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Combining hydroponic crop waste with algae treatment to lessen the effects of nutrient waste streams

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Research Article

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Abstract

Globally, controlled environment agriculture (CEA) is growing, yet little is understood about nutrient losses in these systems or how to lessen pollution that results. This project explores the possibility of using algae to clean effluent from hydroponically grown vegetables. The 4-layer nutrition film technology (NFT) vertical farming rack produced 132 heads of lettuce in total. The hydroponic system's waste was used to grow naturally existing algae. At every step of manufacturing, measurements were made of nitrogen (N), phosphorus (P), and other trace elements (Ca, Co, Cu, Fe, K, Mg, Mn, Mo, Ni, and Zn). Findings: The applied mineral nitrogen (N) and phosphorus (P) had an overall nutrient utilization efficiency (NUE) of 88.7% and 59.4%, respectively. The complete system NUE of N and P was 99.5% and 95.0%, respectively, after algal treatment of waste streams, greatly lowering waste headed for sewage. Large amounts of Ca, Cu, Fe, and Zn from the rooting sponges employed in this experiment were discovered to be ingested by the crops; these elements may have been made accessible by mineralization and the presence of a somewhat acidic fertilizer solution. The rooting sponge's overall waste production, which accounts for around 53% and 6% of the system's total N and P intake, raises concerns about the system's overall NUE. Conclusions: This research shows that using algae to remediate wastewater streams from controlled environment agriculture (CEA) techniques, including hydroponics, is effective and requires minimal work. In order to enhance the environmental credentials of new CEA systems, further efforts by academics and the CEA industry to better regulate nutrient streams are advised.

KEYWORDS

Vertical farming, nitrogen, phosphorus, controlled environment agriculture, and the circular economy

1 | INTRODUCTION

The two most crucial elements of very productive agricultural systems are probably the control of **water and nutrients**. In order to replenish the nutrients extracted from systems via harvested output, intensive food production need a continuous supply of nutrients. Approximately 161 Tg of nitrogen (N) and 17.1 Tg of phosphorous (P) are supplied to agricultural land worldwide each year as fertilizers (Yuan et al., 2018; Zhang et al., 2021). The majority of applied nutrients usually end up lost to the wider environment, with only a small fraction eventually consumed by humans, even though the nutrient use efficiency (NUE) of these applications varies greatly depending on numerous factors (e.g., crop type, environmental conditions, application rates, etc.). Over 80% of applied N and 25%–75% of applied P are thought to be lost in some manner into the environment when the whole chain is taken into account globally (Sutton et al., 2013). This leads to significant energy waste (such as the Haber-Bosch process) and the loss of limited resources (such as mined

sedimentary phosphorite and potash), in addition to raising the cost of fertilizer for food growers. Nutrient losses from agricultural systems have very detrimental effects on the ecosystem in addition to the financial cost. According to estimates, the planetary barrier for N is at least two times larger on a global scale (Fowler et al., 2013; Steffen et al., 2015). This indicates that, in terms of N, humanity's safe operating area in relation to the earth system has been gravely violated, with food production systems directly responsible for the bulk of this pollution. Nitrogen oxides (NO_x), nitrous oxide (N₂O), and ammonia (NH₃) are air pollutants that cause harmful N losses from food systems. As air pollutants, NH₃ and NO_x directly impact human health (e.g., Pozzer et al., 2017), but they also harm biodiversity by causing N deposition in delicate ecosystems (Payne et al., 2017). With almost half of human emissions directly linked to food production, N₂O is a strong greenhouse gas that contributes around 6% of the potential for global warming (Tian et al., 2019). In addition to air emissions, the majority of N and P losses from food systems find their way into natural aquatic bodies via leaching and runoff, which causes widespread eutrophication and serious harm to aquatic biodiversity and water quality (Malone & Newton, 2020). The combined effects of poor fertilizer application (N and P in particular) on human health and the environment may have significant financial implications that surpass the value of the crop produced (e.g., Van Grinsven et al., 2013). Compared to conventional farming practices, controlled environment agriculture (CEA) systems provide an alternative approach to nutrient management (e.g., van Delden et al., 2021). By using soilless growth techniques like hydroponics and aeroponic systems, CEA systems provide completely regulated waste streams, while traditional systems depend on the bulk delivery of fertilizers to exposed soils. Crops may be cultivated in inert medium in these closed systems (such as indoor or vertical farming), and nutrients stay in a recirculated solution that stays in the system until it is flushed (Rufí-Salís et al., 2020). Depending on the needs of the plants, fertilizer compounds are usually applied gradually throughout a crop cycle. In some situations, they might be recycled for a second crop cycle. Some of the additional elements will be used by the crops, but some salts will stay in the solution, and salinity will progressively increase. In addition to preventing the development of pathogens (such bacteria or algae), flushing of nutrient streams usually happens when the solution above a salinity threshold. Although treatment of waste from CEA systems is not currently common and waste is flushed directly into sewage systems after specific thresholds have been exceeded, growers have complete control over nutrient losses, so steps can be taken to improve NUE far beyond what is possible in conventional agricultural systems. Unlike leaching from traditional agricultural fields, sewage waste is usually industrially processed to eliminate contaminants before being discharged into the environment, although this processing has its own environmental effects. N₂O emissions may be significant when nitrogen is present (Law et al., 2012), and the removal of N and P from wastewater can be costly and energy-intensive (e.g., Karamati-Niaragh et al., 2019). Although the idea of creating a circular economy to cut waste in agricultural systems has been covered in many studies (e.g., Barros et al., 2020; Toop et al., 2017), CEA systems other than aquaponics seldom ever use it (e.g., Goddek et al., 2015; Shafahi & Woolston, 2014). Aquaponic systems circulate water in a closed system while using fertilizer waste from aquaculture systems—typically fish—to feed crops. Although individual systems' water efficiency and nutrient recycling may be improved in this way, the technologies' economic viability is sometimes limited, particularly when it comes to large-scale production. It is very difficult to maximize ideal productivity for both the hydroponic and aquaculture systems simultaneously due to limitations on nutrient contents (i.e., fertilizer concentration), pH, and environmental conditions of both systems (i.e., ideal crop conditions will harm the fish and vice-versa). Treating waste solutions separately, postflushing from the crop system but before release into sewage streams, is a more practical way to achieve a circular economy approach within commercial scale CEA crop production systems (such as vertical farming) that are likely to emerge in the upcoming decades. Algae development is one such method of treating waste streams without incurring exorbitant expenditures (Abdel-Raouf et al., 2012). Algae are more resilient than crops and may thrive in a range of environments. Microalgal biorefineries are thought to

