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Comparative assessment of commercially produced cow manure, frass, and cucumber leaf digestates as fertilizers for hydroponically grown basil

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ABSTRACT

The increasing demand for sustainable food production necessitates nutrient management strategies that reduce dependence on inorganic fertilizers. This preliminary study assessed the comparative effects of frass, cucumber leaf, and cow manure digestates supplemented with inorganic fertilizers on hydroponically grown basil. A randomized factorial design was used to evaluate plant growth, yield, and nutrient use efficiencies. Fertilizer treatments comprising 33% frass digestate, 33% cucumber leaf digestate, and 100% cow manure digestate produced statistically similar ($p > 0.05$) basil plant height and fresh and dry biomass yields. However, nutrient use efficiencies differed significantly ($p < 0.05$) between treatments. Cucumber leaf digestate recorded the highest nitrogen, phosphorus, and potassium use efficiencies, exceeding frass digestate by 26.5%, 156.1%, and 71.4%, respectively. Compared to cow manure digestate, cucumber leaf digestate improved nitrogen, phosphorus, and potassium use efficiencies by 59.1%, 162.5%, and 61.5%, respectively. These findings demonstrate that agricultural waste-derived digestates, particularly cucumber leaf digestate, can enhance nutrient use efficiency while maintaining yield, thereby offering potential to reduce inorganic fertilizer inputs and improve sustainability in controlled-environment food production.

1. Introduction

Greater food production capacity is needed as the global population continues to grow [1]. Chemical fertilizers have contributed to nearly a 50% increase in food production and have supported progress toward self-sufficiency for food in many countries [2,3]. However, excessive reliance on inorganic fertilizers poses significant environmental risks, including groundwater contamination, soil acidification, eutrophication, and greenhouse gas emissions [4–7]. The primary challenge facing agricultural production is to feed a growing population with limited resources, while avoiding or minimizing detrimental effects on environmental integrity [8]. One solution to ensuring a consistent food supply in a rapidly changing world is implementing integrated nutrient management (INM) practices.

Integrated nutrient management (INM) offers a strategy to address this challenge by combining organic, inorganic, and biological nutrient sources in an economically and ecologically balanced manner [9]. The primary objective of INM is to optimize both the quality and quantity of nutrients supplied to crops to enhance uptake efficiency and productivity [10,11]. INM has been shown to increase yields by 8 –150% in crops such as rice, maize, millet, groundnut, and sunflower [12–15], while also reducing dependence on costly chemical fertilizers [10].

Most INM research has been conducted under soil-based field conditions research [11,16,17]. Comparatively little attention has been given to the application of INM principles in hydroponic systems, where nutrient delivery dynamics differ fundamentally from soil environments. Although hydroponics is increasingly used for fruits, vegetables, herbs, and ornamental crops in both domestic and commercial settings [18], and offers advantages such as year-round production, higher yields, improved crop quality, and provides a better return on investment [18,19], the performance of waste-derived digestates as nutrient sources in these systems remains insufficiently understood. In particular, limited research has evaluated agricultural or organic waste digestates as partial substitutes for conventional hydroponic nutrient solutions [20,21], and examined their effects on nutrient use efficiency.

This preliminary study assessed the comparative effects of cow

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manure, frass, and cucumber leaf digestates supplemented with inorganic nutrients on hydroponically grown basil. We hypothesized that differences in digestate nutrient composition would maintain comparable basil growth and yield across treatments but results in significant differences in nutrient use efficiencies.

