [47]. In our study, a better growth was observed in the intensive group with a significant 1.4 times higher shoot number, 1.9x leaf area, and 1.6x leaf length.

The growth parameters of M. spicata showed relatively good results under commercial cultivation conditions (height 38.4–51.0 cm). Peppermint production (Mentha piperita) was only slightly better in a coupled gravel backyard aquaponics system in combination with common carp (Cyprinus carpio, 59.2 cm) and Nile tilapia (Oreochromis niloticus, 63.2 cm) under the same late summer to autumn conditions and an experimental time of 70 days [13]. In brackish and freshwater desert aquaponics, a slightly higher plant height was achieved for Mentha sp. (70 cm) combined with the Nile tilapia red strain (Oreochromis niloticus × blue tilapia O. aureus hybrids) [18]. The mint garden pot production in the present study, applying aquaponics gardening [27], generally also corresponded to earlier experiments in hydroponics [48] or performed even better in the EAU and IAU. Consequently, in terms of fresh plant biomasses, plant heights, and leaf area, the commercial production of spearmint (M. spicata) in peat pots with only starter fertilizer by using aquaponics gardening, especially under intensive African catfish stocking, has no disadvantages compared with other production methods.

Physicochemical water parameters had an influence on the Mentha spicata production depending on the fish stocking density. The general environmental parameters (light, temperature) were optimal for the mint growth, as described for peppermint (M. piperita), with sunny, half-shaded, and damp locations and temperatures between 15.5 and 21.1 °C [15,49]. However, the significant and markedly lower pH value in the aquaponics groups might have impacted the nutrient uptake of M. spicata. The pH levels in the present study were higher than reported for Mentha arvensis, with good growth under slightly acidic conditions with a pH of about 6.5 [15]. Good growth of M. spicata was also reported under higher pH levels between 7.9 and 8.0 and plant lengths from 59.2–63.2 cm in coupled backyard aquaponics combined with common carp (C. carpio) and Nile tilapia (O. niloticus) [13]. Thus, the pH was not decisive for the observed variations in M. spicata growth. Conductivity (EC) was highest in the IAU group (1.3 × EAU; 1.6 × fertilizer control group) because the process water from the intensive rearing of C. gariepinus received a significantly higher feed input per day. In conventional hydroponics, the EC level strongly influences plant growth and was reported to be optimal for, e.g., peppermint (Mentha piperita) at 1.4 dS/m [50]; however, conductivity in aquaponics can be lower at levels from 300–600 μS/cm [2]. In the high-conductivity process water of coupled aquaponics, suitable growth results of Mentha sp. were reported at levels of up to 4500 μS/cm in brackish water, and, similar to the present study, at 1060 μS/cm in freshwater [18]. The highest EC level was observed with 1095.2 μS/cm in the intensive rearing of C. gariepinus, which also had the best growth results of
M. spicata. This demonstrates the importance of the EC level also under aquaponics for mint growth, and that even a relatively low EC of about 1000 achieves a good growth performance under aquaponics gardening conditions.

4.3. Nutrient Ratios and Biomass Relations

Chemical water parameters were strongly affected by the stocking density. With a fourfold increase in catfish biomass under intensive production, the NH$_4^+$ level increased markedly. The highest concentration of NH$_4^+$-N was found in the intensive aquaculture effluent tank, 9.7-fold higher (2.1 vs. 20.5 mg/L) than in the extensive and 85-fold higher than in the control (0.24 mg/L). The original process water had an NH$_4^+$ ratio of 43.9:1, much higher than earlier observed for extensive and intensive African catfish staggered 1 production and dissolved oxygen below 6 mg/L [21]. Nitrate was comparable between both aquaponics (40.0 vs. 43.4 mg/L) and 5.9-fold higher than in the control. Nitrogen-derived plant nutrients are considered major growth-limiting factors for plants. Consequently, our plants grew best under an intensive stocking density, resulting in a duplication of the IAU plant leaf area (Tables 3 and 5). However, Mentha species can also perform well under low nitrogen concentrations. In M. arvensis, good growth was observed under very low levels of ammonia nitrogen (0.81 mg/L) and nitrate (0.22 mg/L) combined with Cyprinus carpio [16]. Obviously, even under the relatively low levels of nitrate from the aquaculture unit combined with relatively high NH$_4^+$-N in the plant nutrient tanks, the intensive production of C. gariepinus provided adequate nutrients for M. spicata cultivation during the present study.

The phosphorous content was also low in both plant units run with extensive (3.3 mg/L) and intensive (8.0 mg/L) effluent waters of African catfish production. The original process water had a P ratio of 2.3:1 between the intensive (3.1 mg/L) and extensive (7.1 mg/L) production units, corresponding to [21], who also reported a comparable P ratio between extensive (5.7 mg/L) and intensive (13.0 mg/L) African catfish staggered 1 production and dissolved oxygen values below 6 mg/L. Phosphorus levels in aquaponics are generally low at approx. 6.6 mg/L [51], similar to the intensive African catfish production in the present study. In backyard aquaponics production of low-level nutrient plants, e.g., basil (Ocimum basilicum), parsley (Petroselinum crispum), and marjoram (Origanum majorana), P levels reached 11.00 mg/L and 16.86 mg/L with production of African catfish (C. gariepinus) and tilapia (O. niloticus), respectively [22]. Much lower P values between 1.55 mg/L and 1.71 mg/L were reported under cultivation of Nile tilapia (O. niloticus) and common carp (C. carpio) in co-cultivation with cucumber (Cucumis sativus), tomato (Solanum lycopersicum), and lettuce (Lactuca sativa) [52]. Similarly, peppermint (Mentha piperita) combined with Nile tilapia (Oreochromis niloticus) grew best with a low PO$_4^-$-P water content of 1.9 mg/L and weekly supplements of micronutrients and Fe [53]. Consequently, the observed phosphorus concentration during the present study was also adequate for the aquaponics gardening experiments with M. spicata and in accordance with earlier results.

The general growth parameters of M. spicata showed good results especially by using process water from intensive catfish farming with low oxygen (<6 mg/L) conditions. The N and P concentrations, as well as the TDN and P to leaf area correlations, were best in the IAU (Figures 7 and 8), with an N/P ratio of 8.2 (Table 5), mainly caused by the higher proportion of phosphorus to TDN (12.38% P) compared to EAU (7.72% P). In contrast, the nutrient concentrations and composition of the control were suboptimal, resulting in reduced plant growth (height). It must be taken into account that the fertilizer utilized for the control group maintains plant metabolism for local markets rather than promoting flowering or growth. This might explain the lower performance of the control compared with both aquaponics groups. If the phosphorus content reaches at least a minimal 1:8 P/TDN ratio, the successful cultivation of M. spicata in aquaponics under the described conditions is possible.

5. Conclusions

The aquaponics (s.l.) cultivation of spearmint (M. spicata) without the use of additional liquid fertilizer was evaluated inside the “FishGlassHouse”, a semi-coupled commercial aquaponics facility in
Northern Germany. Effluents from the intensive aquaculture production of African catfish (C. gariepinus) achieved the best plant growth parameters in shoot number, leaf area, leaf length, and cut fresh biomass. The 4-fold higher fish biomass under intensive stocking (IAU) resulted in a 1.2-fold higher mint production, suggesting that C. gariepinus effluent waters could be used for aquaponics cultivation of spearmint.

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