have mostly positive environmental effects (such as carbon sinks), and they have the potential to produce a number of beneficial products, such as biofuels that have a far less environmental impact than fossil fuels (Deprá et al., 2018). The environmental effect of crop production may be lessened and a secondary product may be produced by cultivating algae using effluent from CEA systems. The nutrient dynamics in a hydroponic vertical farming system used to produce lettuce will be evaluated in this research, as will the algal treatment of waste solution that follows. The project is to demonstrate the potential of circular economy measures that might enhance the environmental credentials of future CEA systems and provide proof-of-concept for the efficacy of algae treatment of waste streams after crop production.

| METHOD

1.1 | Lettuce and algae growth

1.1.1 | Lettuce propagation

Three varieties of lettuce were grown from seed. 150 Root!t® peat propagation sponges (Hydrogarden; Coventry), a butterhead fairly (BF, supplier Enza Zaden), and a warpath iceberg (WI) (supplier both Thompson and Morgan) were soaked for 24 hours in a 6 L solution of deionized water with 18 ml of plant starter solution (Vitalink, Hydrogarden; Coventry, further details in Supporting Information). Before being placed to the hydroponic rack, the unabsorbed portion of this solution was kept in a refrigerator (see below). On April 17, 2019, 150 seeds (50 of each) were planted in the treated sponges. To promote proliferation, seeds were stored for nine days beneath a dark cover. The top 132 seedlings were chosen for transfer to the vertical rack, with a 90% propagation rate. 40 BF, 44 BA, and 48 WI seedlings were selected from this group. |Hydroponic lettuce production Seedlings were moved to a vertical farming rack using the VF5207 4-layer nutrition film method (NFT) (Figure 1, Hydrogarden; Coventry). This system was operated inside at a steady, regulated temperature of 20° C. After adding 80 liters of deionized water to the system, 200 milliliters of Vitalink HydroMax type A and type B fertilizer solutions (Vitalink, Hydrogarden; Coventry; more information in Supporting Information) were added, for a total of 400 milliliters. Additionally, the leftover starting solution from the sponge propagation was added (see above). To lessen the presence of pathogens in the system and provide the crops an oxygen supply, fifty milliliters of hydrogen peroxide solution (OxyPlus, 12%, Hydrogarden; Coventry) were introduced. The pH was raised from 2.9 to 6.5 by adding three milliliters of potassium hydroxide solution (pHup, Vitalink, Hydrogarden; Coventry). White Spectron T8 LED lights were programd to turn on every day between 7:00 AM and 22:00 PM, with 15-minute rest intervals every two hours. The nutritional solution was poured from the solution reservoir at a steady flow. Additional type A and type B fertilizer solutions were added throughout growth on May 10, 2019 (50 ml each), and May 20, 2019 (30 ml each). Every several days, water was added to the solution reservoir (Table 1). All lettuce was harvested on May 31, 2019.

FIGURE 1 (Left) Nine days after planting, seedlings were put in the 4-layer VF5207. (Right) Forty-four days after the seedlings were sown, lettuce was gathered.



