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RESEARCH ARTICLE

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Integration of algae treatment with hydroponic crop waste to reduce impact of nutrient waste streams

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Abstract

Introduction: Controlled environment agriculture (CEA) is expanding globally, but little is known about nutrient losses within these systems, or how to reduce subsequent pollution. This experiment investigates the potential to treat wastewater from hydroponically produced lettuce via the application of algae.

Materials and Methods: A total of 132 heads of lettuce were produced in the 4-layer nutrient film technique (NFT) vertical farming rack. Waste from the hydroponic system was used to cultivate naturally occurring algae. Nitrogen (N), phosphorus (P) and other trace elements (Ca, Co, Cu, Fe, K, Mg, Mn, Mo, Ni and Zn) were measured at each stage of production.

Results: Overall the nutrient use efficiency (NUE) of applied mineral nitrogen (N) and phosphorus (P) was 88.7% and 59.4%. After algae treatment of waste streams the full system NUE of N and P was 99.5% and 95.0% respectively, thus significantly reducing waste heading for sewage. It was found that the crops consumed large quantities of Ca, Cu, Fe and Zn from the rooting sponges used in this experiment, which may have become available due to mineralization and the presence of slightly acidic fertiliser solution. The overall waste produced by the rooting sponge is of concern regarding the full NUE of the system, accounting for approximately 53% and 6% of the total N and P input into the system.

Conclusions: This study highlights that treating wastewater streams from controlled environment agriculture (CEA) methods such as hydroponics with algae is successful and easy to achieve with little effort. Future efforts by researchers and the CEA industry to better manage nutrient streams is recommended to improve the environmental credentials of developing CEA systems.

KEYWORDS

circular economy, controlled environment agriculture, nitrogen, phosphorus, vertical farming

1 | INTRODUCTION

Nutrient and water management are arguably the two most important aspects of highly productive agricultural systems. Intensive food production requires a constant input of nutrients to replace those removed from systems in the form of harvested output. These nutrients are typically added in the form of fertilisers, with approximately 161 Tg of nitrogen (N) and 17.1 Tg of phosphorus (P) applied to agricultural land globally every year (Yuan et al., 2018; Zhang et al., 2021). While nutrient use efficiency (NUE) of these applications varies widely, depending upon many factors (e.g., crop type, environmental conditions, application rates, etc.), the majority of applied nutrients typically end up lost to the wider environment, with only a small fraction being eventually consumed by humans. Considering the full chain at a global scale, it is estimated that over 80% of N and 25%–75% of P applied end up lost in some way into the environment (Sutton et al., 2013). As well as increasing the fertiliser costs of food producers, this results in a large amount of energy wasted (e.g., the Haber–Bosch process) and the loss of finite resources (e.g., mined sedimentary phosphorite and potash).

As well as the economic expense, the environmental impacts of nutrient losses from agricultural systems is highly destructive. On a global scale, the planetary boundary for N has been estimated to be exceeded by at least a factor 2 (Fowler et al., 2013; Steffen et al., 2015). This means that for N, the safe operating space of humanity with respect to the earth system has been seriously transgressed, with the majority of this pollution as a direct result of food production systems. Harmful N losses from food systems occur as atmospheric emissions in the form of ammonia (NH_3), nitrous oxide (N_2O) and nitrogen oxides (NO_x). While NH_3 and NO_x are directly harmful to health as air pollutants (e.g., Pozzer et al., 2017), they also damage biodiversity by contributing to N deposition in sensitive environments (Payne et al., 2017). N_2O is a powerful greenhouse gas, contributing approximately 6% of global warming potential at a global scale, with over half of anthropogenic emissions directly associated with food production (Tian et al., 2019). As well as atmospheric emissions, losses of N and P from food systems largely end up in natural aquatic bodies due to leaching and run-off, which results in mass eutrophication and significant damage to aquatic biodiversity and water quality (Malone & Newton, 2020). Together, the human health and environmental impacts as a result of inefficient nutrient application (N and P in particular) can have large economic costs associated with them, exceeding the value of crop produced (e.g., Van Grinsven et al., 2013).

Controlled environment agriculture (CEA) systems offer a different approach to nutrient management than those of conventional farming methods (e.g., van Delden et al., 2021). While conventional systems rely on mass application of nutrients to exposed soils, CEA systems allow for fully controllable waste streams via the use of soilless growing methods such as hydroponics or aeroponic systems. In these closed systems (i.e., indoor or vertical farming), crops can be grown in inert media, and nutrients remain in a recirculated solution which does not leave the system until it is flushed (Rufí-Salís et al., 2020). Fertiliser compounds are typically added gradually during a crop cycle depending on plant requirements, and can be reused for a secondary crop cycle in some cases. While the crops will consume some of the added elements, certain salts in the solution will remain, and salinity gradually builds. Flushing of nutrient streams typically occurs when the solution exceeds a threshold of salinity, but also to mitigate pathogen growth (such as algae or bacteria). As growers have full control over nutrient losses, steps can be taken to improve NUE far beyond what is possible in conventional agricultural systems; however, treatment of waste from CEA systems is not currently widespread, and waste is flushed directly into sewage systems after certain thresholds have been exceeded. Sewage waste is typically industrially treated to remove pollutants before it is released into the environment (unlike leaching from conventional agricultural fields), but this processing is not without environmental impacts of its own. Removal of N and P from wastewater can be energy intensive and expensive (e.g., Karamati-Niaragh et al., 2019) and N_2O emissions can be substantial where nitrogen is present (Law et al., 2012).

