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Article

A Predictive Model of Nutrient Recovery from RAS Drum-Screen Effluent for Reuse in Aquaponics

Joseph Tetreault [1,*], Rachel L. Fogle [1], Ashly Ramos [1] and Michael B. Timmons [2]

[1] Environmental Science and Sustainability Program, Harrisburg University of Science and Technology, Harrisburg, PA 17101, USA
[2] Department of Biological and Environmental Engineering, Cornell University, Ithaca, NY 14853, USA
* Correspondence: jtetreault@harrisburgu.edu

Abstract: Controlled environment agriculture (CEA) optimizes growth parameters for vegetable and aquaculture production and can be used to address growing global food insecurity. Recirculating aquaculture systems (RAS) generate a nutrient-dense effluent that may result in environmental pollution, but with treatment and integration with hydroponic vegetable production may be repurposed as a naturally derived nutrient solution. This work developed a preliminary model using the system feed rate to calculate a plant-essential nutrient discharge rate in RAS effluent. Loading rate equations were created to calculate the daily mass of nutrients entering the system through fish feed, and discharge rate equations were created to calculate the grams of each nutrient discharged in the effluent per kilogram of feed. Data from previous published work were used for validation. The loading-rate percentage discharged for nutrients present in the effluent was between 2.71% and 64.5%, with several nutrients being prominent pollutants and all being required for vegetable growth. This work provides the preliminary framework for calculating nutrient discharge rates, which can be used to mitigate pollution or develop more precise, naturally derived hydroponic nutrient solutions for a circular bioeconomy in CEA.

Keywords: math model; controlled environment agriculture (CEA); recirculating aquaculture systems (RAS); aquaculture waste mineralization; hydroponics

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1. Introduction

Controlled environment agriculture (CEA) optimizes environmental growth parameters for year-round vegetable and seafood production. This allows greater yields in a smaller area and with less water than traditional agricultural methods [1,2]. The increased utilization of CEA technologies will be required to meet the food demands of the growing global population and counter the reduction in farmable lands from urbanization [3]. Recirculating aquaculture systems (RAS) and hydroponic crop production are two of the most prominent and economically stable CEA methods [1,2]. As food insecurities increase and natural resources become further stressed, these production methods will require additional optimization to operate with limited finite resources.

Extensive waste treatment and removal processes allow RAS to reuse up to 99% of the total system water daily and use 90–99% less water than other aquaculture methods to provide location-independent fresh seafood [2]. As a result of the waste removal processes, RAS generates a nutrient-rich effluent that requires additional treatment before discharge to prevent polluting natural waterways [4–6]. Effluent treatment costs and pollution potential are two primary limitations to the expansion of an economical and sustainable RAS industry [6,7]. Like RAS, hydroponics can result in location-independent production with up to eleven times greater yield, while using less water than its traditional agriculture counterparts [8]. In contrast to RAS, the hydroponic industry is limited by the need for additional nutrient inputs, as it is reliant on the finite mineral reserves and greenhouse gas-producing practices used for mining and generating synthetic nutrient solutions [9,10]. Developing a capture and reuse waste-management system would have a multi-faceted effect on the CEA industry by turning RAS effluent into a value-added product, thereby providing the hydroponic industry with a naturally derived nutrient source.

Aquaponics is the integration of RAS and hydroponics into a single system in which nutrients in fish-culture water are used for soilless crop production. This integration provides the opportunity to utilize dissolved nutrients excreted from fish gills or expelled as aqueous waste [11]. However, aquaponics currently does little for the reuse of the nutrient-dense effluent discharge. Excessive organic carbon (OC) and total suspended solids (TSS) concentrations in the effluent, primarily in the form of fish feces and uneaten feed, prevent immediate reuse in hydroponics [12,13]. Previous research has demonstrated that microbial-based mineralization processes can effectively reduce OC and TSS concentrations and solubilize particulate-bound nutrients to maximize plant availability [14,15]. This treatment provides the potential for reuse of RAS effluent and increased nutrient use efficiency (NUE) in aquaponics [14–18]. Therefore, the objective of this research was to develop a model that utilizes feed composition to calculate individual nutrient-loading rates and system-specific operating parameters in order to calculate the percentage of that loading rate retained in the effluent and predict plant-available nutrient recovery rate.

