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# Scalable coupled aquaponics design: Lettuce and tilapia production using a parallel unit process approach

Joseph Tetreault[1]*, Rachel L. Fogle[1] and Todd Guerdat[2,3]

[1]Environmental Science and Sustainability Program, Harrisburg University of Science and Technology, Harrisburg, PA, United States, [2]Natural Resources Conservation Services, United States Department of Agriculture, Epping, NH, United States, [3]Civil and Environmental Engineering Department, University of New Hampshire, Durham, NH, United States

Coupled aquaponics is the integration of recirculating aquaculture systems (RAS) with hydroponic cropping systems (HCS) into a single system with shared water treatment units. Potential benefits of integration include water conservation, reduced reliance on finite mineral fertilizers, and intensive year-round location-independent production of lean proteins and fresh vegetables. However, coupled aquaponic practitioners have found minimal commercial success to date. This has been mostly due to the use of system designs which are not based on contemporary water treatment principles, especially those for commercial aquaculture. Instead, conventional coupled aquaponic system design has been based on a linear framework assuming fish wastes are readily utilized as plant fertilizers, with minimal emphasis on waste treatment or individual component hydraulic retention times. The result has been economic failures due to misbalancing the cost of inputs, the value of the outputs, and the time required to reach a marketable harvest size for both crops: fish and plants. This manuscript provides theoretical calculations based on existing standards in commercial RAS and HCS for sizing plant, fish, and biofiltration units focused on nitrogenous waste production from fish. Successful integration of HCS and RAS is defined as achieving industry standard production timelines for lettuce (seed to harvest time of 35 days) and Nile tilapia (fry to a 624 g average harvest weight in 35 weeks). Equations and examples to calculate lettuce yield, daily lettuce nitrogen requirement, fish feed rates to achieve specific nitrogen production rates, and fish tank and biofilter volumes are provided.

KEYWORDS

aquaponics system design, recirculating aquaculture system (RAS), commercial aquaponics production, controlled environment agriculture (CEA), nutrient bioeconomy

## 1. Introduction

Coupled aquaponics is the integration of a recirculating aquaculture system (RAS) and a hydroponic cropping system (HCS) where treated fish culture water is used as a nutrient solution for soilless plant production. Individually, RAS and HCS are prominent components of the controlled environment agriculture (CEA) industry where protected growing conditions are strictly manipulated to provide season-independent production to reduce water usage and increase yield in a minimized, location-independent growing area (Resh, 2013; Benke and Tomkins, 2017; Timmons et al., 2018). The CEA industry is an attractive option for decentralized urban food security, and it is expected to grow as the

demand for food and agricultural water are projected to increase by 56 and 60% by 2050, respectively, to meet the needs of the growing global population (Smith and Stwalley, 2018; Boretti and Rosa, 2019; van Dijk et al., 2021). Proponents of aquaponics claim that the integration of RAS and HCS into a coupled system can further optimize CEA production and result in improved environmental sustainability through minimized water and fertilizer use with increased profitability through the sale of multiple locally grown commodities (Love et al., 2014; Goddek et al., 2015; Atique et al., 2022). Additionally, urban food distribution models indicate a market for aquaponics as consumer preference is shifting to regional hubs that provide year-round fresh food production (Feldmann and Hamm, 2015; Broad et al., 2022). Despite the proposed environmental benefits and potential consumer market, commercial-scaled success has been limited.

In practitioner surveys, it was found that the majority of aquaponic systems were not profitable, and that fish production was a substantial source of financial loss (Love et al., 2014, 2015; Pattillo et al., 2022). While aquaponic systems without nutrient supplementation has demonstrated leafy green vegetable production with similar or faster growth rates than hydroponics, it has also been found that the cost of nitrogen (N) and phosphorus (P) by mass were, respectively, up to 14 and 88 times more expensive in fish feed than in inorganic fertilizer salts used in hydroponics (Colt and Schuur, 2021; Atique et al., 2022). These reports suggest that aquaponic systems where fish production is not profitable and is managed predominantly to mineralize feed that is used as the sole nutrient source for plants will likely struggle to cover production costs. A more appropriate production model would meet the fish growth and harvest rates at standards demonstrated to be profitable in the RAS industry. The potential environmental and financial benefits of integrated production could then be achieved by using excess nutrients in culture water for leafy green production commensurate with the HCS industry. This manuscript provides a coupled aquaponic system design template derived from contemporary RAS design principles. This approach focuses on a parallel unit process design for individual fish, plant, and water treatment unit hydraulic retention optimization to maximize fish growth and N production, differing from the conventionally used linear water flow design found throughout much of the published literature on coupled aquaponics.