The concept of developing a circular economy to reduce waste in agricultural systems has been discussed in numerous studies (e.g., Barros et al., 2020; Toop et al., 2017); however, it is rarely applied to CEA systems beyond aquaponics (e.g., Goddek et al., 2015; Shafahi & Woolston, 2014). In aquaponic systems, nutrient waste from aquaculture systems (usually fish) is used to feed crops, and water is circulated in a closed system. While it is possible to increase water efficiency and nutrient recycling of individual systems in this manner, there are often limitations on the commercial feasibility of the methods, especially when it comes to large-scale production. Limitations on nutrient contents (i.e., fertiliser concentration), pH and environmental conditions of both systems means that ideal productivity is extremely difficult to maximise for both the hydroponic and aquaculture system in tandem (i.e., ideal crop conditions will harm the fish and vice-versa). A more pragmatic approach to achieving a circular economy approach within commercial scale CEA crop production (e.g., vertical farming) systems that are likely to emerge in the coming decades is to treat waste solutions separately, postflushing from the crop system, but before release into sewage streams.

One such way in which waste streams could be treated without excessive costs is the growth of algae (Abdel-Raouf et al., 2012). Algae can grow in a variety of conditions and are hardier than crops. The environmental aspects of microalgal biorefineries are considered largely positive (e.g., carbon sinks), with the potential to create a variety of useful products, including biofuels with an environmental footprint significantly smaller than fossil fuels (Deprá et al., 2018). By using wastewater from CEA systems to grow algae, both the environmental impact of crop production can be reduced, and a secondary product may be generated. This study will assess the nutrient dynamics within a hydroponic vertical farming system used to grow lettuce, and the subsequent algal treatment of waste solution. The study aims to provide proof-of-concept of the effectiveness of algal treatment of waste streams postcrop production, and highlight the potential of circular economy steps that may improve the environmental credentials of future CEA systems.

2 | METHOD

2.1 | Lettuce and algae growth

2.1.1 | Lettuce propagation

Three lettuce types were propagated from seed. A butterhead fairly (BF, supplier Enza Zaden), all year round butterhead (BA) and warpath iceberg (WI) (supplier both Thompson and Morgan) 150 Root!t® peat propagation sponges (Hydrogarden; Coventry), were soaked for 24 h in a 6 L solution of deionised water with 18 ml of plant starter solution (Vitalink, Hydrogarden; Coventry, further details in Supporting Information). The unabsorbed remainder of this solution was stored under refrigerated conditions, until added to the hydroponic rack (see below). A total of 150 seeds (50 of each) were planted in the treated sponges on 17/04/19. Seeds were kept under a dark cover for 9 days to encourage propagation. The propagation rate was 90%, and the best 132 seedlings were selected for transfer to the vertical rack. Of these, 40 BF, 44 BA and 48 WI seedlings were chosen.

2.1.2 | Hydroponic lettuce production

Seedlings were transferred to be grown in a VF5207 4-layer nutrient film technique (NFT) vertical farming rack (Figure 1, Hydrogarden; Coventry). This system was run indoors, exposed to a constant controlled temperature 20°C. Eighty liters of deionised water was added to the system, to which 200 ml of Vitalink HydroMax type A and type B fertiliser solutions (Vitalink, Hydrogarden; Coventry, further details in Supporting Information) were added (400 ml total). The remaining starter solution from sponge propagation was also added (see above). Fifty millilitres of hydrogen peroxide solution (OxyPlus, 12%, Hydrogarden; Coventry) was added to reduce pathogens occurrence in the system, and provide an oxygen source for the crops. Three millilitres of potassium hydroxide solution (pHup, Vitalink, Hydrogarden; Coventry) was added to bring the pH up from 2.9 to 6.5. The nutrient solution was pumped from the solution reservoir at a constant flow, and lights (white, Spectron T8 LEDs) were set to come on daily between 07:00 AM and 22:00 PM, with 15 min resting periods every 2 h. During growth, further additions of type A and type B fertiliser solutions were made on 10/05/19 (50 ml each) and 20/05/19 (30 ml each). Water in the solution reservoir was topped up every few days (Table 1). Harvest of all lettuce occurred on 31/05/19,

FIGURE 1 (Left) Seedlings were placed in the 4-layer VF5207 9 days after planting. (Right) Lettuce was harvested 44 days after seeds were planted.

TABLE 1 Dates of activities during hydroponic crop production and waste treatment with algae

Date	Activity	Fertiliser applied (ml)	Water added (l)	pH	EC (mS cm^{-1})
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

Note: The solution pH and electro-conductivity (EC) are reported after each solution addition.

and remaining waste nutrient solution (60 L) was transferred into 5 L jugs for storage in a refrigerated room (4°C).

2.1.3 | Lettuce yield

Each lettuce was harvested from the system individually by hand on 31/05/19, 44 days after seeds were planted. The stem was cut at the base of the plant, and separated into two parts, the leaf and the roots. Leaf mass was weighed wet, and roots were weighed wet while still integrated with the propagation sponge (combined weight). Roots were then separated from the sponge and weighed separately. Replicates (6) of both leaf and root mass were then dried for each of the three lettuce types to establish a wet/dry mass ratio. Samples were dried at 60°C for 48 h until constant weight. The dried samples were then ground via ball milling, and stored in sealed glass vials for further analysis.

2.1.4 | Algae propagation

Sixty liters 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, 2–3 L of the algae solution was passed through a 250 µm stainless steel sieve which 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.