2. Materials and methods

2.1. Plant material and growing conditions

This study was conducted in a controlled environment plant propagation room at Circulus Agtech Inc. (Montreal, Quebec, Canada; 45.5428N and 73.6525 W). Basil seeds (*Ocimum basilicum* cv. Anise; Heirloom Seeds, Montreal, Quebec, Canada) were germinated for 21 d in rockwool and a modified Hoagland's solution, 0.25 x Hoagland solution “A”, “B” and “C” [22]. The seeded rockwool was placed in a polypropylene tray under a light emitting diode (LED) array (5000K; U Technology Corporation, Calgary, Canada) with an intensity range of 200 – 220 μmol m^{-2} sec^{-1}, measured using a light meter (SPQA-4849, LICOR Biosciences, Lincoln, NE, USA). Air temperature, relative humidity (RH), and vapor pressure deficit (VPD) in the germination room were maintained at 21 ± 1 °C, 65 ± 5 %, and 0.87 ± 0.07 kPa, respectively. After germination, consistently sized 3-week-old seedlings (approximately 6 cm tall) were transplanted to an ebb and flow system in the same plant propagation room with an 18/6 h light/dark photoperiod for 42 d (Fig. 1). Each ebb and flow unit comprised a 150-L hydroponic system barrel containing the experimental nutrient solutions and a pump (Hydrotek Hydroponics, Mirabel, Quebec, Canada). The air temperature, RH, and VPD in the plant propagation room were maintained at 29 ± 1 °C, 55 ± 5 %, and 1.83 ± 0.42 kPa, respectively. The environmental CO_2 in the growth room was measured with an air quality monitor (LC-1038, Langkou, Shandong, China) and ranged between 400 and 470 ppm. The initial and final nutrient solution temperatures were 24.1 ± 0.4 °C and 25.6 ± 0.2 °C, respectively, measured with a handheld device (HANNA Instruments, Laval, Quebec, Canada). White LEDs (6500 K; Barrina, Zhongshan Mingcai Lighting Technology Co., Ltd., Guangdong, China) were the lighting source, with an intensity range measuring 600 – 800 μmol m^{-2} sec^{-1}.

2.2. Experimental design and treatments for *Ocimum basilicum*

The frass digestate (FD), cucumber leaf digestate (CLD), and cow manure digestate (CMD) used in this study were produced using the Circulus System (Circulus Agtech Inc, Montreal, Quebec). Briefly, batches of cucumber leaf, frass, and cow manure mixed with water (1200 L per batch) and subjected to mechanical mixing and oxygenation for 4 d at room temperature during a mineralization phase. Batches were transferred into a biofilter after the ammonium-nitrogen and nitrate-nitrogen reached concentrations of 57.6 mg L^{-1} and 14.0 mg L^{-1}, respectively, measured by Vernier Ion-Selective Electrodes (Vernier, Markham, Ontario, Canada). Alkalinity, pH, EC, dissolved oxygen, ammonium concentration, and nitrate concentrations were closely monitored and adjusted to provide optimal conditions for nitrifying bacteria. When the nitrate concentration reached its peak (823.4 mg L^{-1}), the solution was transferred into the separation system for clarification, subsequent filtration, and collection, resulting in the CLD, FD, and CMD that was for experimentation.

A completely randomized experimental design was adopted, consisting of six plants (n = 6) in each treatment group: 1) FD (33% v/v) supplemented with 80 mg L^{-1} nitrate-nitrogen, 40 mg L^{-1} magnesium, and 114.5 mg L^{-1} calcium; 2) CLD (33% v/v) supplemented with 100 mg L^{-1} nitrate-nitrogen, 30 mg L^{-1} phosphorus, 40 mg L^{-1} magnesium, and 143.1 mg L^{-1} calcium; and 3) CMD (100% v/v) supplemented with 80 mg L^{-1} nitrate-nitrogen and 114.5 mg L^{-1} calcium (CMD) (Table 1). Supplemental fertilizer sources were as follows: KNO_3 (Haifa-Group, Matam-Haifa, Israel), $Ca(NO_3)_2{*}4H_2O$, KH_2PO_4, $MgSO_4$, and $(NH_4)_2HPO_4$ (Fisher Scientific, Ottawa, Ontario, Canada). All treatments were provided with 0.5 x (half-strength) Hoagland solution ‘B’ (boron, manganese, zinc, copper, and molybdenum) and ‘C’ (iron and ethylene diamine tetraacetic acid) as reported previously [22]. The initial pH of the nutrient treatments was adjusted to 6.0 ± 5 with either 1 M H_2SO_4 or 1 M NaOH as needed. The treatments' pH and electrical conductivity (EC) were measured before and after treatments using handheld pH and EC meters (HANNA Instruments, Rhode Island, USA). The initial and final pH range for the fertilizer treatments was 5.8 – 5.9 and 6.1 – 6.6, respectively, while the initial and final EC range for the treatments was

Table 1
Fertilizer treatments.

Treatment codes	FD	CLD	CMD
Frass digestate (% v/v)	33%	-	-
Cucumber leaf digestate (% v/v)	-	33%	-
Cow manure digestate (% v/v)	-	-	100%
Inorganic nutrient component	Nitrate-nitrogen (80 mg L^{-1}); Magnesium (40 mg L^{-1}); and Calcium (114.5 mg L^{-1})	Nitrate-nitrogen (100 mg L^{-1}); Phosphorus (30 mg L^{-1}); Magnesium (40 mg L^{-1}); and Calcium (143.1 mg L^{-1})	Nitrate-nitrogen (80 mg L^{-1}) and Calcium (114.5 mg L^{-1})

Inorganic nutrients were supplemented to each digestate solution to achieve comparable target nutrient concentrations appropriate for hydroponic basil production.

