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Production of *Chlorella*-based liquid fertilizer from dairy wastewater to reduce synthetic fertilizer use

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Abstract

The purpose of this investigation was to assess the efficiency of using dairy wastewater-grown *Chlorella* sp. (C) as a liquid organic fertilizer (LOF) when used in combination with inorganic or organic fertilizer on finger millet (*Eleusine coracana* L.). The nitrogen (N), phosphorus (P) and potassium (K) content of the CLOF was 1.00±0.04, 0.58±0.04 and 0.67±0.005 percentage respectively. A greenhouse pot experiment was arranged with nine treatments and four replicates in CRD design. The treatments included T1 – control, T2- 100% inorganic fertilizer (IF), T3 – 75% IF +25% CLOF, T4 – 50% IF + 50% CLOF, T5 – 25% IF + 75% CLOF, T6 – 100% Vermicompost (VC), T7 – 75% VC + 50% CLOF, T8 – 50% VC + 50% CLOF and T9 – 25% VC + 75% CLOF. T4 (50% IF + 50% CLOF) showed the highest values across most agronomic parameters, including: plant height (95.23±2.21 cm), number of leaves (18±1), leaf length (76.33±4.46 cm), leaf width (1.80±0.10 cm), flower number (13±1.00), ear number (13±1.00), tiller number (10.33±0.58), finger number (52±5), fresh grain weight (11.48±1.13 g/plant), and dry grain weight (6.89±1.04 g/plant) which was comparable to T2. Additionally, T8 and T3 showed comparable values in most growth parameters and yield as that of T2. Nutrient analysis of plant tissues confirmed that the use of CLOF improved the nutrient uptake. Although T2 had the highest N (4.62±0.40 g/plant), it was not significantly different from that of T4 (3.92±0.30 g/plant). T4 recorded the highest P (0.36±0.01 g/plant) and K (5.24±0.19 g/plant), also with no significant differences from T2, indicating balanced nutrient contribution from CLOF. This study highlights that CLOF, produced from recycled dairy wastewater, is a promising nutrient source that not only enhances crop performance but also reduces reliance on inorganic or bulk organic fertilizers.

Keywords: *Chlorella* sp., dairy wastewater, *Eleusine coracana,* liquid fertilizer.

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Introduction

The advancement of sustainable agriculture mandates the exploration of alternatives to the extensively utilized inorganic fertilizers. While synthetic fertilizers have significantly boosted agricultural production worldwide, there are growing concerns about the negative environmental impacts of excessive nitrogen and phosphorus use (Sarvi et al., 2021). According to FAO (2021), on average, the worldwide nitrogen application per hectare of cropland has been increased 3.5 times in 2019 to that of 1961 (Alvarez-Gonz´alez´ et al., 2022). Nitrate from these fertilizers easily leaches into groundwater, leading to pollution (Dahan et al., 2014), acidification and terrestrial eutrophication (Tayefeh et al., 2018) and contributing to greenhouse gas effects (Motavalli et al., 2008). Excessive phosphorus application also leads to run off and eutrophication (Sarvi et al., 2021). The farmers in the low-income countries have limited access to inorganic fertilizers because of their escalating prices in recent times (Taghizadeh-Hesary et al., 2021; Mousavi et al., 2021). Therefore, it is vital to alleviate the adverse effects of inorganic fertilizer use (Asadu et al., 2018) while

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ensuring that farmers have access to affordable alternative organic fertilizers or biofertilizers (Kolambage et al., 2024).

Recent trend in research has been attracted towards the usage of algae in agriculture as nutrient source and bio stimulants (Samoraj et al., 2024*). Chlorella* is a green microalga that is rich in nutrient elements specially nitrogen, phosphorous, potassium and micronutrients (Dineshkumar et al., 2020), several functional materials (El-Naggar et al., 2020) and growth promoting factors like cytokinin (Minaoui et al., 2024). Prior research have demonstrated that *Chlorella* genus significantly improved growth and yield of crops: improved yield in grapevine (Nagy and Pinter, 2015), enhanced plant growth, nutritional composition and fruit yield in tomato (Suchithra et al., 2022), increased plant growth parameters and pod yield in common bean (Refaay et al., 2021), influenced the growth of lettuce and biochemical composition (La Bella et al., 2021), stimulated the root system of maize (Martini et al., 2021), significantly increased the growth and carotenoid content in *Medicago truncatula* (Gitau et al., 2021), improved the growth of green gram (Dineshkumar et al., 2020) and bio stimulant effects on *Beta Vulgaris* (Barone et al., 2018) are important studies to mention.

