Science of the Total Environment 833 (2022) 155245

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Carbon dynamics and energy recovery in a novel near-zero waste aquaponics system with onsite anaerobic treatment

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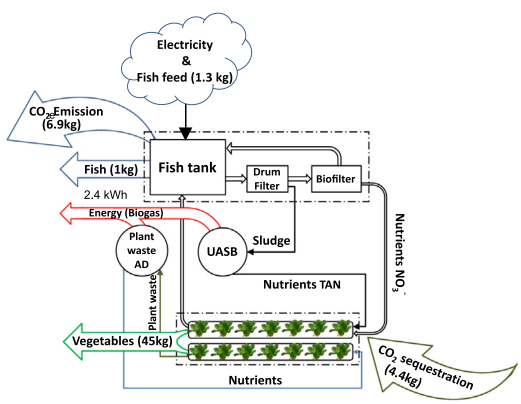
HIGHLIGHTS

- Novel near-zero waste desert aquaponics with C & energy recovery was demonstrated.
- Net CO_2 emission was reduced by 64% via plant carbon fixation.
- Anaerobic digestion was proposed for onsite waste treatment and by-product recovery.
- High-efficiency energy recovery of 0.3 m^3 biogas/kg fish feed was demonstrated.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 7 February 2022
Received in revised form 1 April 2022
Accepted 8 April 2022
Available online 13 April 2022

Editor: Huu Hao Ngo

Keywords:
Aquaponics
Carbon footprint
Anaerobic digestion
Zero-waste

ABSTRACT

Aquaponics is gaining renewed interest to enhance food security. This study aimed to investigate the performance of a novel off-grid aquaponics system with near-zero water and waste discharge, focusing on the carbon cycle and energy recovery that was achieved by the addition of onsite anaerobic treatment of the solid waste streams. Following a stabilization stage, the system was closely monitored for four months. Fish tank water was recirculated via solid and nitrification reactors, from which 66% was recycled to the fish tank directly and 34% indirectly through the hydroponically grown plants. Fish solid waste was anaerobically treated, energy was recovered, and the nutrient-rich supernatant was recycled to the plants to enhance production. Plant waste was also digested anaerobically for further recovery of energy and nutrients. Fish stocking density was 15.3 and over time reached approximately 40 kg/m^3 where it was maintained. Feed (45% protein content) was applied daily at 2% of body weight. Typical fish performance was observed with a survival rate >97% and feed conversion ratio of 1.33. Lettuce production was up to 5.65 kg/m^2, significantly higher than previous reports, largely because of high nutrients reuse efficiency from the anaerobic supernatant that contained 130 and 34 mg/L N and P, respectively. Of the feed carbon, 24.5% was taken up by fish biomass.

Abbreviations: AD, anaerobic digestion; CHP, combined heat and power; DO, dissolved oxygen; DOC, dissolved organic carbon; OC, organic carbon; EC, electrical conductivity; FCR, feed conversion ratio; ORP, oxidation-reduction potential; PWAD, plant waste anaerobic digester; RAS, recirculating aquaculture system; SD, standard deviation; SRP, soluble reactive phosphate; TAN, total ammonia nitrogen; TN, total nitrogen; TOC, total organic carbon; TP, total phosphorus; TS, total solids; TSS, total suspended solids; UASB, upflow anaerobic sludge blanket; VS, volatile solids.

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http://dx.doi.org/10.1016/j.scitotenv.2022.155245

Bioresource recovery
Sustainability

Fish solid wastes contained 38.2% carbon, of which 91.9% was recovered as biogas (74.5% CH_4). Biogas production was 0.84 m^3/kg for fish sludge and 0.67 m^3/kg for dry plant material. CO_2 sequestration was 1.4 higher than the feed carbon, which reduced the system's carbon footprint by 64%. This study is the first to demonstrate highly efficient fish and plant production with near-zero water and waste discharge and with energy recovery that can potentially supply the system's energy demand.

1. Introduction

The contemporary global food system faces the great challenge of increasing food supplies for growing populations while simultaneously minimizing the use of scarce resources (FAO, 2020; Naylor et al., 2021). The challenges associated with conventional food production on soil have been exacerbated by climate change, fluctuating energy and fuel costs, decline in soil productivity, pollution, arable land shrinkage, and urbanization (Goddek et al., 2019). Meeting these challenges will be accomplished through diverse and multifaceted solutions, in which aquacultural and hydroponics food production systems already play a key role in providing people with a consistent, healthy food source (FAO, 2020; Stentiford et al., 2020).

The integration of aquaculture and hydroponics, called aquaponics, is a sustainable food production system in which plants are cultivated in the recirculating water from the fish tanks with the primary goal to reuse the nutrients contained in the uneaten fish feed and fish excretions to grow plants (Graber and Junge, 2009). In addition, aquaponics requires less water than the separate application of aquaculture and hydroponics, as water can be recycled between the plant beds and fish tanks (Somerville et al., 2014).

Aquaponics has been discussed as part of sustainable intensive agriculture, but several limitations, including energy and resource demand, nutrient imbalances, waste management, and different narrow temperature and pH ranges for fish and plants, have limited its widespread application (Goddek et al., 2019; Somerville et al., 2014). Although over 95% of the applied fish feed is ingested, only 20–30% of the nutrients such as C and N is recovered by the fish for growth, the remainder being released into the water by the fish, mainly as ammonia and organic solid waste (Hu et al., 2014; Yogev et al., 2017, 2018). It should be noted that both solids and ammonia are key parameters that should be monitored and removed such that they are maintained at suitably low levels in the fish tanks in order to allow healthy fish growth (Timmons et al., 2018). Typically, suspended solids are removed by a solid filter such as drum filters. In a recirculating aquaculture system (RAS) ammonia is oxidized to significantly less toxic nitrate by bacteria in biofilters such as moving bed bioreactors (Timmons et al., 2018). Both the removed solids and the nitrate have to be further treated to prevent environmental contamination or to provide suitable water quality for the fish.

Efficient onsite treatment of aquaculture waste and its conversion to nutrient and energy sources may be advantageous. Zhu et al. (2021) demonstrated that plant wastes (e.g. roots and inedible parts) from aquaponics could be treated with high efficiency using anaerobic digestion (AD). Similarly is the case with AD of fish sludge from RAS (Quinn et al., 2016; Yogev et al., 2020). More specifically, upflow anaerobic sludge blanket (UASB) reactors that operate with low suspended solids concentrations of less than 3% were demonstrated to perform well for fish sludge treatment (Mirzoyan and Gross, 2013; Yogev et al., 2017). The resulting biogas can be combusted to produce electricity and heat, while the remaining nutrients in the supernatant can be applied, as fertilizer or other products (Yogev et al., 2017). Recently, the potential of integrating onsite waste treatment in aquaponics for near-zero waste discharge with the recovery of nutrients and energy was studied theoretically (Yogev et al., 2016). However, it has not yet been demonstrated in aquaponics, and questions remain about aquaponics' environmental and economic sustainability. The carbon cycle and footprint of the aquaponics systems, especially the carbon dioxide, which is a significant contributor to global warming, has not yet been considered by other studies.

Based on the theoretical model (Yogev et al., 2016), this study aimed to investigate the off-grid operation potential of a novel aquaponics system and its performance under desert conditions with near-zero water and waste discharge. In particular, we focused on (1) the efficiency of energy recovery potential and nutrient reuse via onsite anaerobic digestion and (2) the carbon cycle and footprint. It was hypothesized that understanding the carbon cycle in the system, with a specific focus on anaerobic treatment, would allow significantly reducing the carbon footprint. The latter will be achieved by enhancement of nutrient availability, thus plant production and CO_2 sequestration, as well as by reducing energy demand by biogas production. This study is the first to demonstrate highly efficient combined fish and plant production with near-zero water and waste discharge and with energy recovery that can potentially supply the system's energy demand. In the current study, the model aquaponics system (Yogev et al., 2016) was physically installed in the Negev Desert, and closely monitored for four months in terms of production (fish and plants), water quality, solid treatment and properties, carbon cycle and energy production.