## 2. Scaling limitations of traditional coupled aquaponic designs

Many self-designed aquaponic systems are adapted from a template developed at the University of Virgin Islands (UVI) where a single process flow directs nutrients produced by fish to plants (Rakocy et al., 2006; Love et al., 2014). Scalable commercial application is limited since there is little opportunity for controlling water flow rate, nutrient mass loading rates, and organic carbon accumulation as the specific unit processes are not operated under optimal conditions to meet the individual requirements for ideal fish and crop production (Baßmann et al., 2017; Knaus and Palm, 2017; Yang and Kim, 2020). Optimization of an integrated production system requires a design which utilizes hydraulic retention times (HRTs) for waste treatment and crop

production unit processes (fish and plants) based on established principles in the RAS and HCS industries (Davison, 1997; Chen et al., 2006; Rusten et al., 2006; Resh, 2013; Summerfelt et al., 2016). Many of the single, in-series culture water process flow systems used in published aquaponics research did not meet the individual requirements for each unit process and therefore would be ineffective for developing scalable production systems (Baßmann et al., 2017; Knaus and Palm, 2017; Yang and Kim, 2020; Ani et al., 2021; Dusci et al., 2021) (Figure 1). Utilizing a system design approach proven to be commercially effective for aquatic food production would allow greater scalability and optimization in coupled aquaponic systems.
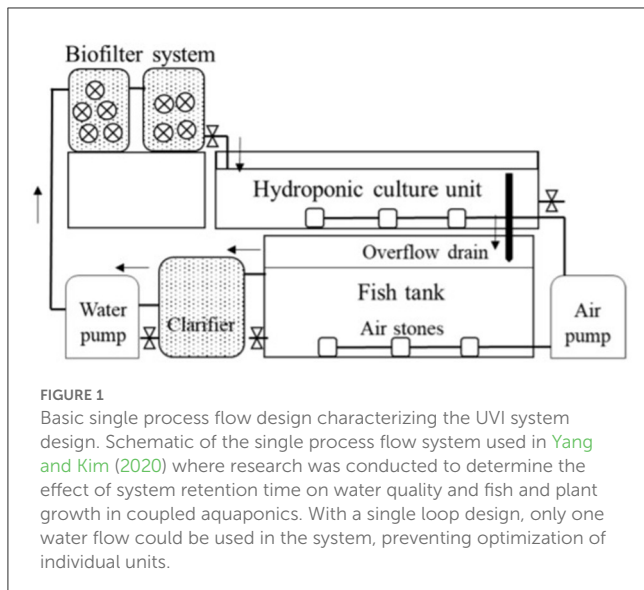
## 3. Potential benefits of adopting contemporary RAS design principles

Applying contemporary RAS engineering principles to develop system design guidelines for consistent productivity is required to enhance economic viability of commercial coupled aquaponics. Adopting a parallel unit process design modeled from RAS engineering principles could separate fish and plant production into isolated, recirculating "loops" within one culture system that shares water treatment unit processes. This retains the benefits of integration while allowing independent unit scaling and operation at contemporary RAS and HCS industry standards (Figure 2). This manuscript provides theoretical calculations derived from existing RAS and hydroponic system design methodologies to size the primary components to estimate fish and crop production rates in an aquaponics system using a parallel unit process approach.

## 4. Designing a coupled aquaponics system with a parallel unit process approach

### 4.1. System surface area and design assumptions

Greenhouse systems are popular because modifications can be made to allow season-independent growth while harnessing natural light and heat. This design is based on commonly available commercial greenhouse dimensions of 29.26 m long and 9.14 m wide, with a total surface area of 267.6 m². The floor area of the greenhouse is divided into four primary zones for efficient area utilization (Table 1). Most of the area is devoted to hydroponic production as this will provide the most consistent revenue source. Nile tilapia (*Oreochromis niloticus*) and lettuce (*Lactuca sativa*) are some of the most commonly grown fish and vegetable, respectively, according to recent aquaponic practitioner surveys and are the basis for all subsequent fish and plant management guidelines (Love et al., 2014; Pattillo et al., 2022). To ensure consistency in estimated yields, it is assumed that supplemental light, air temperature control, and water temperature control are used to maintain ideal growing conditions throughout the year.