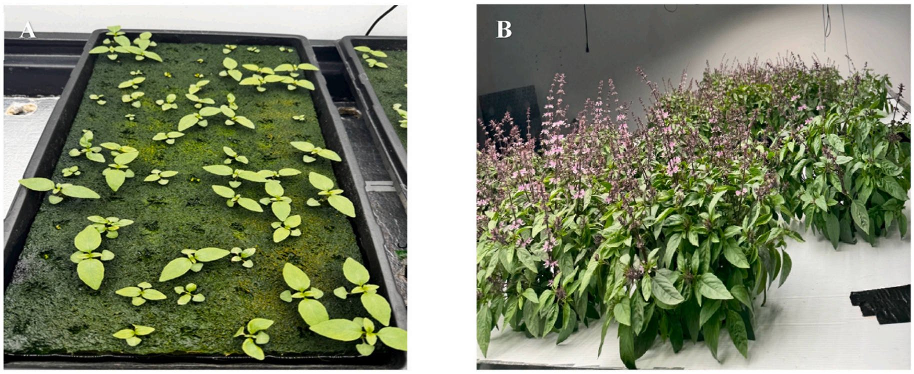

Fig. 1. Basil plant seedlings in rockwool before transplant into the experimental ebb and flow systems (A) and basil plants at harvest (42 d after transplant) (B).

2.2 – 2.9 mS cm^{-1} and 2.7 – 4.7 mS cm^{-1}, respectively (Supplementary Fig. S1). Fertilizer treatment samples (200 mL) were sent to SGS Canada Inc., (Guelph, Ontario, Canada) for elemental analyses (Table 2).

Photosynthetic photon flux density (PPFD) at each plant location was determined at the beginning, between, and at the end of the experimental runs using a light meter (SPQA-4849, LICOR Biosciences, Lincoln, NE, USA) as described previously [23]. Light mapping ensured that each basil plant received consistent PPFD during growth and between replicated runs.

2.3. Basil plant growth parameters

Plant height (cm) was measured from the top of the rockwool to the top of the apical leaf of the basil plant. Fresh root and shoot mass were measured using a Valor 3000 Xtreme Portable Scale (ITM Instruments, Quebec, Canada). To determine dry mass, biomass was dried in an Isotemp Oven (Fisher Scientific, Quebec, Canada) at 65 °C for 48 h. Nutrient use efficiency was calculated from the ratio of crop yield (dry biomass yield) to the total nutrients supplied [24]. Healthy, mature leaves (randomly selected, avoiding the bottom old leaves) were used to determine the amounts of chlorophyll *a and b* with previously reported methodology [25] using Equations (1) and (2):

$$\text{Chlorophyll}_a = 12.21A_{663} - 2.81A_{646} \tag{1}$$

$$\text{Chlorophyll}_b = 20.13A_{646} - 5.03A_{663} \tag{2}$$

Where A_{663} and A_{646} are the absorbance (A) readings at 663 nm and 646 nm, respectively.

2.4. Statistical analysis

This study employed a completely randomized experimental design with six plants in each treatment group, and the experiment was repeated twice, resulting in a total of 12 plants per treatment. Data were statistically analyzed using JMP software (JMP 4.3, SAS Institute Inc.) to evaluate the effect of the treatments on plant growth parameters. Mean values and standard deviation were determined with Microsoft Excel (Microsoft, Redmond, Washington, USA). A one-way ANOVA was conducted at a 95% confidence level ($p < 0.05$), and differences among treatment means were determined using the Tukey-Kramer significant difference test.

Table 2

Mineral composition of the experimental fertilizer treatments comprising frass digestate (FD), cucumber leaf digestate (CLD), and cow manure digestate (CMD) and supplemental inorganic chemicals.