2. Materials and methods

2.1. Aquaponics system and experimental design

The experiments were carried out in a desert aquaponics facility located in a greenhouse with RAS and an adjacent nethouse containing deep water culture hydroponics beds at Sede Boqer Campus of Ben-Gurion University of Negev (BGU), Israel (30° 51′ 8.27″ N, 34° 347′ 0.24″ E, altitude 496 m). The design of the near-zero waste aquaponics system was based on four treatment loops (Fig. 1). The first loop was composed of a 1 m^3 conical HDPE fish tank, in which water was continually pumped by a 12 m^3/h centrifugal pump (HF-50B, Pedrollo Ltd., Italy) with a frequency inverter (EDS800, ENC) to a drum filter (ProfiDrum Eco 45/20, Lopik, Holland).

Subsequently, the water flowed with gravity to aerated moving bed nitrification biofilters, which consisted of two 100 L polypropylene cylinders filled with plastic beads (60% media (v/v); Aridal Bioballs, Israel). The beads' porosity was 80%; their surface area was 860 m^2/m^3 (Yogev et al.,

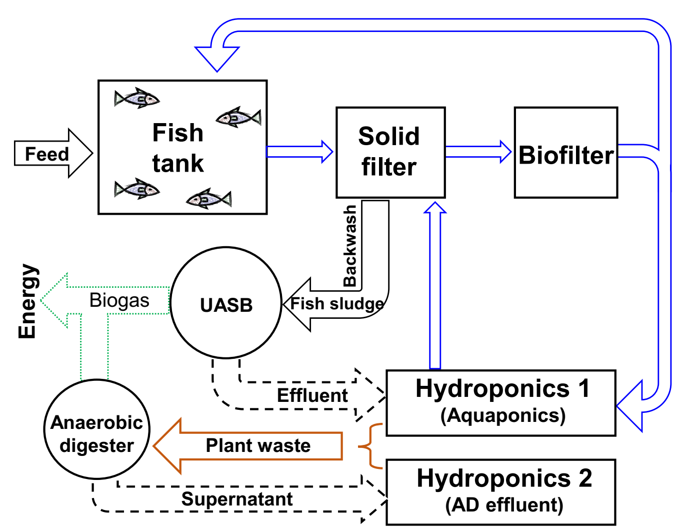

Fig. 1. Schematic representation of the aquaponics research system, its components and treatment loops.

2017). Following this, the water flowed to a 100 L polypropylene splitter tank, splitting the flow back to the fish tank and/or to the hydroponics unit, which is the second treatment loop. From the splitter tank, water was pumped to the hydroponics unit by a centrifugal pump (HF50B, Pedrollo Ltd., Italy) with a frequency inverter (EDS800, ENC) followed by a filter (Arkal 2″ Super Filter, Amiad, Israel) at a rate of about 1 m^3/h.

The hydroponics unit (second treatment loop) was based on deep water culture (DWC) and composed of two plant growth beds (15 m (l) ∗ 0.5 m (w) ∗ 0.3 m (d); total volume: 4.5 m^3). Both streams, the outlets from the hydroponics unit and splitter, flowed with gravity to the lowest point in the system, where the centrifugal pump (mentioned above) pumped the water back to the fish tank at a rate of about 2 m^3/h. In addition, internal water circulation in the plant beds was achieved by a 5 m^3/h aquarium pump (EDEN@PFG, Germany). The latter (as well as the bed aeration) was conducted to maintain uniform water quality in the hydroponic beds.

In the third treatment loop, fish sludge from the drum filter was backwashed to a 130 L sump tank (Plasgad, Israel), from which it was pumped by a 0.06 m^3/h peristaltic pump (Boxer 4500, Uno) into the UASB reactor. The UASB reactor consisted of a 1300 L cylindrical column (height 2.5 m, radius 0.4 m); an inverted funnel at the top of the cylinder allowed for efficient solid-liquid-gas separation and biogas collection (Mirzoyan and Gross, 2013).

The fourth loop was a plant waste anaerobic digester (PWAD) for treating inedible parts (e.g., roots and inedible leaves) of the lettuces produced. The reactor used was a commercial anaerobic system (TG1B0 Biogas System; HomeBiogas, Israel). The digester was composed of a 650 L PVC tank with inlet and outlet pipes that were installed each on one side of the digester. The inlet pipe was used to feed the digester and the effluent overflowed from the outlet pipe and was collected in a sampling tank. The biogas flowed out of the anaerobic digester through an 8 mm gas pipe, passing through a sulfide trap, gas meter (LPG 1500 L/min, Gaoli, China), and moisture trap.

On January 2, 2020, the system was cleaned and catfish (*Clarias gariepinus*; n = 264) fingerlings (average weight 52.25 g) were stocked. The fish were fed 2% of the total stocking biomass daily throughout the trials with a 45% protein, 14% fat commercial catfish feed (Zemach Taarovot, Israel). Water temperature in the fish tank was set to range between 25 and 28 °C and was controlled by three 0.3 kW aquarium heaters (Eheim, Germany).

The fish were weighed before the experiment and every month until harvest. Feed application was adjusted according to actual fish weight. Lettuce seedlings (*Lactuca sativa* cv. *Noga*; Hazera seeds, Israel) from Shorashim nursery (Ein Habsor, Israel) were planted in plastic net cones that were introduced on the floating rafts (50 mm Styrofoam). The plants were grown for 28 days before they were harvested. To maintain relatively uniform plant biomass, seedlings were planted in a staggered manner: every 14 days, half the lettuces were harvested and new seedlings were then added. Overall, at any given time, there were 240 plants. After harvest, six lettuces were randomly selected for sampling. The roots were separated from the shoot and both were weighed (wet weight). Then, they were dried at 65 °C, reweighed, and kept for further analyses. Roots and damaged (inedible) leaves were separated, weighed, and taken as a substrate for the fourth loop anaerobic digester. The feeding rate was recorded and ranged between 4 and 10 kg wet lettuce waste per three days in a batch.

The system was put into operation more than one year before this study, ensuring the aquaponics systems were acclimatized and that bacterial communities in the biofilters were established. An alkalinity buffer in the form of K_2CO_3 or $KHCO_3$ was introduced to the system periodically when its concentration decreased below 50 mg/L as $CaCO_3$.

2.2. Monitoring and analyses

The temperatures in the greenhouse, tanks, hydroponics, and reactors were recorded every 30 min by a data logger thermometer with the precision of 0.1 °C (TM-747D, Thermometer, China). In addition, the total accumulated solar radiant exposure, temperature, wind speed, rainfall, and relative humidity were measured continuously by a local meteorological station with Stevenson shelters (Israel Meteorological Service, 2002, 30.86°N, 34.78°E, elevation 475 m. Sede Boqer, Israel). DO, pH, temperature, EC, and ORP were monitored daily using laboratory meters onsite. In addition, water samples (250 mL each) were collected every 10 days from designated sampling points in the aquaponics system, immediately brought to the laboratory, and analyzed.