TABLE 1 Dates of activities during hydroponic crop production and waste

treatment with algae						
Hydroponic run						
17/04/19	Seed propagation					
26/04/19	Rack transfer	200 (A + B) 18 (Starter)	76 4	5.73	2.1	
07/05/19			8	6.1	1.4	
10/05/19		50 (A + B)	15	5.2	1.5	
15/05/19			10	5.8	1.5	
17/05/19			20	6.2	1.3	
20/05/19		50 (A + B)		5.5	1.7	
31/05/19	Harvest			5.9	1.2	
Algae treatment						
19/06/19	Algae inoculation			5.8	1.1	
18/11/19	Algae filtration			6.9	0.7	

ate	Activity	Fertiliser applied (ml)	Water added (l)	pH
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Note: Following each solution addition, the pH and electro-conductivity (EC) of the solution are recorded. and the 60 L of leftover waste nutrient solution was put into 5 L bottles to be kept in a chilled area at 4° C. Yield of lettuce On May 31, 2019, 44 days after the seeds were sown, each lettuce was manually collected from the system. The stem was divided into the leaf and the roots by cutting it off at the base of the plant. Wet leaf mass and roots were weighed while still incorporated into the propagation sponge (combined weight). After that, the roots were taken out of the sponge and weighed independently. To determine the wet/dry mass ratio for each of the three varieties of lettuce, replicates (6) of both leaf and root mass were dried. Samples were dried for 48 hours at 60° C until their weight remained consistent. The dried samples were then ground via ball milling, and stored in sealed glass vials for further analysis. removed the bulk of the algae (volume depending on mass of algae). A further 400 ml of the sieved solution was then passed through 8 µm filter paper which captured the rest of the algae. Drying solution that had passed through the 8 µm filter paper showed that any residue in the solution was of a negligible mass (<0.01 g L⁻¹). Total algae mass for each container were calculated by determining the g L⁻¹ mass in both filtered fractions, and summing them.

1.2 | Nutrient analysis

1.2.1 | Colourimetry

Samples of nutrient solution were frozen immediately after collection and stored at -18° C until further processing up to 3 months later. Concentrations of NH⁺ and NO⁻ in the solutions were measured using 30 L of nutrient solution remained in the solution reservoir of the vertical rack after crop harvesting. This solution was transferred into 5 L transparent plastic bottles and kept in cold storage until 19/06/19. This provided 12 separate bottles of waste solution in which to carry out further experimentation. A solution of precultured algae had been prepared to inoculate the solution separately. This algae had propagated naturally in solution left in a glasshouse environment, and was chosen for use in this experiment for its robustness in the given conditions. The algae were predominantly spherical green algae of the chlorella type (Figure 2). Eight bottles of waste solution were selected to be kept in an external glasshouse, with exposure to outdoor air and direct sunlight. Five millilitres of the propagated algae solution was injected into three of these bottles of waste solution. A further five bottles of waste solution were left in the glasshouse without inoculation. The remaining four waste solution

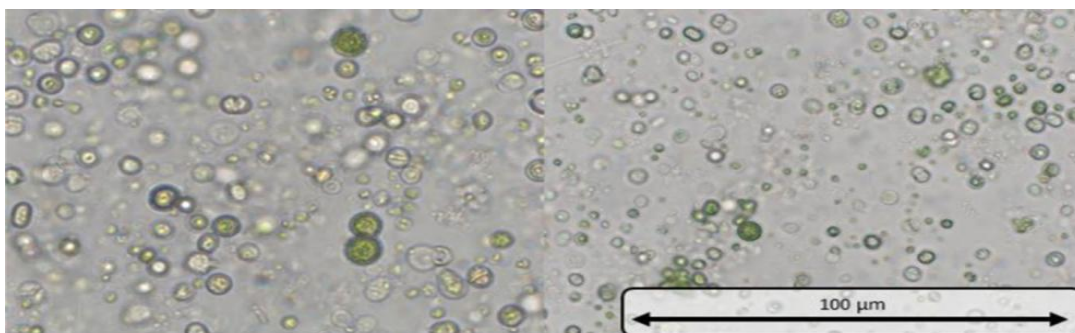
bottles were stored in a dark refrigerated room for the duration of the experiment as a control. The waste solution was left in the glasshouses for 5 months, with the occasional addition of deionised water to top up evaporation losses. On 18/11/19 the waste solution was filtered and the algae was removed and weighed. Filtration occurred in two stages. First, 2–3L of the algae solution was passed through a 250 μm stainless steel sieve which provide the relevant colorimetry reactions. Concentrations of solublereactive phosphorus (SRP; which is the bioavailable portion of dissolved P occurring predominantly as orthophosphate) were determined according to the acid-molybdenum-blue colorimetric method.

| Total carbon and nitrogen content (solids)

Ground plant and sponge material was dried at 40° C until a constant mass. Approximately 3 mg of material was weighed into a tin capsule (Elementx). The samples were analysed via elemental combustion using a FlashSmart2000 organic elemental analyser (Thermo Fisher Scientific) calibrated using atropine (Elementx).

1.2.2 | Total phosphorous content (solids)

Sulfuric acid and hydrogen peroxide were used to digest ground and dried plant material. A borosilicate glass test tube containing around 90 mg of material was filled with two milliliters of concentrated sulfuric acid (Fisher Scientific) and two milliliters of hydrogen peroxide (Fisher Scientific). If the



FI GUR E 2 Magnified photography of naturally occurring chlorella algae present in the waste solution.

If solutions did not become colorless, more hydrogen peroxide was added until they did. Using a heat block (Grant Instruments), the solution was heated to 160° C for two hours. Before analysis, the resultant solution was made up to 100 ml with deionized water and kept at 4° C. Using a Seal AA3 and technique G-103-93 (SEAL Analytical), phosphate concentrations were measured.