**FIGURE 1**
Basic single process flow design characterizing the UVI system design. Schematic of the single process flow system used in Yang and Kim (2020) where research was conducted to determine the effect of system retention time on water quality and fish and plant growth in coupled aquaponics. With a single loop design, only one water flow could be used in the system, preventing optimization of individual units.

## 4.2. Scalable hydroponic production

### 4.2.1. Deep water culture hydroponics

In deep water culture (DWC) hydroponics, plants float on polystyrene rafts in ponds that allow root systems to be fully submerged in nutrient-rich water (Resh, 2013). The ponds provide security against crop loss since sufficient standing water is retained in the event of equipment failure. Furthermore, supplemental lighting is simplified, and harvesting is streamlined in DWC because plants are easily accessible at a uniform elevation. Commercially available rafts are often 0.61 m wide and 1.22 m long, with a variety of options for spacing of grow holes.

Head lettuce, such as Butterhead lettuce, is well-suited to DWC production because it has a lightweight head that can be easily supported by a raft and a relatively small root mass that will not clog the pond. A 5-week seed to harvest timeline for Butterhead lettuce has been established where seedlings are kept in a separate germination area for 2 weeks before being transplanted into a DWC system for 3 weeks (Breckner and Both, 2013; Rakocy and Ebeling, 2018, p. 663–707). Initial transplants require less space than mature plants, and staggering growth into three 1-week phases provides consistent production and efficient space utilization. Ideal spacing for lettuce growth is used to determine the total number of heads across the three different phases and weekly harvest estimates for a system. Each week, lettuce on the phase 3 rafts is harvested, and plants within each phase progress into the next phase growing area. Based on the established growing area and the recommended spacing for lettuce, a 200.67 m$^2$ area could contain 11,067 plants and produce 3,689 heads per week or 191,828 heads per year (Table 2).

### 4.2.2. Nitrogen requirements

Nitrogen (N) is an essential macro-nutrient and is required for lettuce growth (Marschner, 2011). Smaller plants assimilate a smaller N mass each day while larger plants assimilate a greater mass each day. Maintaining a constant number of plants at each

phase allows the calculation of an accurate average daily fish N production rate for ideal plant growing requirements using the following equation (Rakocy and Ebeling, 2018, p. 663–707):

$$P_N = \left( \left( plants\ phase^{-1} * phases \right) * assimilation_N \right) + SF \quad (1)$$

where $P_N$ is the production of g N day$^{-1}$ required for ideal lettuce growth, *phases* is the number of age-based growing sections, *assimilation$_N$* is average g N day$^{-1}$ required by a single lettuce plant, and *SF* is a safety factor to ensure an adequate nutrient mass is always available. The average N assimilation rate of a lettuce plant in a three-phased DWC growing method is 0.01837 g N plant$^{-1}$ day$^{-1}$ (Rakocy and Ebeling, 2018, p. 663–707). Based on this assimilation rate and the addition of a 20% safety factor to ensure sufficient nutrient supply, a DWC pond with 11,067 lettuce plants evenly separated across three age-based phases would require 244 g N day$^{-1}$.

## 4.3. Scalable RAS production

### 4.3.1. Fish feed rate calculations

Fish waste contains high concentrations of total ammoniacal nitrogen (TAN) (Pulkkinen et al., 2019). A daily fish feed rate to produce a desired N loading rate from fish waste can be calculated using the following equation adapted from Timmons et al. (2018):

$$g\ feed = \frac{\frac{P_{TAN}}{PC}}{0.092} \quad (2)$$

where *g feed* is g feed day$^{-1}$ required to produce a specific N mass, $P_{TAN}$ is the specific production rate of N as g TAN day$^{-1}$, *PC* is the protein content of the feed (%), and 0.092 is the average percent of the feed mass excreted as ammonia. A feed rate of 6.63 kg day$^{-1}$ is required to provide 244 g N day$^{-1}$ from feed with a 40% protein content.