Fertilizer component	Treatments		
	FD	CLD	CMD
Digestate (% v/v)	33	33	100
Nitrate nitrogen (mg L^{-1})	218.5 ± 16.3	192.5 ± 9.2	270.5 ± 9.2
Ammonium nitrogen (mg L^{-1})	12.7 ± 4.63	28.8 ± 0.9	0.37 ± 0.2
Chloride (mg L^{-1})	141.5 ± 19.2	169.4 ± 30.5	151.9 ± 29.6
Bicarbonate (mg L^{-1})	89.8 ± 8.84	60.5 ± 21.6	82.1 ± 23.8
Phosphorus (mg L^{-1})	44.0 ± 1.47	19.1 ± 9.3	44.7 ± 0.9
Potassium (mg L^{-1})	375.1 ± 16.6	243.5 ± 1.1	346.7 ± 10.6
Calcium (mg L^{-1})	205.4 ± 9.2	209.1 ± 15.7	167.6 ± 20.0
Magnesium (mg L^{-1})	65.4 ± 5.4	74.6 ± 0.8	79.8 ± 2.1
Sulfate (mg L^{-1})	369.5 ± 32.2	392.3 ± 30.5	124.5 ± 71.0
Sodium (mg L^{-1})	39.2 ± 2.4	18.6 ± 0.3	92.3 ± 2.86
Zinc (mg L^{-1})	0.16 ± 0.03	0.06 ± 0.02	0.22 ± 0.03
Manganese (mg L^{-1})	0.39 ± 0.02	0.11 ± 0.01	0.19 ± 0.07
Copper (mg L^{-1})	0.08 ± 0.01	0.03 ± 0.007	0.36 ± 0.06
Iron (mg L^{-1})	0.58 ± 0.05	0.43 ± 0.06	0.97 ± 0.05
Boron (mg L^{-1})	0.77 ± 0.06	0.52 ± 0.007	0.39 ± 0.03
Molybdenum (mg L^{-1})	0.04 ± 0.01	0.04 ± 0.01	0.03 ± 0.02

3. Results

This is a preliminary study aimed to evaluate the comparative effects of commercially produced organic digestates supplemented with chemical fertilizers on hydroponically grown basil. Representative images of the experimental basil plants grown in the ebb and flow systems containing FD, CLD, and CMD are depicted in Fig. 2. The impacts of the different fertilizer treatments on basil plant growth parameters, including height, biomass yield, and chlorophyll content, as well as nitrogen use efficiency (NUE), phosphorus use efficiency (PUE), and potassium use efficiency (KUE) were measured.

3.1. Plant height and fresh biomass yield

The effects of the experimental fertilizer treatments on basil plant height, fresh shoot mass, and fresh root mass are presented in Fig. 3. No statistically significant differences were observed among treatments for plant height, fresh shoot mass, or fresh root mass ($p > 0.05$; Supplementary Table S1). Numerically, CMD produced the greatest mean plant height (46.3 ± 5.5 cm; Fig. 3A), whereas CLD resulted in the highest fresh shoot and fresh root mass (194.2 ± 37.2 g and 29.1 ± 10.5 g, respectively; Fig. 3B and C). Relative to these highest values, FD and CLD showed modest reductions in plant height, and FD and CMD exhibited lower shoot and root biomass compared to CLD; however, these differences were not statistically significant.

3.2. Dry biomass yield

The effects of the fertilizer treatments on dry shoot and root biomass are presented in Fig. 4. No statistically significant differences were observed among treatments for dry shoot or dry root mass ($p > 0.05$). Numerically, CLD exhibited the highest mean dry shoot and root biomass (Fig. 4), while FD and CMD showed modest reductions in dry shoot and root mass relative to CLD (Fig. 4A and B). However, these differences were not statistically significant.

3.3. Leaf chlorophyll content

Basil plants grown in CMD resulted in a maximum mean value of chlorophyll *a* (1.88 mg g^{-1} ± 0.4), while basil plants grown in CLD resulted in the maximum mean value of chlorophyll *b* (0.57 mg g^{-1} ± 0.06). Basil plants grown with FD and CLD had lower chlorophyll *a* content by 36.8% and 10.5%, respectively, compared to CMD (Fig. 5A). Chlorophyll *a* content differed significantly ($p < 0.05$) among the experimental fertilizer treatments (Supplementary Table S1). The Tukey-Kramer test showed significant differences ($p < 0.05$) between the FD/CLD and FD/CMD treatments for chlorophyll *a* content, while CLD and CMD were statistically similar ($p > 0.05$). Chlorophyll *b* content was lower by 15.8% (FD) and 5.3% (CMD), compared to CLD (Fig. 5B). One-way ANOVA and the Tukey Kramer test showed that all treatments had statistically similar chlorophyll *b* content ($p > 0.05$) (Supplementary Table S1).