2.2 | Nutrient analysis

2.2.1 | 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_4^+ and NO_3^- in the solutions were measured using a SEAL AQ2 discrete analyser (SEAL Analytical) fitted with a cadmium coil. The widely used phenol-hypochlorite (for NH_4^+) and sulfanilamide (NO_2^- and NO_3^- after cadmium coil reduction) methods were used to provide the relevant colorimetry reactions. Concentrations of soluble reactive phosphorus (SRP; which is the bioavailable portion of dissolved P occurring predominantly as orthophosphate) were determined according to the acid-molybdenum-blue colorimetric method.

2.2.2 | 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 (Elemtex). The samples were analysed via elemental combustion using a FlashSmart2000 organic elemental analyser (Thermo Fisher Scientific) calibrated using atropine (Elemtex).

2.2.3 | Total phosphorous content (solids)

Ground and dried plant material was digested using a mixture of sulphuric acid and hydrogen peroxide. Approximately 90 mg of material was weighed into a borosilicate glass test tube and then 2 ml of concentrated sulphuric acid (Fisher Scientific) followed by 2 ml of hydrogen peroxide (Fisher Scientific) was added. If the

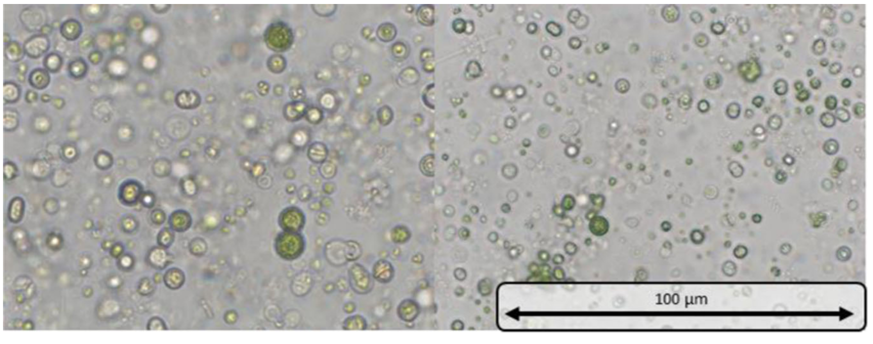

FIGURE 2 Magnified photography of naturally occurring chlorella algae present in the waste solution.

solutions did not turn colourless, additional hydrogen peroxide was added until it did. The solution was heated to 160°C for 2 h on a heat block (Grant Instruments). The resulting solution was made up to 100 ml with deionised water and stored at 4°C before analysis. Phosphate concentrations were analysed using a Seal AA3 following method G-103-93 (SEAL Analytical).

2.2.4 | ICP-MS trace element analysis

Ground and dried plant material was digested using a mixture of nitric acid and hydrogen peroxide. Approximately 100 mg of material was weighed into a borosilicate glass test tube and then 2 ml of Aristar grade concentrated nitric acid (VWR) was added. This was left for 16 h following this, 2 ml of hydrogen peroxide (Fisher Scientific) was slowly added. The mixture was refluxed at 120°C for 2 h then concentrated to approximately 1 ml. The resulting solution was made up to 25 ml with 2% (v/v) Aristar grade nitric acid and stored at 4°C before analysis.

Samples were analysed by ICP-MS using an Agilent 7900 (with octopole reaction system), using HMI mode and employing an RF forward power of 1600 W and RF matching power of 1.8 V, with argon gas flows of 0.70, 0.90 and 0.28 L min^{-1} for nebuliser gas, auxiliary gas and dilution gas, respectively. Sample solutions were taken up into the Micro mist nebuliser using the ISIS 3, integrated sample introduction system. Sample depth was 10.0 mm and the skimmer and sample cones were made of nickel. Helium mode, with a gas flow rate of 5.0 ml min^{-1}, was used to remove any polyatomic interference and to reduce background noise.

The instrument was operated in spectrum acquisition mode and three replicate runs per sample were employed. The masses analysed for each metal were ^{11}B, ^{24}Mg, ^{39}K, ^{48}Ca, ^{55}Mn, ^{56}Fe, ^{59}Co, ^{60}Ni, ^{65}Cu, ^{66}Zn and ^{97}Mo. Internal standards were added online ^{45}Sc, $_{103}Rh$ and ^{193}Ir. Each mass was analysed in full quant mode (one points per unit mass). A series of standards were prepared using Merk multielement standard solution IV and the internal standards prepared from single element standards (1000 mg L^{-1} Sc, Rh and Ir) diluted with 2% v/v HNO_3 (VWR-aristar grade) to give a range of standards. External certified reference materials SLRS-4 and SRM1640a were used to verify the standard calibration graph and to monitor any drift during the analysis.

3 | RESULTS

3.1 | Lettuce and algae harvest

The success of each lettuce plant varied, with a minimum and maximum fresh weight of 0.05 and 87.12 g, respectively. The median fresh weight (leaf only) of all 132 plants was 33.7 g, with a combined fresh harvest mass of 6.3 kg. The mean water content of the fresh crop was 94%, leaving 388.2 g of dry crop matter at the end of the experiment. Of the three lettuce varieties, WI performed best in terms of overall yield (4.17 ± 0.88 g $plant^{-1}$), while the BF variety was suboptimal and some plants failed to grow much beyond germination (1.18 ± 0.09 g $plant^{-1}$). This may have been due to the age of the seeds, which had been in storage for 1 year. While C content was relatively similar across the different varieties (39%–42%), the N and P content of the dry matter varied in line with the size of the crop. The larger lettuces typically had smaller ratios of N and P content, while these nutrients were more concentrated in the smaller plants (Supporting Information: Table S2). The total nutrient uptake of the harvested leaf of 132 lettuce plants from the NFT system was 13.3 ± 1.9 g of N and 1.9 ± 0.3 g of P.