Overall, 13 sample collections were performed during the experiment. Water analyses followed well-established or standard protocols (Baird et al., 2017; Harris, 2007; Latimer, 2019). A membrane syringe filter (25 mm, w/0.45 μm) was used to filter the water samples. The filtered samples were analyzed for TAN using the Nessler method, nitrite by the diazo colorimetric method, and nitrate by the second-derivative method. SRP and TP (followed by persulfate digestion) were measured using the vanadomolybdate method. TOC and TN were analyzed using a Multi N/C 2100S analyzer (Analytik Jena, Germany). Alkalinity was analyzed using the Gran plot method to linearize the data points from the titration (Harris, 2007). TSS of the sludge was measured by centrifuging 50 mL samples at 9500 rpm for 40 min, after which the supernatant was removed, then the sludge was dried for 48 h at 65 °C and weighed on an analytical balance. The concentrations (%) of the major elements in the sludge (C, H, O, N, and S) were determined by the elemental analyzer with a FlashEA™ 1112 CHNS Analyzer (FlashSmart, Thermo Fisher Scientific Inc., UK). Macro- and micro-nutrients (N, P, K, S, Ca, Mg, Fe, Mn, Zn, Cu, B, and Mo) in the water were analyzed by inductively coupled plasma spectroscopy (ICP-OES, FHX22, Spectro Arcos, Germany) following a standard protocol (Baird et al., 2017). The same elements were also analyzed in fish, feed, sludge, plants, and plant wastes following a digestion procedure (Baird et al., 2017; Harris, 2007).

Gas production from the UASB and PWAD was measured by gas meters (LPG 1500 L/min, Gaoli, China). To verify the meter readings, the time to fill a 3 L gas-tight sampling bag (SKC, USA) was recorded once a week during the study. Additionally, gas from the bags was directly pumped into a portable gas analyzer (BIOGAS 5000 Biogas Analyzer, England) and analyzed for CH_4 and CO_2. Ammonia and hydrogen sulfide in the gas were measured using the Kitagawa gas detector tube system (Komyo Rikagaku Kogyo, Japan).

2.3. Carbon dynamics and energy recovery potential

An input-output model to support balances concerning the carbon cycle and footprint in the near-zero waste aquaponics was developed. There are two primary input sources of organic carbon (OC) in aquaponics: fish feed and CO_2 fixation by plant photosynthesis. Fig. 2 represents a diagram of carbon transformation and biological processes in an aquaponics system.

In the aquaculture part, the daily feed carbon input was calculated by multiplying the daily amount of feed added into the system by the OC content of the feed (C_F, 46.74%). The mass of overall OC was added through feed during the experimental period (*T* in days). Finally, carbon transformation and balance were calculated based on the actual inputs and measured OC concentrations in the various units of the aquaponics according to the simplified balance equation:

$$\sum_T \Delta TOC_i * V_i = \sum_T M_{feed} C_F - MC_{fish} - CER_{RAS} - Q_{fs} C_{fs} - Q_r \Delta C_{dC} \quad (1)$$

where: ΔTOC_i is the daily change in TOC concentration in unit *i* (g/L/day); V_i is the volume of unit *i* (L); M_{feed} is daily feed mass (g/day); MC_{fish} is the carbon accumulated as fish biomass (g/day); CER_{fish} is the net carbon excretion as CO_2 by biological metabolism in the system (including passive denitrification) (g/day); Q_{fs} is the overall volume of fish sludge from the solid filter (L/day); C_{fs} is the carbon concentration in the sludge that is backwashed from the solid filter (g/L); Q_r is the overall volume of water recirculated through the hydroponics unit (L/day), and ΔC_{dC} is the dissolved TOC difference between outlet and inlet of the stream recirculated through the hydroponics unit (g/L).

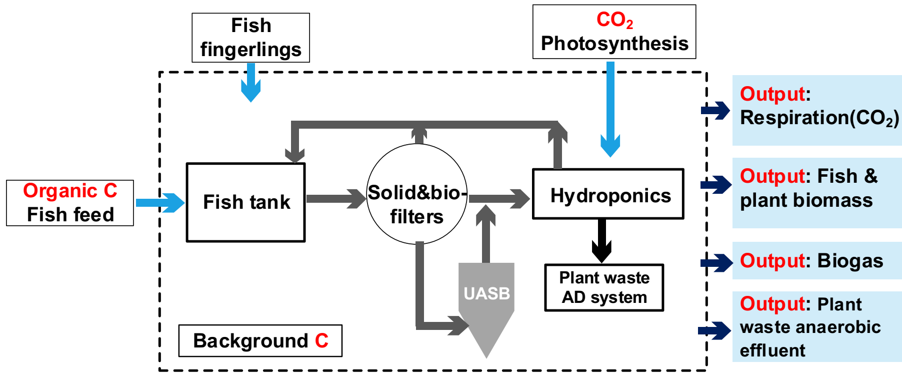

Fig. 2. Schematic diagram of the carbon flow in the aquaponics system. The dashed line shows the system boundary. Blue arrows show inputs, grey arrows show movement within the system boundary, dark blue arrows show exit from the system boundary, and the black arrow shows the plant wastes flow into the AD system.

In the hydroponics part, the total net quantity of carbon (CO_2) fixation C_{plant} through plant photosynthesis was calculated by multiplying the total mass of plant production by its OC content (shoots and roots separately). The carbon in the lettuce can be further divided into carbon in the edible part (M_E) and in the inedible parts (M_W), using experimental plant carbon content (C_E is carbon content of the edible leaf; C_W for the plant waste). The latter is of interest as it can be further utilized in an AD step and thus provide biosources of energy and nutrients.

$$C_{plant} = M_E C_E + M_W C_W \tag{2}$$

The mass of waste OC removed by AD and transferred into bioenergy as biogas in the anaerobic systems (UASB and PWAD) can be described by Eq. (3):

$$\Delta TOC_{reactor} = M_{waste} C_{waste} - V_{biogas} C_{biogas} - Q_{liquid} TOC_{liquid} \tag{3}$$

where: $\Delta TOC_{reactor}$ is the change of TOC content in the anaerobic digester (UASB or PWAD) (g); M_{waste} is the mass of waste (fish sludge or plant waste) inflow to the anaerobic digester (g); C_{waste} represents the carbon content in the waste streams; V_{biogas} is the volume of biogas from anaerobic bioreactors (m^3); C_{biogas} represents the carbon content g/$m^3$of biogas; Q_{liquid} and TOC_{liquid} are the volumes and TOC concentrations respectively of liquid outflux from the anaerobic digester.

The actual amount of biogas available for energy recovery from fish sludge and plant waste in UASB and PWAD, respectively, was measured during the experimental period. Energy production was calculated according to:

$$E_{Prod} = V_{Biogas} E_{Biogas}\, \mu_{CHP\_Eff} \tag{4}$$

where: E_{Prod} is the potential energy produced via biogas from AD, kWh; V_{Biogas} is the biogas volume collected from two anaerobic reactors during the research trial, m^3; E_{Biogas} is energy recovery from biogas, kWh/m^3-biogas; μ_{CHP_Eff} is the energy use efficiency from bioenergy to heating and electricity. Values of 6 and 0.85 are typically reported for E_{Biogas} and $\mu_{CHP\_Efficiency}$, respectively (Evangelisti et al., 2014; Gebauer and Eikebrokk, 2006).

2.4. Data and statistical analysis

The VS removal efficiency in the two AD digesters was calculated according to Eq. (5):

$$VS_{removal} = \sum(VS_{in} - VS_{residue}) / \sum VS_{in} \tag{5}$$

where, VS_{in} is overall input VS of waste (fish sludge or plant waste); $VS_{residue}$ is residue VS in the reactors at the end of the experiments. TOC removal was calculated similarly.