3.4. Nutrient use efficiency

The highest NUE observed was for basil plants grown in CLD (192.5 ± 9.2 NO_3-N mg L^{-1}), followed by FD (218.5 ± 16.3 NO_3-N mg L^{-1}) and CMD (270.5 ± 9.2 NO_3-N mg L^{-1}) (Fig. 6A). NUE was lower by 37.7% and 21.7% for basil plants grown in FD and CMD, respectively, compared to basil plants grown in CLD (Fig. 6A). One-way ANOVA (Supplementary Table S1) showed significant differences ($p < 0.05$) in NUE between the different fertilizers. The Tukey-Kramer test indicated that there are significant differences ($p < 0.05$) in NUE between FD/CLD and CLD/CMD. There was no significant difference ($p > 0.05$) in NUE between FD/CMD.

The highest PUE observed was for basil plants grown in CLD (19.1 ±

Fig. 2. Upper panel: Representative images of hydroponically grown basil plants in (A) frass digestate, (B) cucumber leaf digestate, and (C) cow manure digestate 14 d after transplant from rockwool into the ebb and flow systems. Lower panel: hydroponically grown basil plants in (D) frass digestate, (E) cucumber leaf digestate, and (F) cow manure digestate, at harvest (42 days after transplant).

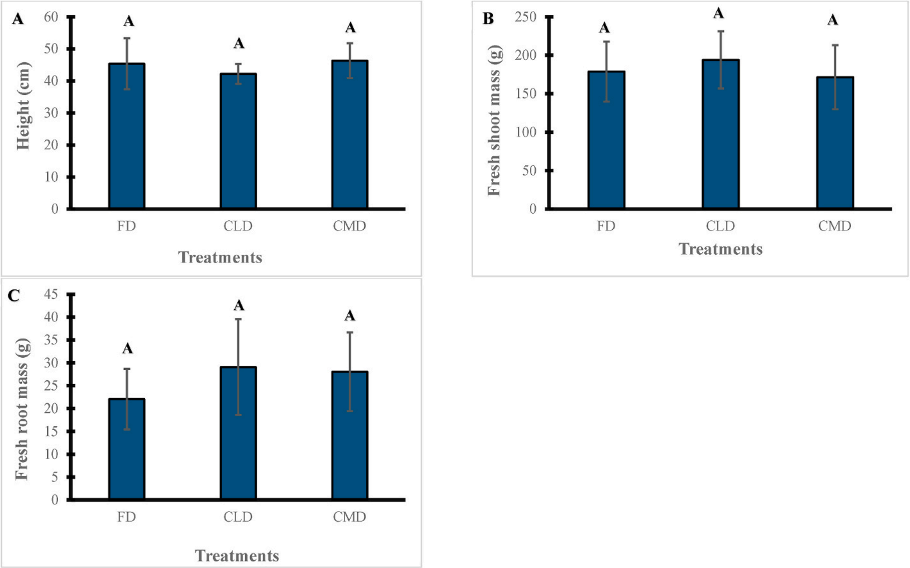

Fig. 3. Effects of the frass digestate (FD), cucumber leaf digestate (CLD), and cow manure digestate (CMD) treatments on (A) plant height, (B) fresh shoot mass, and (C) fresh root mass. Data represent mean values and standard deviation of two replications. Bars with same letters are significantly similar ($p > 0.05$) for the same growth parameter.

9.3 P mg L^{-1}) (Fig. 6B). The second and third highest PUE were observed for basil plants grown in FD (44.0 ± 1.5 P mg L^{-1}) and CMD (44.7 ± 0.9 P mg L^{-1}), respectively. Compared to basil plants grown in CLD, the PUE of FD and CMD was lower by 61.0% and 62.0%, respectively. One-way ANOVA (Supplementary Table S1) showed significant differences ($p < 0.05$) in PUE in the various treatments (Supplementary Table S1). The Tukey-Kramer test indicated that there were significant differences ($p < 0.05$) in PUE between CLD/CMD and CLD/FD. The FD and CMD were statistically similar ($p > 0.05$).

Results from the KUE show that the highest KUE was observed in CLD (243.5 ± 1.1 K mg L^{-1}), followed by CMD (346.7 ± 10.6 K mg L^{-1}), and FD (375.1 ± 16.6 K mg L^{-1}) (Fig. 6C). The KUE observed in FD and CMD was 41.7% and 38.1% lower compared to the CLD treatment. One-way ANOVA showed a significant difference ($p < 0.05$) between the fertilizer treatments (Supplementary Table S1). Further analysis using the Tukey-Kramer test showed significant differences ($p < 0.05$) in KUE between the following treatments: CLD/FD and CLD/CMD. The treatments FD/CMD were statistically similar ($p > 0.05$).