2. Materials and Methods

2.1. Existing Data for Nutrient Production Model Development

2.1.1. Aquaponic System Description

Data used in development of this predictive model were collected from an aquaponics system using Nile Tilapia (*Oreochromis niloticus*) operated at the University of New Hampshire's (UNH) Kingman Farm Recirculating Aquaponic Research Greenhouses (KFRAG), located in Madbury, NH, USA. This coupled system was operated under commercial hydroponic and RAS production standards and designed to provide pilot-scale results that could be modeled for commercial systems. The layout of the system is shown in Figure 1, and it is fully described in previous work by the authors [19–22]. At the time of data collection, the system had been operating at feed and waste production rates established in the literature as commensurate with industrial RAS standards for over one year without any prominent changes to the system that would influence the data analysis [23,24]. All nutrients used to grow crops were supplied through the fish feed (3 mm floating, Finfish Silver, 40% protein, 10% lipid; Zeigler Bros. Inc., Gardner, PA, USA) except for periodic diethylenetriamine penta-acetic acid (DTPA) iron (III) salt additions to maintain required iron (Fe) concentrations for optimum lettuce growth, and daily additions of potassium carbonate (K_2CO_3) for biofilter management. Water samples for analysis were taken from the system sump each week. Iron (Fe) was maintained between 1.8 and 2.3 mg/L based upon weekly measurements and additions and alkalinity was maintained at 40 mg/L calcium carbonate through daily measurements and additions [25,26]. A constant biomass approach was used to maintain a fish-stocking density of 36 kg/m^3. Bi-weekly fish biomass was measured and adjusted by removing fish to ensure that 1,300 g per day of feed would provide optimal fish-growth rates. A rotating drum screen (PR Aqua model RFM2014) fitted with 54-micron filtration mesh was used for solid waste removal.

2.1.2. Nutrient Analysis of Feed and Effluent Used in Model Development

Tetreault et al. (2021) characterized the nutrient profile of the fish feed used in the system and the drum screen effluent before and after microbial mineralization [20]. All nutrient analysis was conducted by a commercial, hydroponic fertilizer laboratory service (JR Peters Laboratory, Allentown, PA, USA). The macro- and micro-nutrient composition of the fish feed is shown in Table 1, where macro-nutrient masses are reported as a percentage of the total feed mass, and micro-nutrient masses are reported as milligrams of nutrient per kilogram of feed.

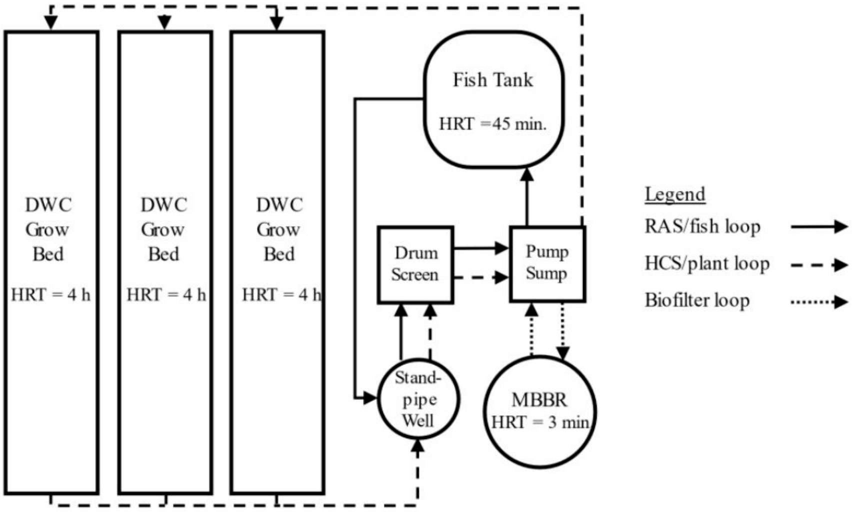

Figure 1. Components of the KFRAG system. This flow schematic shows the basic component layouts and retention times of the KFRAG system; adapted from Fogarty (2021) and originally published and fully described in Tetreault et al. (2023) [21,22].