1.2.3 | ICP-MS trace element analysis

Nitric acid and hydrogen peroxide were used to digest dried and ground plant material. Two milliliters of Aristar grade concentrated nitric acid (VWR) were introduced to a borosilicate glass test tube containing around 100 milligrams of the substance. After 16 hours, 2 milliliters of hydrogen peroxide (Fisher Scientific) were gradually added. After two hours of refluxing at 120° C, the mixture was concentrated to about 1 ml. Using 2% (v/v), the final solution was produced up to 25 ml. Nitric acid of Aristar grade, kept at 4° C until analysis. Amplex were analyzed by ICP-MS using an Agilent 7900 (with octopole reaction system) in HMI mode, with argon gas flows of 0.70, 0.90, and 0.28 L min⁻¹ for nebulizer gas, auxiliary gas, and dilution gas, respectively. The RF forward power was 1600 W and the RF matching power was 1.8 V. The ISIS 3 integrated sample introduction system was used to transfer sample solutions into the Micro mist nebulizer. The skimmer and sample cones were composed of nickel, and the sample depth was 10.0 mm. In order to eliminate any polyatomic interference and minimize background noise, helium mode was used with a gas flow rate of 5.0 ml min⁻¹. Three duplicate runs were used for each sample, and the device was run in spectrum collection mode. 11B, 24Mg, 39K, 48Ca, 55Mn, 56Fe, 59Co, 60Ni, 65Cu, 66Zn, and 97Mo were the masses examined for each metal. Online, 45Sc, 103Rh, and 193Ir internal standards were introduced. Full quant mode analysis (one point per unit mass) was performed for

each mass. Merk multielement standard solution IV and internal standards made from single element standards (1000 mg L⁻¹ Sc, Rh, and Ir) diluted with 2% v/v HNO₃ (VWR-aristar grade) were used to create a variety of standards. The standard calibration graph was verified and any variation throughout the study was tracked using external certified reference materials SLRS-4 and SRM1640a.

2 | RESULTS

2.1 | Lettuce and algae harvest

Each lettuce plant had a different level of success, with a minimum fresh weight of 0.05 and a maximum of 87.12 g. With a total fresh harvest mass of 6.3 kg, the median fresh weight (leaf alone) of all 132 plants was 33.7 g. At the conclusion of the trial, 388.2 g of dry crop matter remained after the new crop's mean water content was 94%. WI outperformed the other two lettuce types in terms of total production (4.17 ± 0.88 g plant⁻¹), whereas the BF variety was subpar and some plants did not develop much beyond germination (1.18 ± 0.09 g plant⁻¹). The seeds' age—they had been stored for a year—might have contributed to this. The dry matter's N and P contents varied according to crop size, while the C content of the several types was very consistent (39%–42%). N and P content ratios were generally lower in bigger lettuces, but these nutrients were more concentrated in smaller plants (Supporting Information: Table S2). A total of 13.3 ± 1.9 g of N and 1.9 ± 0.3 g of P were absorbed by the harvested leaves of 132 lettuce plants from the NFT system. It was ineffective to manually separate the lettuce roots from the sponge material. Most of the tiny strands were still lodged in the sponge material, but the bigger roots could be removed. The total mass of all plants was 7.92 ± 1.32 g, with the average dry root mass retrieved by hand per plant (all kinds) estimated to be 0.06 ± 0.01 g. Before germination, the average dry weight of the sponges was 3.36 ± 0.19 ; after harvest, it was around 3.47 ± 0.13 . The total root mass in the system is calculated to be 22.44 ± 1.65 g, or around 4.5% of the total dry mass of the plants, assuming that this weight rise is solely caused by root development.

2.1.1 | Algae harvest

At the conclusion of the trial, the total mass of algae in waste solution containers that were given an algal spike was greater. The solutions' algal concentrations varied greatly, with dry mass ranging from 0.47 to 2.36 g L⁻¹. Compared to the dry mass of algae recovered from the unspiked solutions (0.87 ± 0.77 g L⁻¹), the mean dry mass of the spiked algal solution was 1.41 ± 1.1 g L⁻¹, or around 40% more. Both the spiked and unspiked solutions had comparable elemental compositions of the algae (Supporting Information: Table S2). A total of 84.6 ± 66 g of dry algae material would be predicted to be collected if all 60 L of waste solution was treated with algae spiking. Of this, 2.97 ± 2.33 g N and 0.33 ± 0.09 g P would be recovered from the solution prior to flushing. Elements differed significantly across samples for both the lettuce and algal species, according to trace metal analysis (Supporting Information: Table S3). The WI variety had considerably greater levels of calcium (Ca), molybdenum (Mo), and cobalt (Co) than the other two kinds, but significantly lower levels of potassium (K), magnesium (Mn), and zinc (Zn) (see Supporting Information: Table S3). Zn, iron (Fe), and copper (Cu) concentrations were much greater in the algae than in the leaf materials. The leaf harvest accounted for the majority of the total elemental intake, with algae absorbing very little of the nutrients K, Mg, Ca, Mo, and Ni.

| Carbon flow

At the start of the experiment, rooting sponges with a total of 228.8 ± 13.0 g C were introduced to the NFT system. Following harvest, rooting sponge and roots together weighed 225.8 ± 10.2 g C. This indicates that throughout lettuce development, the sponge material (132 plugs) lost around 3 g of carbon. Lettuce leaf materials yielded a total of 159.7 ± 22.3 g of carbon, and if all waste solution had been spiked with algae, an additional 35.9 ± 28.0 g of carbon would have been produced. 192.5 ± 39.4 g C is the predicted total net absorption of carbon in the system (Supporting Information: Table S4).