The high-water consumption and expensive growth media used in conventional microalgae cultivation limit its commercial potential (Arora et al., 2023). However, recent developments in cost-effective microalgae cultivation have explored the use of various types of wastewaters for their cultivation. This approach offers dual benefits, namely, bioremediation and production of valuable biomass at a lower cost (Liu et al., 2021). Various kinds of wastewater medium have been used for the successful cultivation of *Chlorella* including landfill leachate (Saadat et al., 2023), wastewater of sewage (Sharma et al., 2021, Renuka et al., 2016), rose oil processing effluent (Uysal and Ekinsi, 2021), cattle wastewater (Jain et al., 2022), domestic wastewater (Álvarez-González et al., 2022) and parboiled rice mill effluent (Kariyawasam Hetti Gamage et al., 2023).

Due to the increased demand for milk, the global dairy industry has rapidly expanded, resulting in substantial waste discharge into nearby water bodies. The discharge of these wastewaters into waterways without appropriate treatments leads to serious environmental harm, such as eutrophication and groundwater pollution (Jindal et al., 2019). A synthetic dairy industry effluent (Loganathan et al., 2021) and dairy wastewater from industry (Biswas et al., 2021) have been reported to be viable growth media for microalgae.

Liquid organic fertilizers (LOF) contain a broader spectrum of nutrients, including both macro and micronutrients. Plants absorb these fertilizers more efficiently because the nutrients are in a soluble state, allowing quicker uptake than solid fertilizers (Solihin et al., 2019). The benefits of foliar fertilization include rapid nutrient absorption by plant tissues, improved nutrient translocation to developing plant parts, elimination of leaching and fixation losses in soils, controlled nutrient uptake by crops, and enhanced crop yield and quality through better nutrient utilization (Vasundhara and Chhabra, 2021), which results in lower environmental pollution compared to soil application. However, applying fertilizer only to leaves may limit plant growth. Combining leaf and soil applications can reduce the need for chemical fertilizers and increase crop yields (Niu et al., 2021). Thus, combining soil cum foliage application is advantageous than sole usage.

One of our previous studies (Kariyawasam Hetti Gamage et al., 2023), reported successful usage of *Chlorella* sp cultivated in wastewater from parboiling of rice as a co-organic fertilizer. In this previous study *Chlorella* was applied as soil application as well as foliar application. However, the availability of parboiled wastewater is not guaranteed year-round, as paddy is a seasonal crop. Moreover, soil application requires large amount of biomass. In this background, this study aimed to investigate the specific research question, whether CLOF as foliar application, when combined with soil-applied either inorganic or organic fertilizers, could serve as a partial substitute while still achieving comparable growth, yield, and nutrient uptake in finger millet (*Eleusine coracana* (L.). The uniqueness of this study stems from the circular economy model, where dairy wastewater is repurposed as a growth medium for generating a liquid organic fertilizer from *Chlorella* sp.

Material and Methods

Cultivation of Chlorella in dairy industry effluent

The dairy industry effluent from the North Lanka Family Foods (PVT) Ltd at Palai, Northern Province of Sri Lanka, was obtained from the sump meant for wastewater collection. The *Chlorella* sp. culture was obtained from the Department of Civil Engineering, Faculty of Engineering, University of Jaffna. The pre-cultured *Chlorella* was inoculated into the dairy effluent medium and cultivated under conditions similar to our previous work (Kariyawasam Hetti Gamage et al., 2023), which used parboiled rice mill effluent. Briefly, the

cultivation was carried using dairy wastewater in an open raceway reactor (250 L capacity), with a paddle wheel to mix, halogen lamps to illuminate throughout and at ambient laboratory conditions (28–30 °C). After two weeks, the *Chlorella* biomass was filtrated from the media. The filtrate was also centrifuged to effectively separate the biomass. The biomass was oven-dried for 24 hours at 105 °C and stored under 4 °C until further analysis and usage.

Characterization of dairy industry effluent and organic nutrient sources

The dairy effluent, vermicompost and *Chlorella* biomass were analysed for selected parameters such as moisture content (oven drying), total nitrogen (Haluschak, 2006), phosphorous (Halajnia et al., 2007), potassium (Kalra, 1971) and total organic carbon (Hoogsteen et al., 2015). The Electrical Conductivity (EC) and pH were measured by EC and pH meter. The heavy metal content of the *Chlorella* biomass was assessed by digestion (EPA, 2007) followed by ICP-MS (EPA, 1994) analysis.

CLOF preparation for foliar spray

A homogenized solution was prepared by dissolving twenty-five grams (25g) of fine powdered biomass in 100 ml distilled water followed by shaking. From the stock solution, two hundred milli litres (200 ml) was taken and dissolved in 1000 ml distilled water to apply as foliar spray. The amount of CLOF application was decided by balancing the total nitrogen as per Department of Agriculture recommendation for finger millet either as organic or inorganic fertilizers in the respective treatment combinations.