Table 1. Fish Feed Nutrient Composition. The nutrient profile of Zeigler Bros. Inc., Finfish Silver, 40% protein, 10% lipid feed, taken from Tetreault et al. (2021) [20].

Macro-Nutrients						
Nutrient		**N** *	**P** *	**K** *	**Ca** *	**Mg** *
Feed		6.44	0.97	0.96	1.17	0.14
			Micro-nutrients			
Nutrient	Fe †	Mn †	B †	Cu †	Zn †	Na †
Feed	209	91.8	5.90	46.5	89.6	2051

* Reported as a % of the total feed mass. † Reported as milligrams of nutrient per kilogram feed.

A 200 L sample of drum screen effluent from KFRAG was collected over a continuous 72 h period without interruption. A composite subsample of the effluent was then separated into aqueous and particulate fractions prior to nutrient analysis with 1.5-micron glass-fiber filters. The results of the aqueous and particulate analysis were normalized to 1 L of effluent. The total concentration of each nutrient was calculated by adding the normalized aqueous and particulate results. Details on normalized nutrient analysis are provided in Tetreault et al. (2021) [20]. The total concentration and the percentage of that concentration in aqueous and particulate fractions are shown in Table 2.

Nutrients in the aqueous fraction of the effluent were considered plant available. Research has demonstrated that dissolved nutrients in RAS effluent are suitable for hydroponic fertilization, and that microbial mineralization processes can solubilize a significant percentage of the particulate-bound mass of each nutrient to permit plant assimilation [18]. The supplementation of K_2CO_3 and an 11% DTPA Fe (III) salt into the sump tank at KFRAG prevented the accurate calculation of loading rates of K and Fe from fish feed, and these nutrients are therefore excluded from further analysis. Previous work from the authors characterizing the effect of anaerobic treatment on the mineralization of particulate-bound nutrients in the same RAS effluent from KFRAG is displayed in Table 2. The effect of anaerobic mineralization on nutrient solubilization and assumed plant availability is shown in Table 3. Except for zinc (Zn), there was a significant increase in the percentage of the total mass of each nutrient after mineralization.

Table 2. Drum-screen effluent nutrient analysis adapted from Tetreault et al. (2021) [20]. The combination of aqueous and particulate nutrient masses in the drum screen effluent was normalized to 1 L of effluent to calculate total nutrient concentration and percentage of total in aqueous and particulate fractions.

Nutrient	Total Drum-Screen Effluent (mg/L)	Aqueous (%)	Particulate (%)
Macro-nutrient			
N	143	88.54	11.46
P	5.13	31.76	68.24
Ca	21.3	72.80	27.20
Mg	17.6	96.93	3.07
Micro-nutrient			
Mn	0.16	80.43	19.57
B	0.00	N/A	N/A
Cu	0.15	80.04	19.96
Zn	0.74	94.20	5.80

Table 3. The effect of anaerobic treatment on nutrient solubilization adapted from Tetreault et al. (2021) [20]. Anaerobic mineralization increased the plant availability of macro- and micro-nutrients. The standard deviation reported in the Post Treatment column is from the replicate (n = 3) reactors used in Tetreault et al. (2021) [20]. There were no statistically significant differences between the mineralization results between replicates.