### 4.3.2. Fish production schedule

Staggered tilapia production is used to ensure a constant feed and N production rates and to increase fish harvest frequency. DeLong et al. (2009) and McGinty and Rakocy (2015) provide estimates for tilapia growth rates under intensive aquaculture production standards from fry to harvest weight. A daily feed rate per fish was calculated using those growth rates in conjunction with the following equation from Timmons et al. (2018):

$$g\ feed\ fish^{-1} = \frac{\left( weight_{final} - weight_{initial} \right)^* FCR}{\left( age_{final} - age_{initial} \right)} \quad (3)$$

where *g feed fish$^{-1}$* is the average feed consumption day$^{-1}$ fish$^{-1}$ over a chosen timeframe, *weight$_{final}$* is the average weight fish$^{-1}$ in g at the end of this phase, *weight$_{initial}$* is the weight fish$^{-1}$ in g at the start of this phase, *FCR* is the average feed conversion ratio at the given age range, *age$_{final}$* is fish age in days at the end of the phase, and *age$_{initial}$* is the fish age in days at the start of the phase. Phased production is determined by fish age, desired harvest frequency, or desired number of culture tanks. A five-phased production system can be utilized for a 7-week harvest
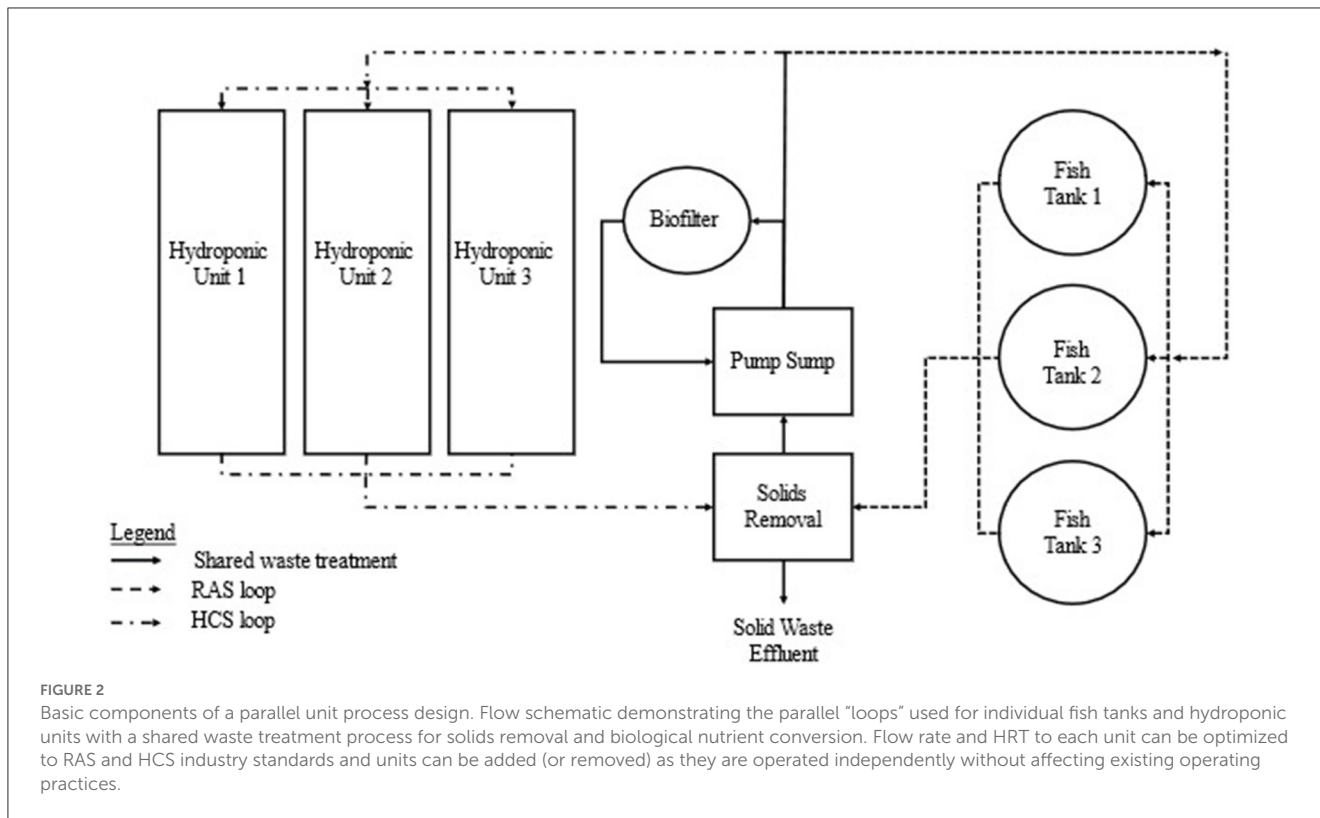
**FIGURE 2**
Basic components of a parallel unit process design. Flow schematic demonstrating the parallel "loops" used for individual fish tanks and hydroponic units with a shared waste treatment process for solids removal and biological nutrient conversion. Flow rate and HRT to each unit can be optimized to RAS and HCS industry standards and units can be added (or removed) as they are operated independently without affecting existing operating practices.