Manual separation of the lettuce roots from the sponge media was not efficient. While the larger roots could be extracted, the majority of the smaller strands remained embedded in the sponge material. The average dry root mass extracted by hand per plant (all varieties) was estimated to be 0.06 ± 0.01 g, which amounted to a total mass of 7.92 ± 1.32 g for all plants. The average dry weight of the sponges after harvest was approximately 3.47 ± 0.13 each, compared with 3.36 ± 0.19 before germination. Assuming this weight gain is entirely due to root growth, the total root mass in the system is estimated to be 22.44 ± 1.65 g, approximately 4.5% of the total dry mass of the plants.

3.1.1 | Algae harvest

Containers of waste solution which received a spike of algae ended up with a higher overall mass of algae present at the end of the experiment. There was a large degree of variation in algal concentrations in the solutions, with dry mass ranging from 0.47 to 2.36 g L^{-1}. The mean dry mass of the spiked algae solution was 1.41 ± 1.1 g L^{-1}, approximately 40% higher than the dry mass of algae recovered from the unspiked solutions (0.87 ± 0.77 g L^{-1}). The elemental composition of the algae was similar in both the spiked and unspiked solutions (Supporting Information: Table S2). Assuming all 60 L of waste solution was treated with algae spiking, a total of 84.6 ± 66 g of dry algae material would be expected to be harvested, of which 2.97 ± 2.33 g N and 0.33 ± 0.09 g P would be extracted from the solution before flushing.

Trace metal analysis revealed that elements varied widely across samples for both the algae and lettuce varieties (Supporting Information: Table S3). Potassium (K), magnesium (Mn) and zinc (Zn) content of the WI variety was significantly lower than the other two varieties, while calcium (Ca), molybdenum (Mo) and cobalt (Co) was significantly higher (see Supporting Information: Table S3). The algae contained significantly higher concentrations of Zn, iron (Fe) and copper (Cu) when compared to the leaf materials. Total uptake of elements was dominated by the leaf harvest, with algal uptake of some nutrients (i.e., K, Mg, Ca, Mo and Ni) being negligible.

3.1.2 | Carbon flow

A total of 228.8 ± 13.0 g C was added to the NFT system in the form of rooting sponges at the beginning of the experiment. After harvest, a weight of 225.8 ± 10.2 g C was recovered in the form of rooting sponge and roots combined. This represents an overall loss of approximately 3 g C from the sponge material (132 plugs) during lettuce growth. A total of 159.7 ± 22.3 g of carbon was extracted in the form of lettuce leaf materials and a further estimated 35.9 ± 28.0 g C would have been generated if all waste solution was spiked with algae. The total net uptake of C in the system is estimated at 192.5 ± 39.4 g C (Supporting Information: Table S4).

3.2 | Nutrient use efficiency

3.2.1 | Nitrogen and phosphorus

Throughout the experiment, a total of 15.02 g of N and 3.19 g of P were added to the system as mineral fertiliser (Supporting Information: Table S5). The initial concentrations of available N and P were 15.2 ± 0.2 mg NH_4-N L^{-1}, 111.3 ± 1.1 mg NO_3-N L^{-1} and 27.3 ± 0.3 mg P L^{-1} (accounting for both fertiliser and starter solution). After harvest, 60 L of waste solution remained, with nutrient concentrations of 0.3 ± 0.2 mg NH_4-N L^{-1}, 60.3 ± 12.7 mg NO_3-N L^{-1} and 12.3 ± 3.14 mg P L^{-1}. Postharvest concentration of NH_4 were considerably lower compared to initial concentrations in the system (2% of initial), while NO_3 and P concentrations remained relatively high (54% and 45% of initial, respectively).

After algae treatment and harvest, concentrations of NO_3 and P dropped considerably in both the spiked and un-spiked containers. NO_3 and P concentrations in the algae spiked containers fell by 99.93% and 89.35%, respectively as a result of the algae treatment (Supporting Information: Table S5). However, NH_4 concentrations rose slightly during the algae treatment, increasing 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 un-spiked algae containers, respectively.

Traditionally, assessing nutrient use efficiency (NUE) involves comparing crop outputs with fertiliser inputs; however, in the case of this system, the relatively inert organic materials used as rooting media also acted as a source of nutrients which the plants have used. Therefore we present NUE as a % of both nutrients used from the mineral fertiliser additions alone, and nutrients used from the addition of fertiliser and rooting sponge. The rooting sponge contained a total of 17.03 ± 0.97 g N and 0.22 ± 0.05 g P before germination which represents approximately 53% and 6% of the total N and P inputs in the system. After harvest, the sponge material accounted for 16.4 ± 1.3 g N and 0.18 ± 0.05 g P, which highlights a mineralization of N and P into the system during the experiment. For the purpose of following nutrient outputs, root materials are considered part of the sponge material as separation would not occur before disposal in a commercial system.