Nutrient	Untreated Effluent (% Aqueous)	Post Treatment (% Aqueous)
Macro-nutrient		
N	88.54	93.83 ± 4.23
P	31.76	99.53 ± 0.20
Ca	72.80	98.93 ± 0.45
Mg	96.93	99.78 ± 0.07
Micro-nutrient		
Mn	80.43	99.52 ± 0.26
B	0.00	N/A
Cu	80.04	91.61 ± 11.7
Zn	94.20	86.85 ± 5.18

2.2. Nutrient Production Model Assumptions

Our objective for this model is to predict the nutrient recovery rate in drum screen effluent based on fish feed supplied over a given time. The following assumptions were used to develop this model:

1. A constant daily fish-feed rate is used;
2. The only discharge from the system is through the drum filter;
3. A microbial-mineralization treatment process is used to maximize plant availability of nutrients in the effluent by removing OC and TSS;
4. The nutrients in the water column occupied by fish and the system stay constant in a mature system with a constant feed rate and, therefore, do not affect mass quantification of the nutrients generated from the fish-feeding system that are collected from the drum filter discharge.

This model calculates the total mass of nutrients in a known mass of fish feed (from previous feed analysis) and the mass of plant-available nutrients collected in drum screen effluent that includes both solid and dissolved nutrients. The ratio of these two masses then defines the mass of fish-feed nutrients that become available for plant assimilation per kilogram of feed. Calculated macro-nutrients (N, P, Ca, and Mg) are reported as grams of plant-available nutrient in drum screen effluent per kilogram of fish feed, while calculated micro-nutrients (Mn, B, Cu, and Zn) are reported as milligrams of plant-available nutrient in drum screen effluent per kilogram of fish feed.

2.3. Daily Loading Rate Equations for Macro- and Micro-Nutrients

A nutrient-loading rate based on feed composition can be used to calculate either the total mass of each nutrient added into an aquaponic system each day or the ratio of grams of nutrient per kilogram of feed. After mass analysis of the specific feed, the loading rate for each macro-nutrient added into an aquaponic system can be calculated using Equation (1):

$$NLR_{macro} = \frac{composition\ \% * feed_{total}}{time} \tag{1}$$

where NLR_{macro} is the mass of a chosen nutrient added to the system each day in grams per day; $composition\ \%$ is the percentage of the total feed mass accounted for by the chosen nutrient; $feed_{total}$ is the total mass of feed in grams for which the chosen nutrient mass will be calculated; and *time* is the time interval in days during which all feed was administered.

After mass analysis of the specific feed, the loading rate for each micro-nutrient added into an aquaponic system can be calculated using Equation (2):

$$NLR_{micro} = \frac{\left(\frac{ratio_{mg\ nutrient:kg\ feed}}{1000}\right) * feed_{total}}{time} \tag{2}$$

where NLR_{micro} is the mass of a chosen nutrient that is added to the system each day in milligrams per day, $ratio_{mg\ nutrient:kg\ feed}$ is the milligrams of the chosen nutrient per kilogram of feed as reported in Tetreault et al. (2021), $feed_{total}$ is the kilograms of feed for which the chosen nutrient mass will be calculated, and *time* is the number of days over which all feed was administered [20].

2.4. Discharge Rate Calculations for Macro- and Micro-Nutrients in RAS Effluent

The total discharge rate for a chosen nutrient accounts for dissolved and particulate-bound fractions, and can be calculated using Equation (3):

$$NDR_{total}^{effluent} = \frac{[nutrient] * effluent_{discharge\ rate}}{1000} \tag{3}$$

where $NDR_{total}^{effluent}$ is the discharge rate for the sum of the aqueous and particulate-bound fraction of a chosen nutrient in milligrams per day; $[nutrient]$ is the sum of the aqueous and particulate-bound concentrations of the nutrient in the drum screen effluent in milligrams per liter; and $effluent_{discharge\ rate}$ is the volume of drum screen effluent generated by the system in liters per day.

The plant-available discharge rate for a chosen macro-nutrient from RAS drum- screen effluent can be calculated using Equation (4):

$$NDR_{plant\ available}^{effluent} = \left(\frac{\left(\frac{NDR_{total}^{effluent}}{NLR_{macro}}\right) * aqueous\ \%}{100}\right) * composition\ \% * 1000 \tag{4}$$

where $NDR_{plant\ available}^{effluent}$ is the plant-available production rate of a chosen macro-nutrient in RAS effluent in grams of nutrient per kilogram of feed; $NDR_{total}^{effluent}$ is the discharge rate for the sum of the aqueous and particulate-bound fraction of a chosen nutrient in milligrams per day; NLR_{macro} is the mass in grams of a chosen nutrient that is added to the system each day; $aqueous\ \%$ is the percentage of the nutrient's total concentration that is dissolved in the effluent; $composition\ \%$ is the percentage of the total feed mass accounted for by the chosen nutrient; and 1000 is the multiplier required to convert the results to grams of nutrient per kilogram of feed.