TABLE 1 Area allotment for greenhouse zones.

| Greenhouse zone | % of area | Area (m²) |
|---|---|---|
| Hydroponics | 75% | 200.67 |
| Fish rearing and water treatment | 15% | 40.13 |
| Harvesting space | 5% | 13.38 |
| Storage | 5% | 13.38 |
| Total | 100% | 267.56 |

The approximate percentage of the total area used for the primary zones of a commercial coupled aquaponics greenhouse are indicated.

interval with fry starting at 0.5 g and harvest when growth rates plateau and feed conversion ratio (FCR) increases upon reaching an average weight of 624 g (Losordo et al., 2000; McGinty and Rakocy, 2015) (Table 3).

The average feed rate fish$^{-1}$ day$^{-1}$ across all phases is used to determine the total fish population required to consume a desired total feed rate to produce specific N mass each day, and can be calculated using the following equation:

$$average\ g\ feed\ fish^{-1} = \frac{(\sum_1^n phase_1 + phase_2 + \ldots + phase_n)}{n}$$
(4)

where *average g feed fish*$^{-1}$ is the average g feed fish$^{-1}$ day$^{-1}$ across all growth phases, $n$ is the total number of growth phases, and *phase* is the g feed fish$^{-1}$ day$^{-1}$ for each phase. In the five-phased system described in Table 3, the average feed rate fish$^{-1}$ across all phases is 3.96 g day$^{-1}$. This average feed rate fish$^{-1}$ and the total system feed rate from Equation 2 can be used to calculate

the total fish population that must remain evenly distributed across all growth phases to fully consume the total system feed rate to produce the required daily N loading rate. The total fish population can be calculated using the following equation:

$$fish_{total} = \frac{feed\ rate_{system}}{average\ g\ feed\ fish^{-1}\ phase^{-1}}$$
(5)

where $fish_{total}$ is the number of fish required across all growth phases to produce the desired mass of N day$^{-1}$, *feed rate*$_{system}$ is the g feed day$^{-1}$ required to produce the desired mass of N day$^{-1}$, and average g feed fish$^{-1}$ phase$^{-1}$ is the average g feed fish$^{-1}$ day$^{-1}$ across all growth phases. A system feeding 6.63 kg day$^{-1}$ with an average feed rate of 3.96 g feed fish$^{-1}$ phase$^{-1}$, would require 1,674 fish evenly distributed across all growth phases. A five-phased grow-out would require 335 fish phase$^{-1}$. Each harvest would yield 209 kg of fish, for a yearly production of 1,553 kg.

### 4.3.3. Fish culture tank volume

The water volume of a tank can be calculated when the number of fish, final weight, and maximum stocking density are known using the following equation:

$$V = \frac{fish_{tank}}{\left(\frac{density_{final}}{weight_{harvest}}\right)}$$
(6)

Where $V$ is the volume of water required in a fish tank in m³, $fish_{tank}$ is the number of fish in each tank, $density_{final}$ is the maximum desired stocking density in kg m$^{-3}$, and $weight_{harvest}$ is the average weight in kg of fish at harvest. The

TABLE 2  Phases of hydroponic lettuce growth.

| Phase | Age (days) | Spacing (m$^2$ plant$^{-1}$) | % of pond area | Area (m$^2$) | Rafts phase$^{-1}$ | Plants phase$^{-1}$ |
|---|---|---|---|---|---|---|
| 1 | 14 | 0.003 | 5% | 10.0 | 14 | 3,689 |
| 2 | 21 | 0.010 | 19% | 38.1 | 52 | 3,689 |
| 3 | 28 | 0.041 | 76% | 152.5 | 205 | 3,689 |

Hydroponic lettuce production was divided into three 1-week phases. Each phase increases in area as individual maturing plants required a greater spacing. The same number of plants at each phase allows consistent production rates and the development of an average daily N requirement for the hydroponic unit.