A total of 13.3 ± 1.9 g N was extracted from the system in the form of lettuce crop (Figure 3). The crop N-NUE could be represented as 88.7% if only fertiliser input is considered. A total

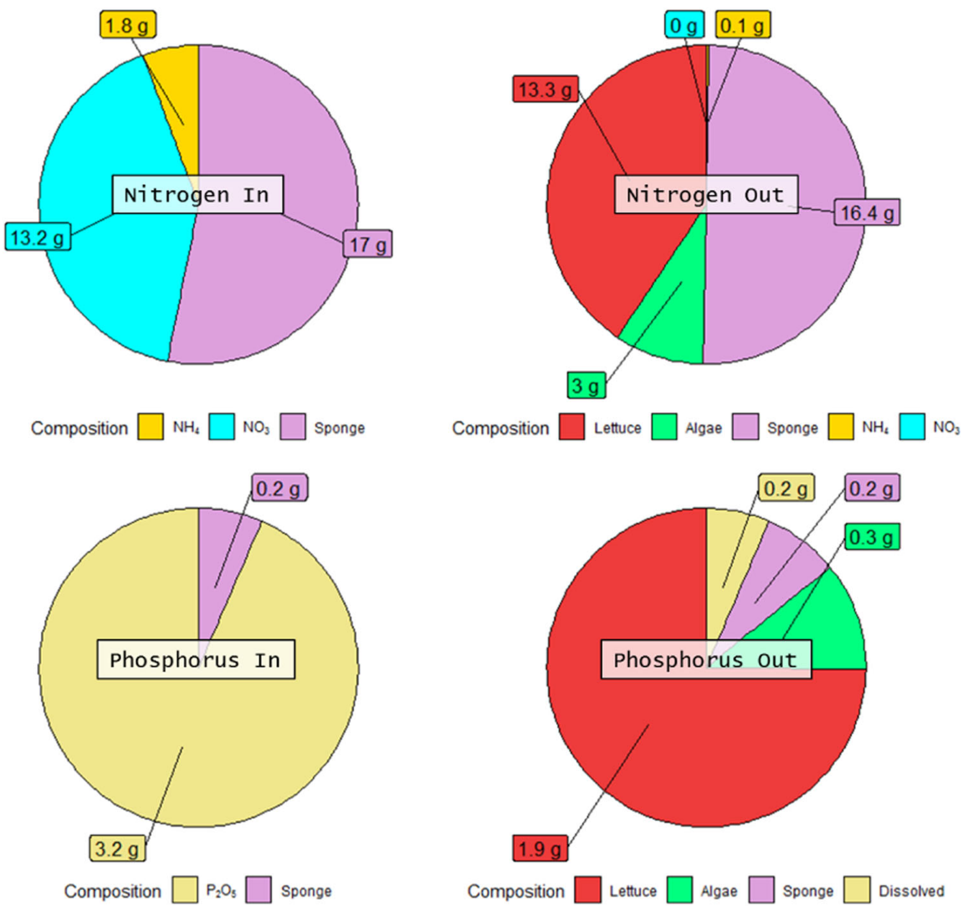

FIGURE 3 Total N and P inputs into the system (left), and outputs from the system after crop harvest and algae treatment (right). Sponge materials include root content. Nutrient extraction via algae can be assumed as dissolved waste from the initial system if flushing had occurred after crop harvest.

of 16.3 ± 3.0 g N was extracted from the system in the form of lettuce or algae which represents a 108.5% N-NUE if only fertiliser input is considered, which could be considered impossible. The crop N-NUE considering all N inputs (fertiliser and rooting sponge) is estimated to be 41.6%, while the full system N-NUE considering all N inputs is 50.9% (Table 2). A total of 1.9 ± 0.3 g P was extracted from the system in the form of lettuce crop (Figure 3). The crop P-NUE could be represented as 59.4% if only fertiliser input is considered and 29.7% considering all P inputs. Including algae extraction, the P-NUE of the full system is approximately 34.1%.

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
Inputs				
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
Harvests				
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
NUE fertiliser only				
Crop NUE	%		88.7 ± 12.3	59.4 ± 8.7
System NUE	%		108.5 ± 19.8	68.1 ± 11.3
NUE fertiliser and sponge				
Crop NUE	%		41.6 ± 6.4	29.7 ± 4.6
System NUE	%		50.9 ± 9.9	34.1 ± 5.9

Note: NUE is calculated separately considering only fertiliser inputs, and for both fertiliser and rooting sponge inputs combined. Mean values presented with 95% confidence intervals.

Abbreviation: NUE, nutrient use efficiency.

The net flow of N and P in and out of the system in the form of rooting sponge (and roots within) does not vary largely, with only a slight change in N, lost from the material during crop growth (Figure 3). The majority of N and P present in the harvested crops are therefore provided by the fertiliser compounds applied. After harvest of the lettuce crop, an estimated 3.62 g NO_3-N and 0.02 g NH_4-N would have been flushed from the system, representing 24.2% of the applied mineral N fertiliser. After algae extraction (spiked), this waste drops significantly to just 0.08 g N, or 0.53% of the applied mineral N fertiliser. Input of P into the system is dominated by the applied mineral fertiliser (94%). As the overall mass of P in the rooting sponge does not change significantly during crop growth and harvest, the NUE of the system is better aligned with the conventional method of comparing crop harvest with applied fertiliser. After harvest, 0.74 g of P would have been flushed from the system, representing approximately 23.2% of the applied P mineral fertiliser. After algae extraction (spiked), this waste drops to just 0.16 g P, or 5% of the applied P mineral fertiliser (Figure 3).