2.2 | Nutrient use efficiency

2.2.1 | Nitrogen and phosphorus

A total of 3.19 g of P and 15.02 g of N were fed to the system as mineral fertilizer throughout the experiment (Supporting Information: Table S5). When fertilizer and starting solution were taken into consideration, the initial concentrations of accessible N and P were 15.2 ± 0.2 mg $\text{NH}_4\text{-N L}^{-1}$, 111.3 ± 1.1 mg $\text{NO}_3\text{-N L}^{-1}$, and 27.3 ± 0.3 mg P L^{-1} . 60 L of waste solution with nutrient contents of 0.3 ± 0.2 mg $\text{NH}_4\text{-N L}^{-1}$, 60.3 ± 12.7 mg $\text{NO}_3\text{-N L}^{-1}$, and 12.3 ± 3.14 mg P L^{-1} were left over after harvest. While NO_3 and P concentrations were quite high (54% and 45% of initial, respectively), postharvest NH_4 concentrations were much lower than initial concentrations in the system (2% of original). NO_3 and P contents significantly decreased in both the spiked and unspiked containers during algal treatment and harvest. The algae treatment reduced the amounts of NO_3 and P in the algae-spiked containers by 99.93% and 89.35%, respectively (Supporting Information: Table S5). NH_4 concentrations, however, increased somewhat throughout the algae treatment, going from 0.3 ± 0.2 in the postharvest waste to 1.3 ± 0.9 and 1.5 ± 0.7 mg N L^{-1} in the spiked and unspiked algae containers, respectively. In this method, the comparatively inert organic materials employed as rooting medium also served as a source of nutrients that the plants have used. Traditionally, evaluating nutrient utilization efficiency (NUE) entails comparing crop outputs with fertilizer inputs. As a result, we display NUE as a percentage of the nutrients used from both the addition of fertilizer and rooting sponge as well as the nutrients used from the mineral fertilizer additions alone. Before germination, the rooting sponge had 17.03 ± 0.97 g N and 0.22 ± 0.05 g P, or around 53% and 6% of the system's total N and P inputs. Following harvest, the sponge material contained 16.4 ± 1.3 g N and 0.18 ± 0.05 g P, indicating that N and P were mineralized into the system throughout the experiment. Since separation would not take place prior to disposal in a commercial system, root materials are regarded as part of the sponge material for the purposes of tracking nutrient outputs. The system produced a lettuce harvest that contained 13.3 ± 1.9 g of nitrogen (Figure 3). If solely fertilizer input is taken into account, the crop N-NUE might be expressed as 88.7%. A total

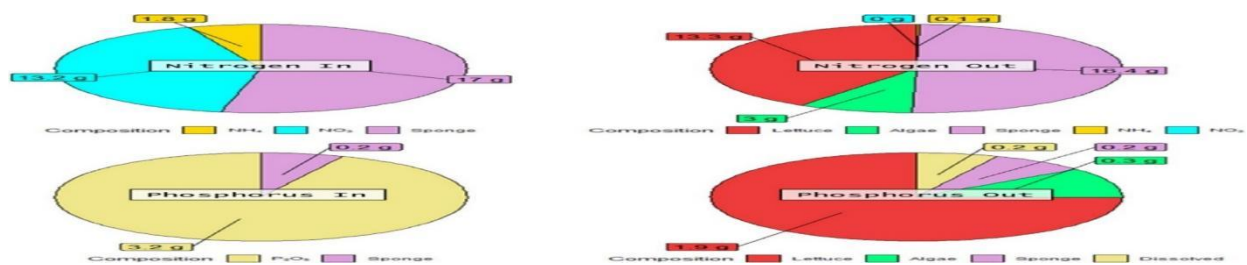


FIGURE 3 The system's total inputs of N and P (left) and its outputs after crop harvest and algal treatment (right). Root content is a component of sponge materials. If flushing had taken place after crop harvest, nutrient absorption via algae may be thought of as dissolved trash from the original system. If just fertilizer input is taken into account, 16.3 ± 3.0 g N was extracted from the system in the form of lettuce or algae, which constitutes a 108.5% N-NUE and may be deemed implausible. The complete system N-NUE, taking into account all N inputs, is 50.9%, while the crop N-NUE, taking into account all N inputs (fertilizer and rooting sponge), is assessed to be 41.6% (Table 2). A lettuce crop containing 1.9 ± 0.3 g P was taken out of the system (Figure 3). If fertilizer input is the sole factor taken into account, the crop P-NUE might be expressed as 59.4%.