The specific growth rate (SGR, %/day) was calculated according to Eq. (6):

$$SGR = (\ln W_e - \ln W_b)/d \times 100 \tag{6}$$

where, W_e is the average of fish weight at the ending, g; W_s is the average of fish weight at the beginning, g; d is the total rearing day, day.

Means and standard deviations (SD) were calculated based on triplicates of each result. A t-test was applied to determine a significant ($\rho < 0.05$) difference in plant biomass between lettuce grown with supernatant from different systems. The statistical software Origin 9.0 was used to carry out the statistical analyses.

3. Results and discussion

3.1. Aquaponics system performance

As summarized in Appendix A, Table A.1, the environmental conditions were suitable for the growth of lettuce and catfish as demonstrated below and reported by others (Murray et al., 2014; Somerville et al., 2014; Timmons et al., 2018).

3.1.1. Water quality

The water quality of the aquaponics system components was monitored daily during the experiment (Table 1). The pH average was 7.2 ± 0.8 in all units, suitable for fish, plant, and biological reactors. The water temperature was regulated at around 28.1 °C, optimal for fish growth. It should be noted that this temperature might cause stress to many lettuce types (Resh, 2016), but it is suited to the Noga variant (Hazera Seeds, Israel), which grows well in summer. The average NO_3-N and SRP concentrations in the plant beds were 84 and 20 mg/L, respectively (Table 1), and lower than in other hydroponics or aquaponics systems reported by previous researchers (Delaide et al., 2021; Nozzi et al., 2018). Interestingly, a recent study demonstrated that solids treatment (i.e., such as in this study) resulted in a supernatant that was more bioavailable to plants than a commercial nutrient solution despite its lower nutrient concentration (Lobanov et al., 2021). It was also reported that operating the aquaculture unit at a lower nutrient concentration may improve fish growth and welfare (Yildiz et al., 2017).

TSS is mainly made up of organic materials (VSS/TSS = 0.86) consisting mainly of fish excretions and a small portion of uneaten feed that is separated from the water by the drum filter and reused as the substrate for the UASB reactor. Mean TSS concentrations were reasonably low and stable, averaging 12.5 ± 4.1 mg/L and 4.4 ± 2.7 mg/L in the fish tank and biofilter, respectively, suggesting suspended solids removal of 65% by the drum filter and enabling low TSS levels at the safe range for fish growth (Campanati et al., 2021). Average alkalinity ranged from 31 to 78 mg/L as $CaCO_3$ in the system and decreased over time, mainly

Table 1
Daily water quality measurements and 10-day sampling concentrations of nutrients for the aquaponics research trial from January 15 to May 14, 2020. Units are in mg/L unless reported differently.

Parameters mean ± SD (range)	Aquaponics system			Hydroponics with PWAD[1] supernatant
	Fish tank	Biofilter	Hydroponics of aquaponics	
pH	7.18 ± 0.36 (6.15–8.03)	7.09 ± 0.41 (6.13–7.93)	7.21 ± 0.33 (6.24–8.09)	7.03 ± 0.29 (5.97–8.11)
EC (mS/cm)	1110 ± 167 (763–1469)	1124 ± 172 (1764–478)	1104 ± 186 (742–1457)	778 ± 124 (602–1083)
Dissolved oxygen	9.2 ± 1.1 (7–12)	9.6 ± 1.2 (7.4–12)	8.7 ± 1.3 (6.7–11.9)	8.5 ± 1.2 (4.7–11.6)
Temp (°C)	28.1 ± 1.9 (22.4–32.4)	28.4 ± 1.8 (22.2–32.4)	27.8 ± 2.4 (21.3–31.1)	20.1 ± 4.5 (10.8–32.9)
Total ammonia-N	0.56 ± 0.51 (0.09–1.81)	0.48 ± 0.44 (0.05–1.43)	0.93 ± 0.58 (0.07–1.77)	0.83 ± 0.68 (0.11–2.29)
NO_3-N	79 ± 18 (46–106)	80 ± 19 (48–112)	84 ± 19 (47–110)	28 ± 13 (10–46)
NO_2-N	0.05 ± 0.09 (0–0.36)	0.09 ± 0.08 (0–0.28)	0.25 ± 0.44 (0–1.49)	0.34 ± 0.79 (0–2.85)
SRP	17 ± 4 (9.0–23)	17 ± 4 (9.0–24)	20 ± 5 (14–27)	36 ± 12 (22–61)
TSS	12.5 ± 6.4 (4–20)	4.4 ± 2.1 (0–7)	5.6 ± 3.4 (2.0–9.0)	8.4 ± 6.1 (2.0–15)
Alkalinity (as $CaCO_3$)	62.5 ± 7.3 (31–78)	60.6 ± 7.2 (47–76)	64.7 ± 7.2 (50–82)	135 ± 22.6 (79–175)

[1] PWAD: plant waste anaerobic digestion.

due to nitrification, which produces 2 mol of protons per mole of nitrogen. K_2CO_3 or $KHCO_3$ was added to the system periodically when alkalinity decreased. Potassium-based buffers were used to enhance plant growth as its concentration in fish feed (with respect to N) is low.

It is worth noting that only 6.81 m^3 (12.3 L/kg lettuce) freshwater was used to compensate water losses, which were mainly due to plant evapotranspiration (78%), harvested biomass (7.3% as plants and 0.3% as fish), evaporation from RAS (~14%) and unaccounted spills. These numbers show high water efficiency compared to standard hydroponics (Barbosa et al., 2015; Love et al., 2015) because of the near-zero discharge system (Fig. 1). However, a long-term operation might require higher water exchange to reduce the effect of accumulating salts on plant growth.

3.1.2. Fish production

Initial fish density was 15.3 kg/m^3, with a 0.93%/day specific growth rate. Fish density was maintained throughout the research at below 40.2 kg/m^3, with an average density of 27.4 kg/m^3 after four months. The fish survival rate was 97%, and the overall feed application was 35.1 kg, resulting in an average FCR of 1.33 (Tables 2 and A.2). Overall, these findings are similar to previously reported values for catfish (Pinho et al., 2021; Yogev et al., 2017).

3.1.3. Plant production

Lettuce was grown hydroponically in two adjacent systems. One system received its nutrients from the aquaponics, i.e., using the fishpond effluent and the supernatant from the UASB treated fish sludge, as discussed in Section 3.2.1 below. The second hydroponics system received its nutrients from the supernatant of the anaerobic digester of the PWAD, as discussed in Section 3.2.2 below.

Each lettuce growth cycle was 28 days; consequently, lettuce performance is based on the average of eight cycles for both of the systems. Initial and harvest plant weight was on average 2 g and 591 g, respectively (Table 2 and A.3), resulting in an average yield of 5.65 kg lettuce/m^2. The reported yield was significantly higher than many previous reports on hydroponics (e.g., Resh, 2016; Nozzi et al., 2018), and even those from desert environments such as Barbosa et al. (2015). They reported that monthly yields of 3.4 kg/m^2 are achievable year-round in Yuma, Arizona, USA. As each plant variant has a different growth performance, comparing lettuce that is not of the same variants is challenging. It is most likely that the high performance was due to the strain used (Noga, Shorashim Nursery) together with the high desert radiation and nutrient load from the aquaponics. Specifically, nitrogen was continuously supplied as a mixture of nitrate from the nitrification reactor and TAN from the UASB, which supported higher plant growth than a similar application of solely nitrate or TAN (Bar-Yosef et al., 2005). Moreover, it is likely that the excretion

Table 2
Performance of the near zero-discharge desert aquaponics system and hydroponics with plant waste anaerobic digestion (PWAD) supernatant from January 15 to May 14, 2020.