3.2.2 | Trace elements

The total input of trace elements into the system was heavily dependent on the content of the rooting sponge material (Table 3). The rooting sponge contained elevated concentrations of K, Ca, Zn, Fe and Cu, which drastically increased availability of these nutrients for the lettuce crops compared to just the mineral fertiliser inputs (Table 3). This extra availability of trace elements has a large impact on the NUE considering only fertiliser inputs. NUE of Ca, Zn and Cu all exceed 200% of applied mineral fertiliser. If all trace metal inputs are considered (fertiliser and rooting sponge), NUE is below 100% for

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: NUE of both lettuce and algae combined is calculated separately considering only fertiliser inputs (% FI), and for both fertiliser and rooting sponge inputs combined (% Total). Mean values presented with 95% confidence intervals.

Abbreviation: NUE, nutrient use efficiency.

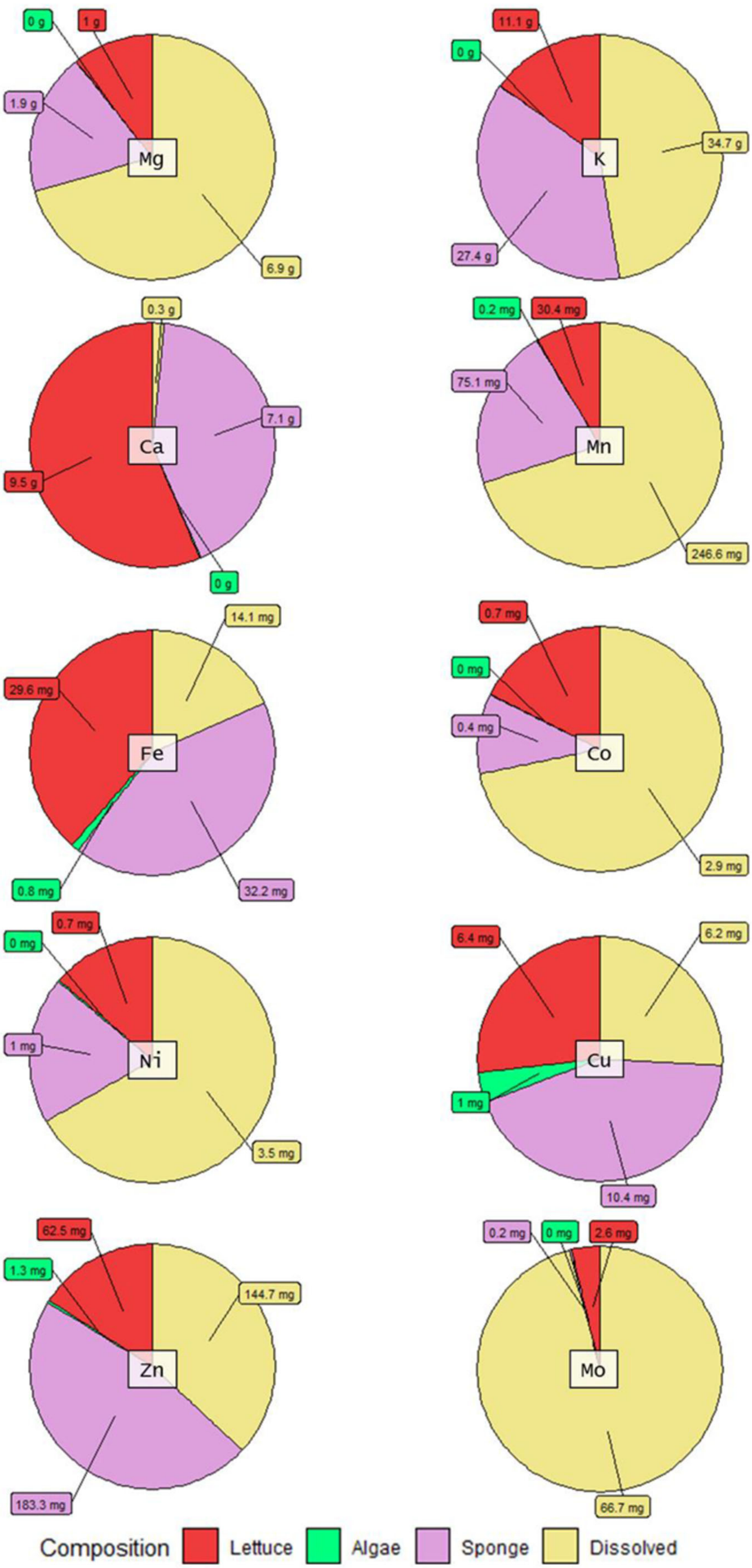

FIGURE 4 Outputs of trace elements from the system after crop harvest and algae treatment

each of the trace elements, showing that the crops are extracting trace elements from the sponge during growth in the NFT system. Trace element NUE varied from a low of 11.0% of available Mn, to 97.3% of available Ca (Table 3 and Figure 4). With the exception of Ca, a relatively large fraction of the trace elements were lost in the final waste solution from the system that would be flushed into sewage in comparison to N and P (Figure 4).