The plant-available discharge rate for a chosen micro-nutrient from RAS drum-screen effluent can be calculated using Equation (5):

$$NDR^{effluent}_{plant\ available} = \left(\frac{\left(\frac{NDR^{effluent}_{total}}{NLR_{micro}} \right) * aqueous\ \%}{100} \right) * ratio_{mg\ nutrient:kg\ feed} \tag{5}$$

where $NDR^{effluent}_{plant\ available}$ is the plant-available production rate of a chosen micro-nutrient in RAS effluent in milligrams of nutrient per kilogram of feed; $NDR^{effluent}_{total}$ is the discharge rate for the sum of the aqueous and particulate-bound fraction of a chosen nutrient in milligrams per day; NLR_{micro} is the weight in milligrams of a chosen nutrient added to the system each day; and $ratio_{mg\ nutrient:kg\ feed}$ is the mass (in milligrams) of the chosen nutrient per kilogram of feed as reported in Tetreault et al. (2021) [20].

3. Results

3.1. Daily Nutrient Loading Rates at KFRAG

The loading rates for macro- and micro-nutrients from fish feed in the KFRAG system per kilogram of feed are shown in Table 4 and were calculated using Equations (1) and (2) and the reported feed rate of 1300 g per day over a 72 h data-collection period.

Table 4. Nutrient loading rates from fish feed. The specific nutrient-loading rates for KFRAG based on 1300 g of feed per day were calculated using Equations (1) and (2) with data from Tetreault et al. (2021) [20]. These results were used to normalize data to grams of nutrient per kilogram of feed.

Nutrient	KFRAG Loading Rate (g/day)	Loading Rate (g Nutrient/kg Feed)
N	83.72	64.4
P	12.61	9.7
Ca	15.21	11.7
Mg	1.82	1.4
Mn	0.11934	0.0918
B	0.00767	0.0059
Cu	0.06045	0.0465
Zn	0.11648	0.0896

3.2. Daily Effluent Discharge Rates at KFRAG

The total discharge rate for macro- and micro-nutrients from the drum screen effluent at KFRAG was calculated using Equation (3) and data reported from Tetreault et al. (2021) [20]. Supplementation of K_2CO_3 and DTPA iron (III) salts at KFRAG prevented accurate calculation of K and Fe discharge rates directly from feed rates. The discharge rate and subsequent percentage of the loading rate that are wasted are shown in Table 5.

The plant-available discharge rates for macro- and micro-nutrients from the drum screen effluent at KFRAG were calculated using Equations (4) and (5) and data from Tetreault et al. (2021) [20]. These are dependent on nutrient solubility. The plant-available discharge rates for macro- and micro-nutrients from the untreated and microbially mineralized drum-screen effluent at KFRAG are shown in Table 6.

Table 5. Plant essential nutrient-discharge rate from KFRAG system drum screen based on a 1300 g per day feed rate. The percentage of the loading rate from fish that is discharged is also shown. Rates were calculated using Equation (3) and data from Tetreault et al. (2021) [20].

Nutrient	KFRAG Discharge Rate (g/day)	% of Loading Rate
Macro-nutrient		
N	9.533	11.4
P	0.342	2.71
Ca	1.420	9.34
Mg	1.173	64.5
Micro-nutrient		
Mn	0.011	8.94
B	0.000	0.0
Cu	0.010	16.5
Zn	0.0493	42.4

Table 6. The plant-available macro-nutrient (A) and micro-nutrient (B) discharge rates from KFRAG system drum screen. The discharge rates of untreated and microbially mineralized effluent are shown. Rates were calculated using Equations (4) and (5) and data from Tetreault et al. (2021) [20].