Parameters (mean ± SD)[1]		Aquaponics	Hydroponics with PWAD supernatant
Fish feed application (kg)[2]		35.1	–
Organic carbon in fish feed (%)		47.8	
Fish biomass production (kg)		26.4	–
Organic carbon in fish (%)		48.9	
FCR		1.33	–
Survival (%)		97	–
Solid content of fish (%)		26.0 ± 1.1	–
Fish density range (kg/m^3)		15.3–40.2	–
Plant wet weight (g)	Shoot	488 ± 59	539 ± 54
	Root	29.9 ± 3.6	51.6 ± 5.2
Organic carbon (%)	Shoot	38.3	36.9
	Root	37.7	37.3
Root/shoot ratio (%)		6.1 ± 0.4	9.6 ± 0.9
Root allocation (%)		5.8 ± 0.5	8.7 ± 0.8
Lettuce yield in total[3] (kg)		553.9	632.4
Solid content of plants (%)		4.96 ± 0.21	4.74 ± 0.13
Organic carbon in fish sludge (kg)		5.84	–
Organic carbon in plant wastes (kg)		2.55	2.67
Biogas (fish sludge)	Cumulative volume (m^3)	10.02	–
	CH_4 concentration (%)	74.5 ± 1.5	–
Biogas (plant wastes)	Cumulative volume (m^3)	14.1	–
	CH_4 concentration (%)	59.6 ± 1.8	–
Water replenishment (m^3)		6.81	5.73

[1] Mean ± SD: part of the data shown as mean ± SD.
[2] Fish feed consumption is the dry weight, while fish biomass increases and plant yield is the wet weight.
[3] Growth period 121 days; plant bed surface 7.5 m^2; plant density 22 plants/m^2.

of organic compounds by fish and by microbial activity in the aerobic biofilters (Timmons et al., 2018), micronutrients, and other compounds like organic acids from the supernatant of the UASB may also have enhanced plant growth (Delaide et al., 2021; Zhu et al., 2021).

Interestingly, the lettuce that was fertilized with supernatant from PWAD had even higher production ($\rho < 0.05$) than the aquaponics treatment (Table 2). It is speculated that essential minerals that support plant growth, such as Fe, Mg, Ca, and trace element concentrations in the plant waste supernatant (Zhu et al., 2021), were similar to the ratio of nutrients needed for lettuce and were significantly higher than those from the UASB reactor (Table 3). Additionally, due to the low ORP in the anaerobic reactor, many metals, such as Fe, Zn, Mn, and others, were found in reduced form (i.e., Fe^{2+}, Mn^{2+}), which are more soluble and available for plant uptake (Resh, 2016). These micronutrients have a positive effect on lettuce quality and nutritional value, mainly by the biofortification effect of increasing both concentrations and bioavailability of vitamins and minerals in the edible parts of plants (Sahin, 2021). Although beyond the scope of this study, it should be noted that in terms of nutrient uptake, the system might not have reached a steady-state, and nutrients fluctuated and accumulated (e.g., P and N). This observation suggests that the plant bed size was not optimized for fish feed loads, and the potential lettuce production could have been higher.

3.2. Onsite solid waste treatment

Onsite anaerobic solid waste treatment in two separate reactors (fish sludge and plant waste) was part of the system and served three purposes in addressing what are considered significant barriers to the success of aquaponics (Goddek et al., 2019; Zhu et al., 2021), namely: (1) onsite treatment to reduce the environmental and economic burden; (2) a significant source of nutrients via utilization of the nutrient-rich supernatant; and (3) carbon recovery and reuse as an energy source via the production of biogas. The latter was of specific interest in the current study.

3.2.1. Treatment and utilization of fish sludge

Fish sludge was collected, characterized (Table 3), and treated anaerobically in a UASB reactor. Sludge characteristics were typical and comparable to previous reports on fish sludge (Mirzoyan and Gross, 2013; Yogev et al., 2017).

It should be noted that, as expected, the fish sludge contained a low C:N ratio of 6.1, which is not considered ideal for AD and efficient methane production (Mirzoyan and Gross, 2013; Quinn et al., 2016). However, it has been demonstrated that, after a long acclimation time as is the case in this study (or through the use of a "starter"), it is possible to "produce" an acclimated microbial population that can anaerobically digest fish sludge efficiently, with the formation of high-quality biogas.

Sludge removal was determined as the difference between the cumulative mass of TS, VS, and TOC introduced throughout the study and the total mass of these parameters in the reactors at the end of the study, see Eq. (5). The fraction of VS in TS between the raw sludge and digested solid decreased from 86% to 36%, which is in agreement with previous findings (Mirzoyan and Gross, 2013), and with high efficiency of VS removal, which was around 98% (Table 3). The range of TOC removal was 93–98% in the UASB reactor (Table 3) and was higher than in previous reports (Gebauer and Eikebrokk, 2006; Mirzoyan and Gross, 2013). This increase is attributed to acclimated microbial inoculum (Quinn et al., 2016) and the relatively stable high temperature in the greenhouse (Zhu et al., 2021). These results demonstrate the high potential for sludge-mass reduction and the minimization of the negative environmental impact of fish sludge.

Table 3
Characteristics of raw fish sludge, digested fish sludge in upflow anaerobic sludge blanket (UASB) and its supernatant, plant wastes before digestion (raw) and after its anaerobic digestion (PWAD) as well as the supernatant of the PWAD. Data presented as mean ± SD.

Parameters	UASB in aquaponics			PWAD[1] for lettuce wastes		
	Raw fish sludge	Digested fish sludge in UASB	Supernatant of UASB	Raw plant wastes	Digested solid of PWAD	Supernatant of PWAD
pH	7.2 ± 0.4	–	7.1 ± 0.2	–	–	7.6 ± 0.3
EC (mS/cm)	1.2 ± 0.2	–	1.7 ± 0.3	–	–	6.1 ± 0.6
ORP (mV)	–	–	−386 ± 8	–	–	−384 ± 12
TOC (ppm[1])	1142 ± 624	353,376 ± 9078	51 ± 10	19,563 ± 2419	359,930 ± 11,590	210 ± 15
TN (ppm)	188 ± 28	53,315 ± 1414	130 ± 32	1949 ± 102	35,140 ± 1570	423 ± 73
TAN (ppm)	–	–	123 ± 32	–	–	381 ± 53
C: N ratio	6.1 ± 1.2	6.6 ± 0.9	0.39 ± 0.08	10.04 ± 0.83	10.2 ± 0.2	0.50 ± 0.04
TP (ppm)	82 ± 14	26,377 ± 744	34 ± 4	447 ± 20	13,237 ± 318	46.1 ± 8.7
N:P ratio	2.3 ± 0.5	2.0 ± 0.3	3.8 ± 0.2	4.4 ± 0.2	2.7 ± 0.2	9.2 ± 0.6
VS (ppm)	2059 ± 638	689,554 ± 23,576	43 ± 20	38,718 ± 1047	658,109 ± 34,116	202 ± 29
TS (ppm)	2485 ± 624	–	115 ± 37	50,291 ± 621	–	439 ± 36
Macro- and micro-nutrients						
B (ppm)	1.7 ± 0.3	86 ± 12	1.10 ± 0.19	2.63 ± 0.18	56 ± 1	1.45 ± 0.30
Ca (ppm)	133 ± 32	56,601 ± 3467	92.2 ± 8.4	1075 ± 71	66 ± 2	82 ± 12
Cl (ppm)	125 ± 29	6012 ± 2719	158 ± 13	299 ± 28	61,550 ± 1409	187 ± 30
Cu (ppm)	2.1 ± 0.9	2464 ± 585	0.05 ± 0.01	1.45 ± 0.18	63 ± 1	0.16 ± 0.01
Fe (ppm)	8.1 ± 1.9	11,546 ± 3068	3.2 ± 0.1	62.3 ± 3.8	2722 ± 103	0.6 ± 0.2
K (ppm)	184 ± 37	2848 ± 874	183 ± 11	1138 ± 75	8436 ± 165	866 ± 278
Mg (ppm)	24.0 ± 3.7	3431 ± 363	16.4 ± 1.4	229 ± 9	6914 ± 95	51 ± 2
Mn (ppm)	1.1 ± 0.8	775 ± 200	0.2 ± 0.06	3.98 ± 0.45	260 ± 5	0.12 ± 0.04
Na (ppm)	64 ± 17	1363 ± 392	103 ± 8	306 ± 25	2274 ± 66	171 ± 31
S (ppm)	39.8 ± 4.8	23,911 ± 4162	4.4 ± 2.4	162 ± 11	3209 ± 88	20 ± 6
Si (ppm)	6.1 ± 0.4	537 ± 59	0.24 ± 0.11	121 ± 7	3239 ± 251	14 ± 1
Sr (ppm)	0.9 ± 0.1	119 ± 43	0.21 ± 0.06	3.59 ± 0.22	281 ± 4	0.22 ± 0.23
Zn (ppm)	8.0 ± 2.1	2733 ± 292	0.18 ± 0.03	6.35 ± 0.62	387 ± 9	0.45 ± 0.05
Anaerobic digestion efficiency analysis						
TOC removal (%)		95.9 ± 2.3			92.8 ± 3.1	
VS removal (%)		98.1 ± 1.8			97.6 ± 2.4	
CH_4 concentration in biogas (%)		74.5 ± 1.5			59.6 ± 1.8	
Biogas production rate (L/day)		83 ± 8			116 ± 11	
Biogas production rate (L/g TOC)		1.86 ± 0.66			1.73 ± 0.03	
Biogas production rate (L/g VS)		1.01 ± 0.36			0.87 ± 0.01	