4. Discussion

The results from this preliminary study demonstrated that

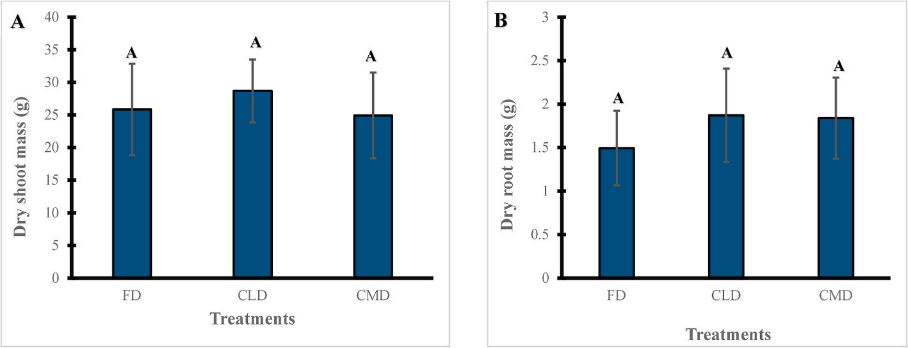

Fig. 4. Effects of the frass digestate (FD), cucumber leaf digestate (CLD), and cow manure digestate (CMD) on (A) basil dry shoot mass and (B) basil dry root mass. Data represent mean values and standard deviation of two replications. Bars with the same letters are significantly similar ($p > 0.05$) for the same growth parameter.

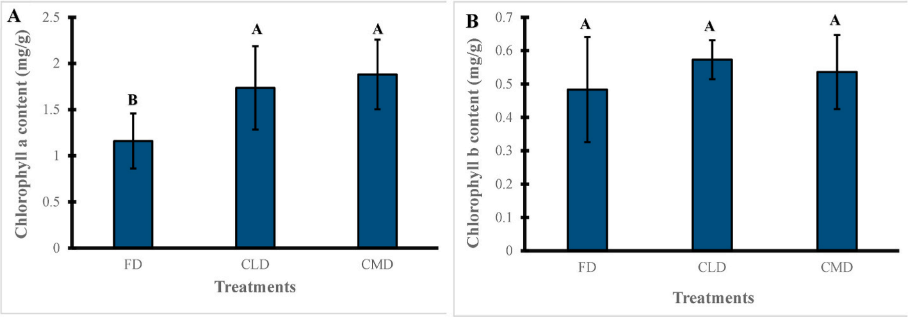

Fig. 5. Effects of the frass digestate (FD), cucumber leaf digestate (CLD), and cow manure digestate (CMD) on (A) chlorophyll *a* content and (B) chlorophyll *b* content in hydroponically grown basil. Data represent mean values and standard deviation of two replications. Bars with different letters are significantly different ($p < 0.05$) for the same growth parameter.

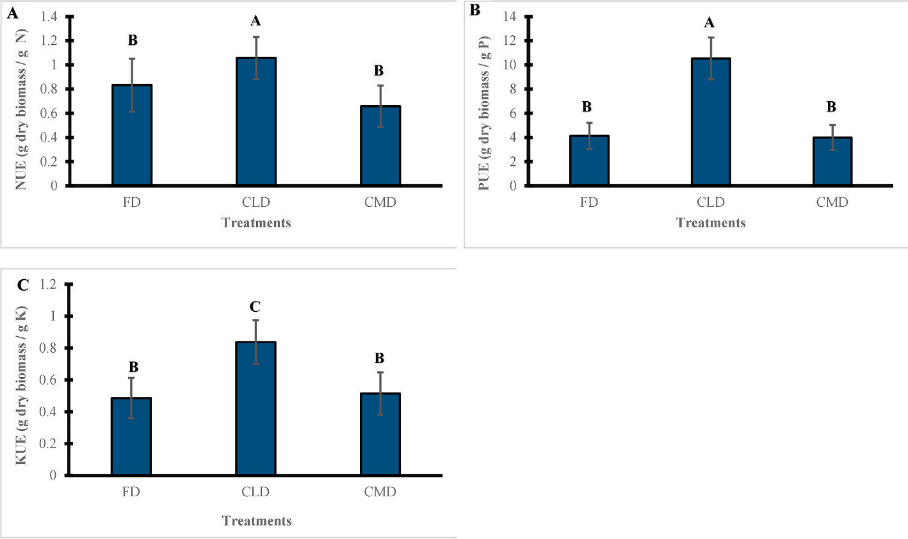

Fig. 6. Effect of frass digestate (FD), cucumber leaf digestate (CLD), and cow manure digestate (CMD) on (A) nitrogen use efficiency (NUE), (B) phosphorus use efficiency (PUE), and (C) potassium use efficiency (KUE). Data represent mean values and standard deviation of two replications. Bars with different letters are significantly different ($p < 0.05$) for the same growth parameter.

differences in FD, CLD, and CMD nutrient composition maintain comparable basil growth and yield across treatments but resulted in significant differences in nutrient use efficiencies.