TABLE 3  Phased fish production based on desired daily $N$ production rate.

| Phase | Start age in days (weeks) | End age in days (weeks) | Start weight (g) | End weight (g) | FCR | Feed rate (g day$^{-1}$ fish$^{-1}$) |
|---|---|---|---|---|---|---|
| 1 | 1 (1) | 49 (7) | 0.5 | 24 | 1.1 | 0.54 |
| 2 | 50 (8) | 98 (14) | 24 | 130 | 1.2 | 2.65 |
| 3 | 99 (15) | 147 (21) | 130 | 277 | 1.4 | 4.29 |
| 4 | 148 (22) | 196 (28) | 277 | 439 | 1.6 | 5.40 |
| 5 | 197 (29) | 245 (35) | 439 | 624 | 1.8 | 6.94 |

This five-phased approach consistently maintains a desired system feed rate to produce the required daily N mass for ideal plant growth. Fish number is kept constant across each phase. Feed rate increases as fish weight and FCR increase to ensure growth rates commensurate with the RAS industry.

TABLE 4  Tank volume based on final fish weight and stocking density.

| Phase | Fish population | Final fish weight (g) | Tank volume (m$^3$) |
|---|---|---|---|
| 1 | 335 | 24 | 0.20 |
| 2 | 335 | 130 | 1.09 |
| 3 | 335 | 277 | 2.23 |
| 4 | 335 | 439 | 3.67 |
| 5 | 335 | 624 | 5.22 |

This five-phased approach maintains a consistent fish population at each phase but conserves the physical footprint of fish production by sizing each tank to the final estimate average weight of an individual fish at the end of each phase.

tank volume for each of this five-phased production method will house 335 fish and a maximum stocking density of 40 kg m$^{-3}$ and is shown in Table 4. A 20% safety factor for fish numbers in Phase 1 may be beneficial to account for higher juvenile mortality rates.

### 4.3.4. Moving bed biofilm reactor volume

Moving bed biofilm reactors (MBBR) are commonly used in RAS to transform fish lethal TAN into the safer nitrate using multiple heterotrophic bacteria whose growth is facilitated on aerated media (Pulkkinen et al., 2019). Growth media volume in an MBBR is dependent on daily TAN production rates from fish waste, and can be calculated using the following equation (Timmons et al., 2018):

$$V_{media} = \left( \frac{P_{TAN}}{SSA_{media} + SF} \right) \qquad (7)$$

where $V_{media}$ is the volume of growth media in m$^3$, $P_{TAN}$ is the daily TAN production in g day$^{-1}$, $SSA_{media}$ is the specific surface area in m$^2$ m$^{-3}$ of the media for bacteria growth, and $SF$ is a safety factor to ensure complete nitrification occurs. A system that produces 244 g N day$^{-1}$, uses media with a 500 m$^2$ m$^{-3}$ SSA, and has a 20% safety factor would require 0.59 m$^3$ of MBBR media. Research has demonstrated that MBBR is effective when 55% full of media (Timmons et al., 2018). An MBBR requiring 0.59 m$^3$ of media would necessitate a total volume of 1.07 m$^3$.

## 5. Discussion

Coupled aquaponic management improvements are often considered from only a fish or plant optimization perspective in systems designed with a single process flow (Yang and Kim, 2020; Ani et al., 2021). In an evaluation of tilapia stocking density on water quality, Ani et al. (2021) determined that lower densities resulted in more suitable dissolved oxygen (DO), TAN, nitrite, and nitrate conditions for ideal fish health than more densely stocked systems. These results have limited applicability to a CEA industry focused on intensive production and rapid yields. Based on diagrams in Ani et al. (2021), a single process flow system was used in the study and did not allow independent control over fish tank and biofilter HRTs, both of which have established parameters for maintaining appropriate DO, TAN, nitrite, and nitrate conditions in commercial RAS at stocking densities greater than any used in the study (Rusten et al., 2006; Summerfelt et al., 2016; Timmons et al., 2018; Ani et al., 2021).