[1] The unit ppm for liquid and sludge is mg/L and for solid mg/kg.

During the study, 4843 L of UASB supernatant was released to the plant beds. The supernatant pH was close to neutral, and all the parameters were elevated (Table 3). Diluting the supernatant with the fishpond effluent before its introduction to the plant beds allowed some control over the TAN/NO_3^- ratio. This is of particular importance in the hydroponics subsystem of the aquaponics system, which operated at a good NO_3-N/TAN ratio of 1.1 based on loads. This ratio improves plant growth (Bar-Yosef et al., 2005), and is superior to the use of only one N source, whether it is TAN or NO_3^- (Roosta and Hamidpour, 2011). Utilizing the supernatant of the UASB for plant growth introduced an additional 629 and 125 g of N and P to the plant bed, which supported an additional 277 kg of fresh lettuce in practice. This additional yield was about 49% of the total lettuce biomass.

The concentrations of dissolved nutrients varied greatly between sludge and supernatant, especially Fe, K, P, and Ca of the supernatant, with averages of 3.2 mg/L, 183 mg/L, 31.8 mg/L, and 92.2 mg/L, respectively (Table 3), and which were reused as nutrients for plant growth. In addition, trace metals, such as zinc (Zn), manganese (Mn), and boron (B) ions, were found in low concentrations in the UASB supernatant (Table 3) and thus satisfy the limits of these trace elements for plant growth (Resh, 2016; Somerville et al., 2014). Ahmed et al. (2021) found that using fish waste as a nutrients solution for hydroponics lead to sub-optimal growth. They reported low micronutrient concentrations in fish waste compared to the Hoagland and Arnon solution. The mobilization of these micronutrients after AD is likely the reason for the improved growth in the current study.

3.2.2. Treatment and recovery of lettuce waste

Plant waste was collected, characterized (Table 3), and treated anaerobically in an onsite "HomeBiogas" anaerobic digestor. This approach in general and specifically for lettuce waste is considered as a sustainable and environmentally friendly treatment solution (Plazzotta et al., 2020). The reactor's ORP was, on average, −384 mV with a pH of 7.6 (Fig. 3a), supporting a high rate of AD (Zhu et al., 2021). This was also indicated by the high and stable TOC and VS digestion efficiency over time, which averaged 92.8% and 97.6%, respectively (Table 3). Supernatant TN concentration averaged 423 mg/L, of which TAN accounted for 90% (Fig. 3b), with negligible or undetectable concentrations of NO_2-N and NO_3-N. Interestingly, the N/P ratio in the supernatant was 9.2, which is considered optimal for plant growth and similar to artificial nutrient solutions such as the Hoagland solution (Shaver and Melillo, 1984). Overall, 86%, 76%, and 95% of N, P, and K were mobilized from the lettuce waste into the supernatant, which supported lettuce growth in the adjacent hydroponics system. Overall, 1186 kg of lettuce was produced, 907 kg as edible parts and 279 kg as waste, of which approximately 7.5% was roots waste and 16.5 inedible lettuce leaves. The quantity of waste for both inedible leaves and roots were relatively low. For example, Plazzotta et al. (2017) reported of at least 35% inedible lettuce leaves waste. Moreover, the root to shoot ratio (6.1–9.6%; Table 2) was also smaller than previous reports of 11 to 30%, in other hydroponics or aeroponics systems (Li et al., 2018). Similar reduction in root/shoot ratio following use of AD supernatant to irrigate plants was also reported by Wang et al. (2019) and is attributed to higher nutrient availability. Practically, the lower quantity of waste corresponded with higher edible portion.

3.3. Biogas production and energy recovery

The volume of biogas produced in the UASB reactor averaged 0.93 m^3/kg-VS. The methane concentration in the biogas ranged between 70.8% and 76.2%, with an average of 74.53% (Table 4), which is sufficient for direct use in a generator (Gebauer and Eikebrokk, 2006; Zhu et al., 2021). As expected, the biogas production rate increased as the temperature rose (from January to May), as well as the total volume, due to the increasing feeding load (from 103 g/day to 124 g/day). As a result, the highest biogas production rate reached 98 L/day, while the lowest was 69 L/day (Table 3). This methane production rate was higher than previously reported values for brackish RAS fish sludge (Mirzoyan and Gross, 2013), probably because of a higher and more stable temperature in the reactor, which averaged 31 °C, and lower salinity (Gebauer and Eikebrokk, 2006).