Basil grown with CMD exhibited the highest plant height; however, overall growth performance was statistically comparable across treatments. CLD treatment produced greater fresh and dry biomass, although differences were not significant compared to the rest of the treatments. These preliminary findings indicate that all digestate treatments (CLD, FD, and CMD), when supplemented with inorganic nutrients, could be capable of sustaining comparable basil growth under hydroponic conditions. Previous field-based studies have demonstrated that integrating organic manures with chemical fertilizers enhances basil growth and biomass relative to inorganic fertilizers alone [26–29]. Similarly, hydroponic studies have shown that partial substitution of nutrient solutions with organic inputs, such as vermicompost teas or animal-waste-derived liquid fertilizers, can maintain or even improve crop productivity [30,31]. Collectively, these findings support the principle that combining organic and inorganic nutrient sources can sustain plant growth while reducing dependence on full-strength chemical nutrient solutions. The comparable biomass production observed in the present preliminary study may be attributed to the complementary nutrient release dynamics of organic and inorganic sources. Organic fertilizers typically provide a gradual and sustained nutrient release [32], whereas inorganic fertilizers supply readily available nutrients but may result in rapid nutrient fluctuations [33]. The integration of both sources may therefore promote a more balanced nutrient supply, supporting stable growth and biomass accumulation in hydroponic basil.

Chlorophyll is a key photosynthetic pigment for plants, largely determining their photosynthetic capacity and, consequently, plant growth [34]. The higher chlorophyll *a* content observed under CMD suggests that differences in digestate nutrient composition, particularly nitrate-nitrogen availability, may have influenced pigment synthesis. In contrast, the similar chlorophyll *b* content across treatments indicates that all digestate-inorganic nutrient combinations provided adequate nutrient supply to maintain photosynthetic function. These results align with previous findings that integrated organic and inorganic fertilization can enhance chlorophyll concentration through improved nutrient balance [28].

Nutrient use efficiency is of particular interest as a major target for crop improvement [35]. Plant growth, physiological activity, and harvestable yield obtained per unit nutrient are the metrics used to determine nutrient use efficiency [36]. In the present study, basil grown with CLD exhibited significantly higher NUE, PUE, and KUE compared to FD and CMD, while FD and CMD were statistically similar. Although biomass differences among treatments were not statistically significant, the consistently higher NUE, PUE, and KUE observed in CLD likely contributed to its greater biomass accumulation.

The higher NUE, PUE, and KUE observed in CLD are notable, given that CLD did not contain the highest absolute concentrations of these nutrients. This suggests that nutrient use efficiency may be influenced by nutrient composition and solution characteristics rather than concentration alone. CLD contained a greater proportion of ammonium-nitrogen relative to the other treatments, resulting in a mixed nitrate-ammonium nitrogen supply. Previous research indicates that an appropriate or balanced ratio of nitrate-ammonium nitrogen enhances plant growth and promotes the absorption and utilization of nitrogen and phosphorus [37,38]. In addition, CLD had the lowest initial and final EC, indicating lower overall salt concentration in the nutrient solution. The EC is an indicator of the nutrient solution's electrolyte concentration and salt concentration [39]. It is related to the amount of ions available to plants in the root zone [40]. Higher EC levels, as observed in CMD and FD, may reduce nutrient uptake efficiency due to increased salinity. For example, a previous study reported a significant decrease in plant phosphorus uptake due to salinity stress [41]. The comparatively lower EC in CLD may therefore have contributed to improved nutrient utilization under the conditions of this study. However, as this was a preliminary study, further detailed investigations are required to validate these observations and to clarify the mechanisms underlying the improved nutrient use efficiency associated with CLD.