TABLE 2 Inputs and harvested outputs of N and P Crop NUE is calculated using only lettuce crop output while system NUE combines both lettuce and algae harvests

Unit Mass		N	P
<i>Inputs</i>			
Fertiliser input	g	15.0 ± 0.2	3.2 ± 0.03
Root and sponge	g	466 ± 17.2	17.0 ± 1.3
			0.22 ± 0.05
<i>Harvests</i>			
Lettuce harvest	g	388.2 ± 53.7	13.3 ± 1.9
			1.9 ± 0.3
Algae harvest	g	84.6 ± 66.0	3.0 ± 2.3
			0.3 ± 0.2
<i>NUE fertiliser only</i>			
Crop NUE	%	88.7 ± 12.3	59.4 ± 8.7
System NUE	%	108.5 ± 19.8	68.1 ± 11.3
<i>NUE fertiliser and sponge</i>			
Crop NUE	%	41.6 ± 6.4	29.7 ± 4.6
System NUE	%	50.9 ± 9.9	34.1 ± 5.9

Note: NUE is computed both for fertilizer inputs alone and for the combination of fertilizer and rooting sponge inputs. 95% confidence intervals are shown with mean values. Nutrient usage efficiency, or NUE, is an acronym. 29.7% while taking into account all P inputs. The P-NUE of the whole system, including algae extraction, is around 34.1%. With just a little shift in N lost from the material throughout crop development, the net flow of N and P into and out of the system in the form of rooting sponge (and roots therein) does not alter much (Figure 3). Therefore, the fertilizer chemicals used supply most of the N and P found in the harvested crops. An estimated 3.62 g NO₃-N and 0.02 g NH₄-N, or 24.2% of the applied mineral N fertilizer, would have been flushed from the system after the harvest of the lettuce crop. This waste drastically decreases to only 0.08 g N, or 0.53% of the provided mineral N fertilizer, after algae extraction (spiked). The applied mineral fertilizer accounts for 94% of the system's P input. The NUE of the system is more in line with the traditional way of comparing crop harvest with applied fertilizer since the total mass of P in the rooting sponge does not vary much throughout crop growth and harvest. Following harvest, 0.74 g of P, or around 23.2% of the applied P mineral fertilizer, would have been removed from the system. This waste decreases to only 0.16 g P, or 5% of the provided P mineral fertilizer, after algae extraction (spiked) (Figure 3).

2.2.2 | Trace elements

The rooting sponge material's composition had a significant impact on the system's overall trace element intake (Table 3). When compared to merely the mineral fertilizer inputs, the rooting sponge's higher concentrations of K, Ca, Zn, Fe, and Cu significantly enhanced the lettuce crops' access to these nutrients (Table 3). When just fertilizer inputs are taken into account, this additional trace element availability significantly affects the NUE. Ca, Zn, and Cu NUE are all more than 200% of the applied mineral fertilizer. NUE is less than 100% when all trace metal inputs (fertilizer and rooting sponge) are taken into account.

TABLE 3 Inputs and harvested outputs of all trace elements

Element	Unit	Fertiliser input	Sponge input	Total input	Total harvest	NUE (% FI)	NUE (% total)
K	g	18.4 ± 0.2	27.4 ± 2.7	45.8 ± 2.7	60.3 ± 27	24.2 ± 10.9	18.4 ± 0.2
Mg	g	6.1 ± 0.1	1.9 ± 0.2	8 ± 0.2	1.06 ± 0.28	17.2 ± 4.5	13.2 ± 3.5
Ca	g	2.7 ± 0.03	7.1 ± 0.7	9.8 ± 0.8	9.51 ± 2.24	352 ± 83	97 ± 24
Mn	mg	202 ± 2	75 ± 9	277 ± 9	30.5 ± 7.6	15.1 ± 3.8	11.0 ± 2.8
Mo	mg	69.1 ± 0.7	0.2 ± 0	69.3 ± 0.7	2.6 ± 0.96	3.8 ± 1.4	3.8 ± 1.4
Zn	mg	25.1 ± 0.3	183.3 ± 32.1	208.4 ± 32.1	63.7 ± 18.0	254 ± 72	30.6 ± 9.8
Fe	mg	12.3 ± 0.12	32.2 ± 6	44.5 ± 6	30.4 ± 5.8	247 ± 47	68 ± 16
Co	mg	3.2 ± 0.03	0.4 ± 0.1	3.6 ± 0.1	0.71 ± 0.18	22.4 ± 5.7	19.8 ± 5
Cu	mg	3.2 ± 0.03	10.4 ± 1.8	13.6 ± 1.8	7.38 ± 1.51	232 ± 48	54.3 ± 13.2
Ni	mg	3.2 ± 0.03	1 ± 0.2	4.2 ± 0.2	0.73 ± 0.16	22.8 ± 4.9	17.4 ± 3.9

Note: Fertilizer inputs alone (% FI) and fertilizer and rooting sponge inputs combined (% Total) are taken into account when calculating NUE for both lettuce and algae. 95% confidence intervals are shown with mean values. Nutrient usage efficiency, or NUE, is an acronym. each trace element, demonstrating that throughout development in the NFT system, the crops are removing trace elements from the sponge. The range of trace element NUE was 11.0% of available Mn to 97.3% of available Ca (Table 3 and Figure 4). Compared to N and P, a comparatively substantial portion of the trace elements were lost in the final waste solution from the system that would be flushed into sewage, with the exception of Ca (Figure 4).