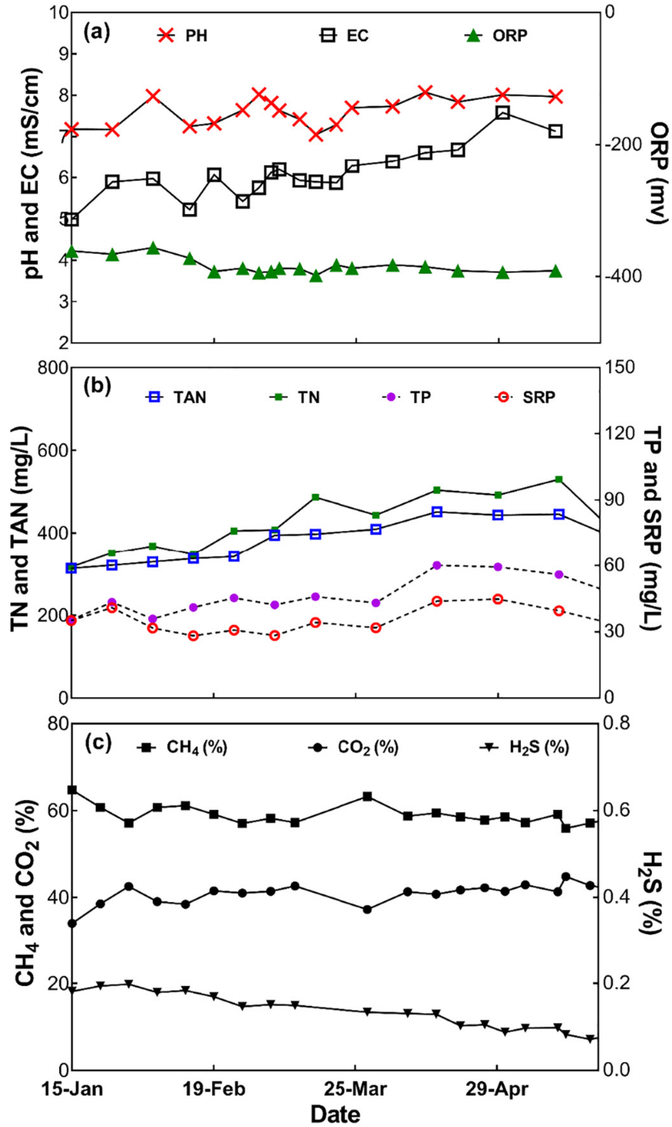

Fig. 3. Operation performance of the semi-continuous onsite anaerobic system digesting lettuce waste (e.g., roots and inedible leaves) under summer desert conditions. (a) Effluent pH, EC, and ORP; (b) supernatant nitrogen concentration (TAN and TN) and soluble reactive phosphorus (SRP and TP) concentration. (c) CH_4 and CO_2 content (%) following anaerobic digestion.

For the AD of lettuce waste, biogas production was calculated to be 0.875 m^3/kg-VS; the methane concentration in the biogas was 59.6 ± 1.8% (Table 4). The mass carbon balance was calculated according to the TOC of the inlet streams from lettuce waste, outlet streams (effluent and biogas), and residues in the digester (Table 4). 92.77% of the introduced carbon was recovered as biogas, and 1.35% was released to hydroponics. It was calculated that 6.39% of the introduced carbon was left in the reactor as undegradable carbon for stable processing AD.

3.3.1. Potential energy recovery

Based on the experimental results with FCR = 1.33 (Table 2), a similar system with standing stock of 1 ton of fish will potentially produce an average of 15 kg/fish/day, 242 kg saleable lettuce/day. Consequently, about 8 kg (38% of feed) and 74 kg (23% of the total plant biomass) of daily solid fish waste and plant waste, respectively, will be anaerobically digested and the potential energy recovery from the system will be about 83.7 kWh/day, of which 38.3 kWh/day will be produced from fish sludge and

Table 4
Overall biogas production and total inlet and outlet organic carbon stream in two pilot-scale biogas digesters (UASB and PWAD[1]) operated with fish sludge and lettuce waste as substrates under summer desert conditions.

Onsite AD reactors	Total volume of biogas	Biogas production rate	Organic C in waste	C in biogas[2]	Organic C accumulated in digester	Organic C discharged with effluent
	(m^3)	(m^3/kg VS)	(kg)	(kg)	(kg)	(kg)
UASB	10.02	0.93 ± 0.11	5.84 ± 0.55	5.37	0.15 ± 0.04	0.24 ± 0.06
PWAD	14.06	0.88 ± 0.01	8.12 ± 0.73	7.53	0.52 ± 0.11	0.11 ± 0.04

[1] Upflow anaerobic sludge blanket, plant waste anaerobic digestion.
[2] CH_4 and CO_2.

45.4 kWh/day from plant waste. It should be noted that there are almost no energy losses when the biogas is used for heating, where it is only 35–40% efficient when converted to electricity by a generator. The energy use efficiency can reach 85% via the use of combined heat and power (CHP), which is an energy-efficient technology that generates electricity and captures heat (Evangelisti et al., 2014).

Boyd and McNevin (2015) reported around 3.1 kWh direct energy use for the production of 1 kg of catfish; so, in order to produce 15 kg of fish per day, around 46.5 kWh/day will be needed directly. Murray et al. (2014) and Calone et al. (2019) reported that the energy required to produce 1 kg of catfish in industrial RAS might typically range from 0.8 to 29.4 kWh/kg, depending on the operation. Love et al. (2015) and Somerville et al. (2014) suggested that the energy required to support water circulation and aeration for hydroponics plant growth is estimated at around 0.12 kWh/kg fresh lettuce. Thus, in order to produce 242 kg of edible lettuce/day (total biomass with waste 316 kg) the required energy would be 37.92 kWh. Overall, the energy consumption for 1 ton of fish in this system is expected to be 84.4 kWh/day. Based on the current results, the aquaponics system produces enough energy with 85% energy use efficiency of CHP from the biogas to support about 84% of the energy demand for its operation, or even the entire demand when heating is not needed in the summer season. Although beyond the scope of this study, it should be noted that the use of solar energy, as an abundant and environmentally clean energy source specifically in the desert regions, may allow complete off-grid operation of the aquaponics system. Since this theoretical energy demand is based on rough estimates, a more detailed study is needed to refine the energy balance of such a system.

To the best of our knowledge, the current study is the first to demonstrate a significant recovery of energy from aquaponics waste streams. Moreover, all the aquaponics organic wastes (plants, wastewater, and sludge) were treated onsite, and no additional costs were incurred for waste treatment. This allows the system to be operated inland, independent of significant water sources and electricity, in almost any terrain.

3.4. Carbon footprint assessment

A total of 35.1 kg of fish feed containing 15.3 kg OC was applied to the fish tank. Feed carbon accounted for 38% of the total carbon directly entering the aquaponics system (Table 5). The initial carbon in the system before the experiments and in the fish fingerlings at stocking accounted for 1.8% and 4.4% of carbon input, respectively. Interestingly, net sequestered atmospheric CO_2 due to photosynthesis by fresh edible lettuces accounted for 16.4 kg of carbon input, equivalent to 4.4 kg CO_2/kg fish (carbon based). Although it was higher than the actual OC input via fish feed (Table 5), it is lower than the overall carbon footprint, including electricity, feed, waste treatment, transport, and production. Boyd and McNevin (2015) and Timmons et al. (2018) reported that the carbon footprint of industrial RAS was about 6.9 kg CO_2/kg fish, meaning the aquaponics practice reduced the RAS carbon footprint by 64%. Moreover, implementing onsite waste treatment may reduce carbon footprint in additional aspects such as transportation for wastes disposal (Striebig et al., 2019) which were not quantified in this work. In addition, this setup can facilitate urban and peri-urban farming, and further reduce the need for long-distance transportation and minimizes carbon footprint (Körner et al., 2021).

The fish biomass at harvest contained 5.5 kg carbon, equivalent to 13.8% of direct output OC. The plants retained about 22 kg carbon (57 kg dry weight lettuce, 38.3% OC content) via photosynthesis, of which 41.0% (16.4 kg C) and 13.7% (5.5 kg C) were found in the edible part and non-edible part (e.g., roots and damaged leaves), respectively. Carbon losses such as through respiration and spontaneous denitrification were calculated at 15.6% of output carbon and about 3.5% of carbon accumulated in different system parts (Table 5). In the AD reactors, AD of fish sludge and plant waste recovered biogas as a potential energy source, which accounted for 13.5 and 12.7% of net input C, respectively (Table 5).