(A)	**Untreated Effluent**		**Post-Mineralization**	
Macro-nutrient	% of mass in aqueous fraction	Plant-available discharge rate (g nutrient/kg feed)	% of mass in aqueous fraction	Plant-available discharge rate (g nutrient/kg feed)
N	88.54	6.49	93.83	6.88
P	31.76	0.08	99.53	0.26
Ca	72.80	0.80	98.93	1.08
Mg	96.93	0.87	99.78	0.90
(B)	**Untreated Effluent**		**Post-Mineralization**	
Micro-nutrient	% of mass in aqueous fraction	Plant-available discharge rate (mg nutrient/kg feed)	% of mass in aqueous fraction	Plant-available discharge rate (mg nutrient/kg feed)
Mn	80.43	6.60	99.52	8.17
B	N/A	0.00	N/A	0.00
Cu	80.04	6.16	91.61	7.05
Zn	94.20	35.7	86.85	35.7

4. Discussion

4.1. Nutrient Recovery for Improved Aquaponic NUE

Despite the growing popularity of aquaponics, many practitioners struggle to achieve financial success [27–29]. A primary limitation to commercial success is the cost of nutrients from fish feed being significantly more expensive by mass than traditionally mined or synthetic fertilizer salts [30]. Production data from a farm-scale aquaponic system were used for preliminary model validation and showed that fractions of most plant-essential nutrients loaded into an aquaponic system from fish feed are discharged. Capturing and reusing the discharged nutrients could lower the cost of nutrients supplied by fish feed and improve NUE in aquaponics. As most of the nutrient mass is dissolved and available for plant uptake in RAS effluent prior to treatment, it is important to identify the essential role of microbial mineralization prior to reuse. A primary goal of this treatment is to remove OC. Excessive OC can consume dissolved oxygen, interfere with plant-nutrient uptake processes, and proliferate pathogenic bacteria in aquaponic and hydroponic systems [31–33]. Continued research on effluent treatment optimization for OC removal is required to further develop a nutrient bioeconomy in CEA.

4.2. Importance of N Recovery and Treatment Method Implications

Improved N management is essential for enhancing aquaponic NUE as it is required in greater mass than any other nutrient for plant growth and is a primary pollutant if discharged without treatment [4,34]. When applied to operating procedures at KFRAG, this model calculated that 11.4% of N loaded into the system was discharged at a rate of 64.4 g of N per kilogram of feed. No N loss was accounted for in this initial model, which would have to be refined on a specific system basis if more data on denitrification are to be collected. Loss of N during operation is expected but will be a system-specific number. Each user should determine this value for their system and adjust accordingly.

The selection of a mineralization method will alter N mass in the treated solution, as commonly used anaerobic processes can remove 85–90% of total nitrogen [20,35]. Aerobic mineralization could maximize recovery potential for reuse in plant production by retaining a greater percentage of the N mass. The average N assimilation rate of butterhead lettuce (*Lactuca sativa*), one of the most common aquaponic crops, from transplant into a system (<1 g) to harvest (150 g) has been calculated at 0.01837 g per day. This rate will result in the support of 54 plants per loaded gram of N assuming production is evenly divided into different growth stages [2]. The calculated plant-available N discharge rate from KFRAG was 6.88 g of N per kilogram of feed. If anaerobic mineralization resulted in 90% N mass lost, only 37 additional lettuce plants could be supported per kilogram of feed. Aerobic mineralization retains a greater N mass, which could influence treatment selection by supporting a greater number of plants. Beyond N retention, additional factors influencing treatment method selection can include the potential of biogas collection and reuse from anaerobic mineralization, and the added cost of constant aeration in aerobic mineralization [36]. While the relative importance and ease of calculating N in feed and plants make it a foundation for understanding nutrient dynamics, additional research on biogas production rates and assimilation rates of other nutrients is required for more precise modeling in aquaponics.