4 | DISCUSSION

4.1 | Nutrient use efficiency in CEA systems

In this experiment, we successfully grew lettuce crops using a stacked NFT system, and demonstrated the NUE of N, P and other important trace elements. Studies showing the NUE of controlled environment agriculture (CEA) are limited, and historically a large proportion of studies using CEA systems in research has been to carry out experimentation on conventionally farmed crops in controlled conditions rather than to establish the NUE of the growing methods itself (e.g., Chan-Navarrete et al., 2014; Nguyen et al., 2016; Ranjan et al., 2019). Where data exists regarding CEA systems, it is usually highly bespoke to the system design and conditions of the experiment, thus direct comparisons are difficult to make. Studies carried out on salad crops in CEA systems have shown a wide range of N-NUEs, covering 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). Data are more difficult to find for other elements to make comparisons, which are poorly represented in literature. Pennisi et al. (2019) report lettuce grown in a somewhat similar method to that in this study with the following NUEs: N (36%), P (36%), K (47%), Ca (43%), Mg (26%) and Fe (90%).

The NUE of various compounds in CEA agriculture is important as it is an indicator of waste, and thus also of economic and environmental impacts. It is estimated that globally, approximately 43% of the direct N applied to agricultural soils reach harvests and biomass production for (animal and human) consumption, while the rest is wasted to the wider environment (Billen et al., 2013; Sutton et al., 2013). This is supported by other studies that find N-NUE of lettuce crops in soils to be in the range of approximately 27%–46% (e.g., Benincasa et al., 2011; Di Gioia et al., 2017). Here we demonstrate that the N-NUE in CEA systems can be significantly higher than that of conventionally grown crops, in this case exceeding 88% efficiency of applied mineral N fertiliser. A P-NUE of approximately 60% is also relatively high compared to conventional farming for which an overall P-NUE of 46% may be expected (e.g., Biswas Chowdhury & Zhang, 2021). However, efficiencies of CEA systems drop significantly when the nutrient content of the (organic) rooting materials are taken into account, and in this study are on par with conventional farming (NUE of 35%–48% N and 25%–34% P). The disposable nature of the rooting media makes direct comparisons difficult between conventional and CEA systems as nutrients are not retained in soils for subsequent harvests.

This experiment highlights the importance of understanding the elemental composition of rooting medium materials, and shows the impact that this can have on the resultant crop. While the total amount of N and P entering and leaving the system in the form of rooting sponge in this experiment is relatively similar, the output included all of the root materials of the plant. This indicates that at least some of the N and P in these materials has been used by the plant to grow. Trace element content of the rooting sponge exceeded that of the fertiliser applied for K, Ca, Zn, Fe and Cu in this system. As a result, the majority of Ca, Zn and Cu harvested from the system has come from the sponge, rather than the fertiliser itself. This study highlights that NUE in the systems is not as straightforward as assessing the ratio of nutrients in the crop against that of mineral fertiliser applied to the system. When considering N in this study, if used rooting sponge is classified as a waste product, then the N-NUE of the system falls from 88.7% to 41.6%. The handling of used organic materials have knock-on effects in terms of environmental impacts. While the materials can be recycled and used as a high nutrient compost, this will certainly result in emissions of greenhouse gases such as CO_2 and N_2O as the material degrades. This study highlights that it is important to consider these materials in future life cycle analysis (LCA) work, and explore the potential for beneficial pairings between rooting materials and crops to provide the ideal nutrients and conditions for crop growth.

4.1.1 | Pollution mitigation in CEA systems

Algae treatment of waste streams is one way in which the environmental impact of industrial scale CEA systems can be mitigated. While it has been reported that growing algae in hydroponic systems can foster a beneficial symbiotic relationship between the plants and the algae (e.g., Žunić et al., 2022), we avoided algal contaminating in this study by applying a low concentration hydrogen peroxide solution, which would have slowly degraded away during the growing process. This study has shown that by using a postharvest treatment of algae, N and P in waste streams can be reduced significantly before flushing. This step would therefore reduce the need for sewage treatment, saving energy and reducing N_2O emissions (via denitrification). The (dry) mass of algae collected from the waste solution was estimated to be 84.6 g, which was approximately 22% of the dry yield of lettuce. Overall waste was reduced to just 0.53% and 5% of the applied mineral N and P fertiliser, respectively.

This study has proven that waste streams from hydroponic crop production are able to produce a secondary algal product; however, this process is not without complication. We deliberately allowed algae from the local environment to contaminate the waste in this experiment due to its adaptability in the circumstances. If a particular algae type was to be grown in these systems (i.e., for food or biofuel production), contamination would have to be removed before

TABLE 4 Examples literature reporting the NUE of N and P in hydroponic systems

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: Results from this study are added for comparison, using the fertiliser only NUE and the total NUE considering organic rooting sponge inputs.
Abbreviations: NFT, nutrient film technique; NUE, nutrient use efficiency.

inoculation (potentially energy intensive), and nutrient conditions optimised. In this study, the algae was almost certainly prohibited in growth due to nitrate limitation, as nitrate concentrations were close to zero by the time algae was harvested. The exact economics and practicalities of algae treatment in an industrial setting are beyond the scope of this particular feasibility experiment, and further investigation would be required to maximise efficiency and production in an integrated treatment system. While algae can grow exponentially fast in ideal conditions, waste treatment will typically result in imbalances and bottlenecks that limit production (nitrate in this study). We show in this study that it is feasible to treat wastewater with algae, but advancing this concept into a commercially feasible application would require considerable development in industrial settings, and likely some trial and error. Timing of treatment, availability of natural artificial light, and the requirement of further nutrients to increase production are all important aspects that could significantly alter the success of incorporating algae treatment. If commercial algae production was to feed from CEA waste streams in future, nutrient management is key to optimising productivity. This may mean adding nutrients or altering pH between crop and algae growth stages, using hydroponic waste as a feed supplement, rather than the whole source.