Analysis of soil

Total nitrogen (Kjeldahl digestion and distillation), available phosphorus (Olsen method) and available potassium (Ammonium acetate extraction), moisture content (oven dry method) electrical conductivity (1:5 soil: water by conductivity meter) and pH (1:5 Soil: water suspension by pH meter) were determined by respective standard methods.

Pot trial

The pot trial was conducted with *Eleusine coracana L.* (Local variety) in complete randomized design having nine treatments (Table 1) and four replicates within a net house, located at the Faculty of Agriculture University of Jaffna, Sri Lanka. Each pot was filled with five kilograms of soil, previously air-dried and sieved (<2 mm). For inorganic treatments, urea, triple super phosphate (TSP), and muriate of potash (MOP) were applied as basal dressing at the rate of 65, 55 and 82.5 kilograms per hectare respectively. Four weeks after basal application, topdressing of urea was done at the rate of 130 $kgha^{-1}$. The inorganic fertilizers and vermicompost were applied to each pot two days and one week ahead of transplanting, respectively, according to the treatments. The amount of CLOF for the treatments were applied to align the total nitrogen application according to the Department of Agriculture recommended rates for the corresponding combination treatments. The CLOF was diluted (1/5 times) and a total of 150 ml, 100 ml and 50 ml per plant was applied to treatments T3 and T7 (75% CLOF), T4 and T8 (50% CLOF) and T5 and T9 (25% CLOF) respectively (Table 1). For each treatment with CLOF, the required amount of nitrogen was applied by changing the volume of spray in eight split doses. The seedlings were transplanted fourteen days after germination in each pot. The pots were irrigated regularly to sustain the moisture content near field capacity. For the foliar application treatments first spray was done one week after transplanting of the seedlings, thereafter, once a week, up to eight weeks. The primary macro nutrient contents namely N, P, and K of the plant biomass were analysed as per methods used for *Chlorella* biomass analysis.

Table 1. Treatment Schedule for Pot Experiment and Amount of CLOF for each Treatment

Treatment	Description	Applied amount of CLOF/plant (ml)
T1	Control (C)	-
T2	100% IF	0
T3	75% IF + 25% CLOF	50
T4	50% IF + 50% CLOF	100
T5	25% IF + 75% CLOF	150
T6	100% VC	0
T7	75% VC + 25% CLOF	50
T8	50% VC + 50% CLOF	100
T9	25% VC + 75% CLOF	150

IF – Inorganic Fertilizers, CLOF – *Chlorella* Liquid Organic Fertilizer, VC - Vermicompost

Data collection

Plant height, leaf number, length of the leaves and width of the leaves were collected once a week. The effective tiller number, number of ears and number of fingers per plant were also recorded. Harvested ears were threshed dried and weighed.

Statistical analysis

Data analysis was performed using Statistical Analytical Software (SAS) University Edition and treatment means were separated using Duncan's Multiple Range Test (DMRT) at a significance level of $P = 0.05$.

Results

Characteristics of the dairy industry effluent and algal biomass

The pH and EC of the dairy effluent were 5.4 and 0.00049 dSm^{-1}. Total nitrogen, phosphorus, and potassium levels in the dairy effluent were 305, 45, and 63 mgL^{-1}, respectively. It has a considerable amount of micro nutrient cations as well. The average dry algal biomass production in the dairy effluent was 0.787 gL^{-1}. In an ambient laboratory condition, 540 litres of dairy effluent yielded 424.71 grams of *Chlorella* biomass. The N, P and K content in dry algae biomass was 5%, 2.33% and 2.68% respectively.

Characterization of CLOF and its' suitability as liquid organic fertilizer

Table 2 compares the physical and chemical properties of CLOF to the required standards for liquid organic fertilizers in Sri Lanka (SLS 1702:2021). The liquid organic fertilizer complies with SLS 1702 standards for pH, electrical conductivity, nitrogen, phosphorus, potassium, and heavy metal content.

Table 2. The comparison between the physiochemical properties of the CLOF and the standards of liquid organic fertilizers according SLS 1702

Physiochemical parameter	Formulated liquid organic fertilizer	*Limits in liquid organic fertilizer
pH	7.4	6.0 – 8.5
EC (ds/m)	9.8	20.0 (max)
Total nitrogen (N)	1%	1% (min)
Total phosphorous (P)	0.58%	0.5% (min)
Total potassium (K)	0.67%	0.5% (min)
Arsenic (As)	<0.000 ppm	0.5 ppm (max)
Lead (Pb)	0.0024 ppm	1.0 ppm (max)
Chromium (Cr)	0.0048 ppm	0.5 ppm (max)
Cadmium (Cd)	<0.000 ppm	0.5 ppm (max)

*SLS 1702: 2021

Physiochemical parameters of vermicompost and soil

The vermicompost had 7.06 of pH and 0.0031 dsm^{-1} of electrical conductivity, and relatively rich in nitrogen (1.12%), phosphorus (1.24%), and potassium (2.8%) (Table 3). The soil was non-saline and classified as sandy clay loam. Compared to optimal levels (Porch and Hunter, 2002), all essential macronutrients (nitrogen, phosphorus, and potassium) were deficient in the soil.