4.3. Micro-Nutrient Deficiencies in Aquaponics

Micro-nutrient deficiencies slow plant growth and prevent full maturation [32]. Aquaponic systems with nutrients supplied only from fish feed have resulted in micro-nutrient-deficient plants [37,38]. This model demonstrates that while plant-essential micro-nutrients are present in fish feed, none are loaded at a rate greater than 0.12 g per kilogram of feed. At 0.00767 g per kilogram of feed, B had the lowest loading rate from fish feed of all nutrients and was the only nutrient that was not present in the effluent. Rodgers et al. (2022) identified B deficiencies and slower growth in aquaponic basil (*Ocimum basilicum*) compared to hydroponic and supplemented aquaponic controls [37]. The supplementation of Fe is commonly practiced in aquaponics as fish feed contains a relatively small mass of Fe compared to plant requirements and these results suggest that similar B additions may be beneficial.

The minimal loading rate of other micro-nutrients is compounded by 8.94%, 16.5%, and 42.4% of the total Mn, Cu, and Zn mass, respectively, being discharged from the system. While the capture and reuse of these nutrients would increase aquaponic NUE and support more optimal growth conditions, it is still possible for micro-nutrient supply to be a limiting factor in aquaponics if growth projections are made from more readily supplied nutrients. Coagulant aids, both organic and inorganic, are effective in thickening RAS effluent into a more nutrient-dense sludge [39,40]. This practice has been primarily studied as a means to increase water reuse rates and reduce effluent volume. Future research on effluent thickening prior to treatment for reuse as a nutrient solution may provide opportunities for concentrating nutrient masses.

4.4. Treated Effluents as Hydroponic Nutrient Solutions

Multiple studies have assessed the effectiveness of microbially treated RAS effluent as a hydroponic nutrient solution [18,41–43]. Delaide et al. (2021), Ezziddine et al. (2021), and

Ahmed et al. (2021) each compared plant growth when fertilized with a treated RAS effluent and a standard hydroponic nutrient solution [18,42,43]. While Ahmed et al. (2021) found no statistically significant differences in growth between treatments, Delaide et al. (2021) and Ezziddine et al. (2021) reported lower growth rates and yields in plants grown with treated effluent vs. those grown with an inorganic solution, with the former study also reporting a lack of P, K, and micro-nutrients in the effluent [18,42,43]. Additionally, each of these studies was conducted with leafy greens. These results suggest that RAS effluent requires thickening or supplementation for increased nutrient concentration to be a comparable alternative to fully inorganic solutions, especially as differences in growth achieved between solutions may be greater in different crops that require a greater nutrient mass.

It is important to note that none of the studies cited above assessed the treated effluent as a supplementation to an existing aquaponic system; they only compared it directly to an inorganic solution. Following inorganic nutrient supplementation in the treated RAS effluent, Delaide et al. (2021) did achieve growth commensurate with a standard hydroponic solution [18]. Additional work on thickening as a means of increasing nutrient concentration is required if the effluent is to be used as the sole nutrient source; however, the treatment and reuse of effluent in an aquaponics system have the potential to supplement existing nutrients with nutrients from dissolved fish wastes that remain in the system and to limit effluent discharge.

5. Conclusions

The results attained from this model confirm that fractions of all plant-essential macro- and micro-nutrients, except B, assessed in this study are discharged in RAS effluent and represent an unutilized, naturally derived fertilizer source for hydroponics. Developing a capture and reuse effluent-management system has the potential to reduce RAS pollution and increase nutrient efficiency in hydroponics and aquaponics. This preliminary model can be used to calculate plant-available nutrient discharge rates unique to a specific system on a gram (or milligram) of nutrient per kilogram of feed basis, and can provide a foundation for managing a nutrient economy in CEA. Validation, application to additional systems, and precise accounting of system denitrification are required to improve model precision. Aquaponic practitioners can use these data to manage precise nutrient profiles for specific crops, reduce supplementation with synthetic fertilizer salts, and increase overall nutrient mass in a system to support a greater number of plants.

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Data Availability Statement: The tables and figures report the data generated in this study. Any data not reported in this study are available on request from the corresponding author. Data were not immediately made publicly available as they are being used in additional manuscripts not yet published.

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