4.1.2 | Other environmental impacts

Water use efficiency (WUE) of agricultural products is becoming more important at a global scale due to the effects of climate change and recycling water within CEA systems is increasing in importance. In this study, 132 L of water was used to produce 6.3 kg of fresh lettuce giving a WUE of approximately 21 L kg^{-1} fresh weight. This is on par with lettuce grown in other hydroponic systems (e.g., Barbosa et al., 2015; Graamans et al., 2018). The WUE of lettuce grown via conventional methods is highly dependent upon local climate and can range from 80 to 1000 L kg^{-1} fresh weight (e.g., Foteinis & Chatzisymeon, 2016; Gallardo et al., 1996; Rothwell et al., 2016). It has been shown in previous studies that lettuce grown via hydroponics has a significantly smaller water footprint than conventional farming (Barbosa et al., 2015; Benke & Tomkins, 2017). This is due to multiple reasons, such as reduction in evapotranspiration and due to the control over the recirculation in the system (i.e., no soil leaching). This study has shown that algae treatment of wastewater has the potential to strip nutrients (i.e., pollutants) from the waste stream, thus providing a beneficial service as well as producing a by-product. The role that algae treatment can have on WUE of systems in the future is unclear, but symbiotic waste treatment between CEA systems is possible, as demonstrated by the aquaponics method. In regions where water availability is limited and sewage infrastructure is lacking, algae treatment may provide a means by which to semi-purify waste streams CEA before water is released or transferred for a secondary use (i.e., irrigation).

While hydroponic systems and CEA in general offers many environmental advantages, the key disadvantage remains the power consumption of the systems and the resultant high carbon footprint of production. In this experiment, artificial fluorescent lighting (full spectrum, white) was used as well as a water pump to circulate nutrients. In total, 192.5 ± 39.4 g C was absorbed by the system during lettuce harvest and algae growth. Arguably, if the system were to run on 100% renewable energy then the system could be classified as a carbon sink, though food production is generally not considered such as the vast majority of products will be released back into the atmosphere after consumption. Realistically, once fertiliser production and consumables are taken into account, the system is unlikely to act as a carbon sink. In this experiment, we did not measure greenhouse gas emission directly from crop production. While production of methane (CH_4) is unlikely in the highly aerated conditions, it is possible that nitrification and denitrification took place in the rooting sponge and nutrient solution during lettuce growth; however, this was likely inhibited by the addition of hydrogen peroxide. During the algal growth stage, the hydrogen peroxide would have been completely degraded, and so microbial activity could have occurred. Emission of N_2O, NH_3 and NO_x are all likely to be negligible from the system, though further research would be required to determine if hydroponic systems do produce these emissions.

Choice of rooting medium has a significant impact on the environmental consequences of hydroponic farming and CEA in general. Rooting media is chosen largely for its inert properties, water holding capacity, cost and availability. Inorganic materials are common, and sent to landfill after use. While organic substances such as the rooting sponge used in this experiment have the advantage of being biodegradable, the source of these materials is important. The rooting sponges used in this experiment are made from peat, extracted from Canada. Extracting peat for compost is controversial due to the ability for peatlands to act as a long-term natural sink and store of carbon. Recycled materials such as coconut husk, tree bark, and cotton (e.g., Arancon et al., 2014; Suvo et al., 2017) have all been used with success in CEA systems and may improve the circular economy of waste products from other industries. Improving sustainability of CEA systems in future may involve using waste rooting materials for further food production. Composting is possible, but the nutrient loaded materials may be suitable for direct use in potting for drip-fed crops (e.g., tomatoes, bell peppers, etc.) or as a feedstock for mushroom farming.

5 | CONCLUSIONS

This study has shown that waste streams from hydroponic lettuce production can be treated with algae production to significantly lower the nitrogen (N) and phosphorus (P) waste generated. This additional step prevents the downstream environmental impacts as a result of water treatment requirements, as well as producing a potentially useful by-product. Overall the N-NUE (88.7%) and P-NUE (59.4%) of the hydroponic system was relatively high in terms of fertiliser applied, but care must be taken when assessing NUE where rooting materials are present in the system. While algae treatment reduced N and P in wastewater to just 0.53% and 5% of the applied mineral fertiliser, respectively, the waste rooting sponge contained approximately 53% and 6% of the total N and P input into the system. This study highlights the importance of understanding all nutrient flows in CEA systems, which are entirely dependent upon the grower to provide and control all required nutrients, as there is no soil present in the system. Future system development should take nutrient flows into account, and where possible design systems which allow for waste recycling and reuse to minimise environmental impacts. Due to its controlled nature, CEA has the ability to drastically improve sustainable food production; however, this is not currently an industry priority. We recommend that CEA system designers consider the circular economy and incorporate an integrated system CEA approach in future industrial scale operations to improve economic and environmental performance of systems.

AUTHOR CONTRIBUTIONS

Nicholas Cowan conceptualised the project and was primary author of the manuscript. Stella White, Justyna Olszewska and Anne Dobel carried out measurements and analysis throughout the project work and contributed to data analysis. Gavin Sim and Lorna Eades prepared samples and carried out analysis of C, N, P and trace elements. Ute Skiba had oversight of the project and all authors contributed to the manuscript

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CONFLICT OF INTEREST

The author declares no conflict of interest.

DATA AVAILABILITY STATEMENT

Data will be made available on the Environmental Information Data Centre (EIDC) after publication.

ETHICS STATEMENT

The authors confirm that they have adhered to the ethical policies of the journal.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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