For plant optimization, Yang and Kim (2020) compared three total system HRTs (6, 9, and 17 h) to determine ideal nutrient loading rates for crops in a single process flow system. The authors acknowledged that the HRTs were chosen based on DWC flow rates and would not be ideal for intensive fish production, again limiting commercial application where data suggest the fish production is key to financial success (Love et al., 2014; Yang and Kim, 2020; Colt and Schuur, 2021). The HRTs for optimal fish waste removal rates,

TABLE 5 Individual hydraulic management in a parallel unit process design.

| Unit | HRT (min) | Example volume ($m^3$) | Example flow rate (gal $min^{-1}$) | Citation |
|------|-----------|------------------------|-------------------------------------|----------|
| DWC pond | 300 | 36.9 | 32.5 | Resh, 2013 |
| Fish tank (Phase 1) | 35–53 | 0.20 | 1.51–1.00 | Summerfelt et al., 2016 |
| Fish tank (Phase 5) | 35–53 | 5.22 | 39.4–26.0 | Summerfelt et al., 2016 |
| MBBR | 3 | 1.07 | 94.2 | Rusten et al., 2006 |

The HRT for each unit was recommended in RAS and HCS literature. The individual flow rates were based on those recommendations and the volume of each unit determined with the equations presented above.

DWC crop nutrient uptake, and TAN conversion are all different and a single process flow system cannot meet the requirements for each component within a coupled aquaponic system (Baßmann et al., 2017; Knaus and Palm, 2017; Yang and Kim, 2020; Ani et al., 2021; Dusci et al., 2021). These results demonstrate that scalability is limited and individual unit improvement without sacrificing optimization in a different unit is difficult to achieve in a linear approach.

In contrast, this work integrates principles proven to be effective in the RAS and HCS industries to provide practitioners with a design template from a N mass balance that permits individual unit control. The isolated loops in a parallel unit process design provide water flow rate control to each component, which can then be operated at ideal conditions regardless of scale (Table 5). Additional loops with different flow rates can be added, or removed, without affecting existing units. This allows multiple hydroponic methods to increase crop diversity and the opportunity to incorporate fingerling production with reduced flow rates, while maintaining the precise HRTs identified to meet differing fish and plant requirements.

## 6. Conclusions

Consumer interest in locally grown CEA produce combined with the growing limitations of traditional agricultural methods to meet vegetable and protein demands indicates the potential for a successful coupled aquaponics industry (Feldmann and Hamm, 2015; van Dijk et al., 2021; Broad et al., 2022). To date, minimal economic success has been achieved through aquaponics, especially if fish production fails to be profitable (Love et al., 2014; Colt and Schuur, 2021). Although RAS is one of the most prominent aquaculture methods, much of the recently published coupled aquaponics literature does not incorporate commercial RAS designs or operating standards into experimental systems when modeling production for practitioner application (Baßmann et al., 2017; Knaus and Palm, 2017; Food Agriculture Organization of the United Nations., 2020; Yang and Kim, 2020; Ani et al., 2021; Atique et al., 2022). This

manuscript provides guidance on estimating plant and fish populations, yearly production, and unit volumes based on crop growing area, daily N mass requirements for lettuce in a 35-day seed to harvest schedule, and daily N mass production from tilapia in a 35-week fry to 624 g harvest schedule. A parallel unit process design adapted from RAS to incorporate an additional HCS loop is proposed to provide greater control over individual units. Unit volumes, HRTs, and fish feed and growth rates are calculated using established RAS production guidelines.

Additional research is required to further support the commercial aquaponics industry. Production data for yield estimates and comparisons to the individual RAS and HCS industries at commercial scale for additional fish species and vegetable varieties or cash crops would further de-risk practitioner adoption. Economic analysis to determine initial investment costs and potential return on investment is also required and may vary depending on environmental control costs by region as well as the fish and crop chosen. The optimization of aquaponic system design and operation is the first step to continue advancing a potential commercial industry.

## Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

## Author contributions

JT: conceptualization, investigation, data curation, writing—original draft, writing—review and editing, and project administration. RF: conceptualization, validation, writing—review and editing, and visualization. TG: conceptualization, writing—review and editing, and project administration. All authors contributed to the article and approved the submitted version.

## Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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