Net wet biomass of 26.4 kg fish production was harvested, which accumulated 3.7 kg OC during the experiment. Of the applied feed carbon, 24.5% accumulated as fish biomass, 38.2% was collected as sludge in the drum filter, and 37.3% was degraded in the fish tank, nitrification biofilter, and hydroponics (Fig. 4). The latter was not directly measured but was calculated to complete the balance to 100%. The collected sludge was transferred to the UASB as a substrate for biogas production. In the UASB reactor, 91.9% of the organic carbon was degraded to 153 g carbon of biogas, 4.13% was discharged with the effluent, and the rest (3.97%) remained as non-degradable organic carbon in the UASB sludge (Table 4).

The carbon mass balance standardized to 1 kg fish feed results in a fish production of 752 g and 33.8 kg of wet saleable lettuces (Fig. 4). Thus, the plant to fish ratio is around 45. Interestingly, although it seems that this is significantly higher than that predicted in a model aquaponics system, for

Table 5
A carbon budget for catfish in a near zero-discharge aquaponics system. This budget provides average gains and losses for carbon (g) during a growing season (January 15 to May 14, 2020) stocked with 264 fish fed to satiation (average of 2% of body weight) with a 45% crude protein diet.

Variable (g)	Jan	Feb	March	April	May	Total	%
C input							
Initial OC[1]	724					724	1.8%
Fish stock	1756					1756	4.4%
Fish feed consumption	1675	3831	4417	3604	1765	15,292	38.3%
Net fixation by plants	2313	5000	5407	5860	3231	21,811	54.7%
Others	26.9	71.8	81.1	83.4	39.5	303	0.76%
Total	6495	8903	9905	9548	5036	39,887	
C output							
Fish at harvest					5498	5498	13.8%
Edible plant	1609	3964	4091	4341	2354	16,359	41.0%
Nonedible plant	704	1037	1316	1520	877	5453	13.7%
Biogas from UASB[2]	528	1181	1560	1276	824	5369	13.5%
Biogas from PWAD[3]	563	1107	1222	1238	929	5058	12.7%
Respiration and denitrification	668	1348	1692	1784	725	6217	15.6%
Residual OC					1386	1386	3.5%
Total	3368	7599	8565	8639	11,716	39,887	

[1] Organic carbon.
[2] Upflow anaerobic sludge blanket.
[3] Plant waste anaerobic digestion.

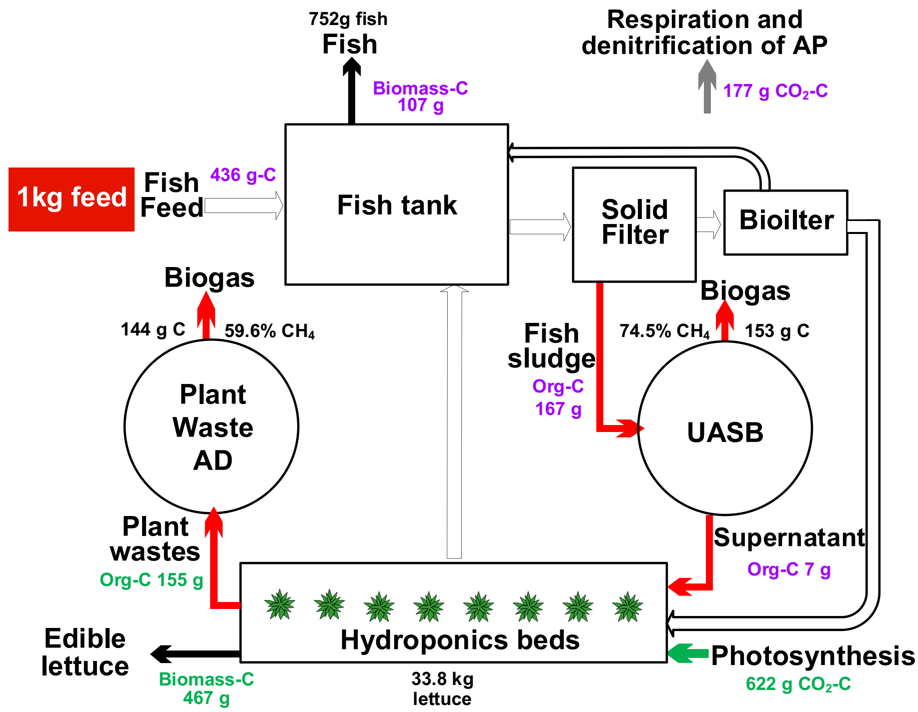

Fig. 4. Carbon mass balance for the different units of the zero-discharge off-grid aquaponics system after normalizing 1 kg feed during the research trial from January 15 to May 14, 2020. White arrows show waterflow movement within the system, dark blue arrows show production (fish and lettuce) from the system, and the red arrow shows the fish sludge and plant waste flow into the AD reactors.

which a tomato to fish ratio of 10 was reported (Yogev et al., 2016), this increase is due to different edible portions in tomatoes (~50%) and lettuce (~94%). When considering total plant production, the system in this study did not reach its full potential, probably as a result of a limited plant growth area and nitrogen losses via spontaneous denitrification.

Results suggest that a significant amount of solid fish waste was recovered as bio-methane in the UASB, a green energy bioresource. The supernatant was used as a high-quality liquid fertilizer in the plant beds. Moreover, unusable parts of the plants, such as roots and inedible shoots, were anaerobically digested in the plant waste AD (Zhu et al., 2021). Interestingly, overall, net CO_2 sequestration was observed (about 0.67 kg plants-C from aquaponics and 0.77 kg plants-C from hydroponics reused the AD biofertilizer for 1 kg feed-C) (Fig. 4), which dramatically reduced the RAS environmental footprint and improved its sustainability.

4. Conclusions

A near-zero waste desert aquaponics system, which combined aquaponics and anaerobic digestion technologies into a closed system, with a small environmental footprint was successfully demonstrated. Results show that 1 kg of feed per day was able to produce about 0.75 kg fish and support 33.8 kg fresh lettuce. The latter is significantly higher than previously reported. The solid fish sludge was treated in the anaerobic digester (UASB) and converted to bio-methane (74.5% CH_4), a green energy source, and to a high-quality liquid fertilizer that was used in the plant beds. Moreover, unusable parts of the plants, such as roots and inedible shoots, were anaerobically digested, producing more high quality biogas (59.6% CH_4) and nutrient solution. Both anaerobic treatments and the higher plant production reduced the RAS carbon footprint by 64% and can potentially support over 80% of the system's energy demand for a standing stock of about 1 ton of fish.

The current study is the first to demonstrate a significant recovery of water, energy, and nutrients from aquaponics waste streams. Further investigations have the potential to improve the performance of the aquaponics operating system. Alternatively, seen from a broader perspective, this concept would allow fish and vegetable production in nontraditional agricultural land, such as rural areas with insufficient electricity supply or in urban environments close to the customer (Körner et al., 2021; Yogev et al., 2016).

CRediT authorship contribution statement

Ze Zhu: Conceptualization, Data curation, Formal analysis, Methodology, Resources, Validation, Visualization, Writing – original draft. **Uri Yogev:** Conceptualization, Investigation, Methodology, Supervision, Writing – review & editing. **Simon Goddek:** Supervision, Writing – review & editing. **Fei Yang:** Funding acquisition, Writing – review & editing. **Amit Gross:** Conceptualization, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing. **Karel J. Keesman:** Funding acquisition, Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work was financially supported by the ICA Foundation, British Council, and Hainan Project (ZDYF2019198). Special thanks to the CSC (201808280001) for support. The authors would like to acknowledge Adrian Barnes and Yaniv Kriger for assistance in the installation and maintenance of the system, Dr. Almog Gafni, and Dr. Amos Russak for their assistance with the system operation and technical support.

Appendix A. Supplementary Tables

Supplementary data are provided in Table A.1, Table A.2, and Table A.3. https://doi.org/10.1016/j.scitotenv.2022.155245.

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