Plants absorbed proportionally more water than nutrients, which increases nutrient concentrations in the remaining solution, resulting in elevated EC values. Previous studies have shown that evapotranspiration can concentrate nutrients in hydroponic solutions and thereby increase EC [42–44]. A recent study shows that an EC of 3.0 mS cm^{-1} significantly promoted the yield of hydroponically grown basil [45]. However, a previous study reported 1.0 – 1.6 mS cm^{-1} as the optimum EC range for hydroponically grown basil [46]. These differences suggest that basil tolerance to EC may vary depending on cultivar, growth stage, and production system. In the present study, initial and final EC ranged from 2.2 to 2.9 mS cm^{-1} and 2.7 - 4.7 mS cm^{-1}, respectively. Despite the observed increase in EC, plant height and fresh and dry biomass yields remained statistically similar across treatments, indicating that the EC levels were within a tolerable range under the experimental conditions. Singh and Dunn [46] also reported an optimal pH range of 5.5 – 6.0 for hydroponically grown basil. In this study, pH increased slightly from an initial range of 5.8 – 5.9 to 6.1- 6.6. The increase in pH may be a result of the nitrate/H^+ cotransporters involved in nitrate uptake [47]. Basil has been shown to tolerate pH values as low as 4.0 without significant reductions in growth or symptoms of nutrient disorders [48], suggesting that the pH conditions observed here were within physiologically acceptable limits.

Global agricultural waste production is estimated at approximately 10 billion tons annually and is projected to increase substantially in the coming decades [49,50]. Agricultural residues such as animal manure and green biomass are often underutilized and may contribute to environmental burdens if not properly managed [51,52]. Increasingly, on-farm composting and anaerobic digestion are being promoted as strategies to convert these residues into value-added products such as biogas and nutrient-rich digestates [53,54]. The present study demonstrates that digestates derived from cultivated green residues (CLD) and animal manures (FD and CMD) can partially substitute inorganic fertilizers in hydroponic basil production without compromising growth performance. Notably, CLD improved nutrient use efficiency despite lower absolute nutrient concentrations, indicating that waste-derived inputs can enhance nutrient conversion efficiency under controlled-environment conditions. These findings suggest that integrating on-farm digestion processes with hydroponic production systems could support localized nutrient recycling, reduce reliance on inorganic fertilizers, and align with emerging policy initiatives promoting circular bioeconomy and sustainable nutrient management strategies.

5. Limitations and future research directions

This study was designed as a preliminary investigation to evaluate the feasibility of using digestates derived from cow manure, frass, and cucumber leaf residues as partial substitutes for inorganic fertilizers in hydroponic basil production. Consequently, the experiment was conducted with two replications rather than the three or more typically recommended for definitive agronomic trials. While this level of replication was sufficient to identify treatment trends under controlled environmental conditions, it may have limited the statistical power to detect smaller differences among treatments. In addition, the absence of a sole inorganic fertilizer treatment (e.g., a standard Hoagland solution) as a control reflects the study's focus on comparing digestate-based nutrient sources rather than benchmarking against conventional hydroponic practices.

Building on these findings, future research should prioritize multi-cycle experiments with increased replication to evaluate the consistency and reproducibility of treatment effects over time. The inclusion of a standard inorganic nutrient solution as a control would enable clearer benchmarking of digestate performance. Additional studies should assess digestate stability and nutrient dynamics in recirculating hydroponic systems, including potential changes in EC, pH, and microbial activity during prolonged use. Expanding trials to other leafy greens and fruiting crops would further test the generalizability of the observed nutrient use efficiency responses. Such work would provide a more comprehensive understanding of the agronomic and operational feasibility of digestate-based nutrient management in controlled-environment agriculture.

6. Conclusion

This preliminary study evaluated digestates derived from frass, cucumber leaf residues, and cow manure as partial substitutes for inorganic fertilizers in hydroponic basil production. Basil biomass (plant height, fresh mass, and dry mass) did not differ significantly among treatments, indicating that all three digestates were capable of sustaining comparable growth when supplemented with inorganic nutrients. Notably, CLD consistently produced the highest NUE, PUE, and KUE. All digestate treatments reduced inorganic inputs of N, P, K, Mg, and Ca to varying degrees, demonstrating their potential to partially replace conventional mineral fertilizers in controlled-environment agriculture. These findings suggest that integrating digestate streams derived from on-farm agricultural residues into hydroponic nutrient management plans may support nutrient recycling and reduce dependence on inorganic inputs. Such approaches align with emerging circular bioeconomy strategies and policy initiatives aimed at improving resource use efficiency and promoting sustainable agricultural systems.

CRediT authorship contribution statement

Patrick Yawo Kpai: Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Molly Keyes:** Writing – review & editing, Investigation. **Oluwafemi Adaramola:** Writing – review & editing, Methodology, Investigation. **Philip Wiredo Addo:** Writing – review & editing, Methodology, Investigation. **Sarah MacPherson:** Writing – review & editing, Conceptualization. **David Leroux:** Writing – review & editing, Conceptualization. **Mark Lefsrud:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jafr.2026.102819.

Data availability

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

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