3 | DISCUSSION

3.1 | Nutrient use efficiency in CEA systems

showed the NUE of N, P, and other significant trace elements using the NFT methodology. There are few studies that demonstrate the NUE of controlled environment agriculture (CEA), and historically, a significant amount of research employing CEA systems has focused on conducting controlled experiments on conventionally farmed crops rather than determining the NUE of the growing techniques themselves (e.g., Chan-Navarrete et al., 2014; Nguyen et al., 2016; Ranjan et al., 2019). Direct comparisons are challenging since the data that is available about CEA systems is often quite specific to the system design and experiment settings. Research on salad crops in CEA systems has shown a broad range of N-NUEs, spanning two orders of magnitude (2% - 104%) (e.g., Consentino et al., 2022; Djidonou & Leskovar, 2019; Pennisi et al., 2019; Santamaria et al., 2002; Yang & Kim, 2020; Wang et al., 2021) (Table 4). It is more challenging to locate data for other components that are underrepresented in the literature. According to Pennisi et al. (2019), lettuce cultivated using a methodology that is relatively comparable to this research has the following NUEs: N (36%), P (36%), K (47%), Ca (43%), Mg (26%), and Fe (90%). In CEA agriculture, the NUE of different chemicals is crucial since it indicates waste and, therefore, the effects on the economy and ecology. Roughly 43% of the direct nitrogen supplied to agricultural soils worldwide is thought to reach harvests and biomass production for human and animal use, with the remainder being lost into the environment (Billen et al., 2013; Sutton et al., 2013). According to previous research (e.g., Benincasa et al., 2011; Di Gioia et al., 2017), the N-NUE of lettuce crops in soils ranges between 27% and 46%. Here, we show that the N-NUE in CEA systems may be

much greater than that of crops produced traditionally; in this instance, the effectiveness of applied mineral N fertilizer exceeded 88%. In comparison to traditional farming, where an overall P-NUE of 46% may be anticipated (e.g., Biswas Chowdhury & Zhang, 2021), a P-NUE of around 60% is likewise rather high. However, when the nutritional content of the (organic) rooting materials is included, CEA system efficiencies drastically decrease and, in this research, are comparable to conventional farming (NUE of 35%–48% N and 25%–34% P). Since nutrients are not maintained in soils for later harvests, direct comparisons between conventional and CEA systems are challenging due to the disposable nature of the rooting medium. This experiment demonstrates the potential effects on the final crop and emphasizes the significance of understanding the elemental makeup of rooting media ingredients. The result of this experiment contained all of the plant's root materials, even though the total quantity of N and P entering and exiting the system in the form of rooting sponge is comparatively identical. This shows that the plant has used at least part of the N and P in these elements for growth. In this system, the rooting sponge's trace element concentration was higher than that of the fertilizer used for K, Ca, Zn, Fe, and Cu. Because of this, the sponge rather than the fertilizer itself has produced the bulk of the Ca, Zn, and Cu extracted from the system. This research shows that determining the ratio of nutrients in the crop to the amount of mineral fertilizer given to the system is easier than determining NUE in the systems. In this research, the N-NUE of the system decreases from 88.7% to 41.6% if used rooting sponge is categorised as a waste product. The way used organic materials are handled has repercussions for the environment. The materials can be recycled and turned into a high-nutrient compost, but as they break down, greenhouse gases like CO₂ and N₂O will undoubtedly be released. In order to offer the best nutrients and circumstances for crop development, this research emphasises the need of taking these materials into account in future life cycle analysis (LCA) work and investigates the possibility of advantageous combinations between rooting materials and crops.

3.1.1 | Pollution mitigation in CEA systems

One method of reducing the environmental effect of industrial-scale CEA systems is algae treatment of effluent streams. We prevented algal contamination in this study by using a low concentration hydrogen peroxide solution, which would have gradually degraded away during the growing process, despite reports that growing algae in hydroponic systems can promote a beneficial symbiotic relationship between the plants and the algae (e.g., Léunić et al., 2022). This work has shown that N and P in waste streams may be considerably decreased prior to flushing by using a postharvest treatment of algae. As a result, less sewage treatment would be required, conserving energy and lowering N₂O emissions (via denitrification). The estimated (dry) mass of algae extracted from the waste solution was 84.6 g, or around 22% of the dry yield of lettuce. Only 0.53% and 5% of the applied mineral N and P fertiliser, respectively, were wasted overall. The ability of waste streams from hydroponic crop cultivation to generate a secondary algal product has been shown by this research; nevertheless, this method is not without complications. Because algae can adapt to the conditions, we purposefully allowed them to infect the garbage in our experiment. Contamination would need to be eliminated before a specific variety of algae could be cultivated in these systems (for example, to produce food or biofuel).

Source	Crop	N-NUE (%)	P-NUE (%)	Method
This study (fertiliser only)	Lettuce	76-101	51-68	NFT
This study (total inputs)	Lettuce	35-48	25-34	NFT
Santamaria et al. (2002)	Rocket	18-19		Chamber
Djidonou and Leskovar (2019)	Lettuce	22-95		NFT
Pennisi et al. (2019)	Lettuce	36-63	36-46	NFT
Yang and Kim (2020)	Lettuce, Basil	13-16	11-14	NFT
Wang et al. (2021)	Kale	63-104		NFT
Consentino et al. (2022)	Lettuce	3-20		Drip-fed

Note: The study's findings are included for comparison using the complete NUE taking into account the inputs of organic rooting sponges and the fertilizer-only NUE. NFT is for nutrient film technology, while NUE stands for nutrient usage efficiency. TABLE 4: Examples of literature describing the NUE of N and P in hydroponic systems inoculation (which may need a lot of energy) and nutrient conditions optimised. Since nitrate concentrations were almost nil by the time the algae were taken, it is very likely that nitrate restriction in this research prevented the algae from growing. Further research would be necessary to optimise efficiency and production in an integrated treatment system, since the precise economics and practicality of treating algae in an industrial context are beyond the purview of this specific feasibility experiment. Under the right circumstances, algae may develop exponentially quickly, but waste treatment usually causes imbalances and bottlenecks that restrict output (in this case, nitrate). In this work, we demonstrate the viability of using algae to clean wastewater, however turning this idea into a commercially viable use would need significant industrial development and probably some trial and error. The availability of artificial light, the timing of treatment, and the need for additional nutrients to boost production are all crucial factors that might drastically change the outcome of using algae therapy. Nutrient control is essential to maximising productivity if commercial algae production were to feed from CEA waste streams in the future. This might include utilising hydroponic waste as a feed supplement rather than the whole source, adding nutrients, or changing pH between crop and algae development phases.

3.1.2 | Other environmental impacts

Due to the consequences of climate change, water use efficiency (WUE) of agricultural goods is growing increasingly significant globally, and recycling water within CEA systems is becoming more crucial. 6.3 kg of fresh lettuce were produced in this trial using 132 L of water, yielding a WUE of around 21 L kg⁻¹ fresh weight. This is comparable to lettuce cultivated in other hydroponic systems (Barbosa et al., 2015; Graamans et al., 2018). The WUE of conventional-grown lettuce might vary from 80 to 1000 L kg⁻¹ fresh weight, depending on the local climate (e.g., Foteinis & Chatzisyseon, 2016; Gallardo et al., 1996; Rothwell et al., 2016). Previous research has shown that hydroponically produced lettuce uses a lot less water than conventional farming (Barbosa et al., 2015; Benke & Tomkins, 2017). This is caused by a number of factors, including decreased evapotranspiration and the system's control over recirculation (i.e., no soil leaching).

According to this research, algae treatment of wastewater has the ability to remove nutrients (i.e., contaminants) from the waste stream, offering both a useful function and a byproduct. Although it's uncertain how algae treatment will affect systems' WUE in the future, the aquaponics approach shows that symbiotic waste treatment across CEA systems is feasible. Algae treatment may provide a way to semi-purify waste streams CEA before water is discharged or transferred for a secondary use (such as irrigation) in areas with limited water supply and inadequate sewage infrastructure. Although there are several environmental benefits to hydroponic systems and CEA in general, the biggest drawback is still the systems' large carbon footprint and electricity usage. In this experiment, a water pump was used to circulate nutrients and artificial fluorescent lights (full spectrum, white). The system absorbed 192.5 ± 39.4 g C during the development of algae and the harvesting of lettuce. Although food production is often not taken into consideration since the great majority of goods would be released back into the environment after consumption, it is arguable that the system might be categorised as a carbon sink if it ran entirely on renewable energy. Practically speaking, the system is unlikely to function as a carbon sink if fertiliser production and consumables are taken into consideration. We did not directly assess greenhouse gas emissions from crop production in this experiment. It is plausible that nitrification and denitrification occurred in the rooting sponge and nutrient solution during lettuce development, even though methane (CH₄) synthesis is unlikely in the highly aerated circumstances. However, this was probably suppressed by the addition of hydrogen peroxide. The hydrogen peroxide would have been totally broken lowered throughout the period of algal growth, enabling microbial activity.

Although further investigation would be necessary to ascertain if hydroponic systems actually emit N₂O, NH₃, and NO_x, these emissions are probably insignificant. The environmental effects of hydroponic farming and CEA in general are greatly influenced by the choice of rooting media. The main reasons rooting medium is selected are its availability, affordability, water-holding capacity, and inert qualities. After usage, inorganic materials are often disposed of in landfills. The biodegradability of organic materials, like the rooting sponge utilised in this experiment, is a benefit, but the source of these materials is crucial. The peat used to make the rooting sponges in this experiment is imported from Canada. Because peatlands may serve as a long-term natural carbon sink and storage, extracting peat for compost is contentious. Recycled materials including cotton, tree bark, and coconut husk have all been successfully included into CEA systems (e.g., Arancon et al., 2014; Suvo et al., 2017) and might enhance the circular economy of waste products from other sectors. Utilising waste rooting materials for further food production might be one way to

improve the sustainability of CEA systems in the future. The nutrient-rich materials may be used directly in potting for drip-fed crops (such as tomatoes, bell peppers, etc.) or as a feedstock for mushroom farming, however composting is an option.

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