Table 3. Physicochemical properties of the soil and vermicompost

Physicochemical property	Value
Soil	
pH	7.98
EC	36 $\mu S\ cm^{-1}$
Texture	Sandy clay loam
Bulk density	1.55 $g\ cm^{-3}$
Organic matter	0.21%
Total nitrogen	125.2 $mg\ kg^{-1}$
Available nitrogen	28 $mg\ kg^{-1}$
Available phosphorous	14.01 $mg\ kg^{-1}$
Available potassium	93.54 $mg\ kg^{-1}$
Vermicompost	
pH	7.06
EC	0.0031 ds/m
Total nitrogen	1.12%
Total phosphorous	1.24%
Total potassium	0.73%
Organic matter content	28.67%

Effect of the CLOF on finger millet plants

Growth parameters

The influence of the treatments on plant height, leaf number, leaf length, leaf width and flower number at ear initiation is shown in Table 04. T4 (50% IF+50% CLOF), recorded the highest values in all the parameters, while the significantly lowest was recorded in T1 (C). Except T5 (25% IF + 75% CLOF), all the inorganic treatments (T2, T3 and T4) recorded better values than most of the organic treatments in the measured growth parameters. However, T8 (50% VC + 50% CLOF) also recorded comparable values as that of T2 in the measured growth parameters.

Table 4. The effect of different treatments on plant height, leaf number, leaf length, leaf width eight (08) weeks after transplanting and flower number fourteen (14) weeks after transplanting

Treatment	Plant height (cm)	Leaf number	Leaf length (cm)	Leaf width (cm)	Flower number
T1	55.57±8.86^{e}	10.00±0.00^{f}	43.47±0.95^{f}	0.90±0.00^{e}	3.00±0.00^{e}
T2	92.27±2.16^{abc}	16.33±0.58^{ab}	68.93±1.99^{bc}	1.57±0.06^{b}	11.00±1.00^{b}
T3	93.97±0.68^{ab}	17.00±0.00^{ab}	69.97±1.37^{b}	1.60±0.10^{b}	8.00±1.00^{c}
T4	95.23±2.21^{a}	17.67±1.15^{a}	76.33±4.46^{a}	1.80±0.10^{a}	13.00±1.00^{a}
T5	85.8±3.03^{cd}	14.67±1.53^{cd}	62.37±4.74^{d}	1.40±0.00^{cd}	7.00±1.00^{cd}
T6	88.13±1.29^{bcd}	14.00±1.00^{de}	65.03±2.17^{cd}	1.33±0.12^{d}	6.00±1.00^{d}
T7	84.73±3.04^{d}	13.67±0.58^{de}	60.60±0.56^{de}	1.27±0.06^{d}	6.00±1.00^{d}
T8	91.43±1.16^{abc}	16.00±0.00^{bc}	69.03±0.81^{bc}	1.50±0.10^{bc}	8.00±1.00^{c}
T9	81.93±1.36^{d}	13.00±1.00^{e}	57.53±0.70^{e}	1.27±0.06^{d}	6.00±1.00^{d}

T1- Control, T2-100% IF, T3-75% IF + 25% CLOF, T4-50% IF + 50% CLOF, T5-25% IF + 75% CLOF, T6-100% VC, T7-75% VC + 25% CLOF, T8-50% VC + 50% CLOF, T9-25% VC + 75% CLOF

Means (±SD) denoted by the same letter indicate no significant difference according to Duncan's test at $p<0.05$

Figure 1 (A) and (B) display the impact of the treatments on number of effective tillers and root length. While T4 (10.33±0.58) produced the greatest number of effective tillers, this was not statistically significant compared to T2 (9.67±0.58). T8 (50% VC + 50% CLOF) (8.33±0.58) and T3 (75% IF + 25% CLOF) (8.67±0.58) had comparable number of tillers, which showed a significantly lower number than T2 and T4, but significantly higher than all other treatments. The lowest tiller number was recorded in T1 (C) (2.67±0.58). The significantly highest root length was recorded in T4 (50% IF + 50% CLOF) (52.90±1.49 cm). T2 (100% IF) (49.60±0.75 cm) and T3 (75% IF + 25% CLOF) (49.30±0.72 cm) showed similar root length, which was suggestively higher than all other treatments except T4 and T2.

Reproductive parameters

Figure 1 (C) and (D) show the impact of various treatments on the number of ears and fingers of the finger millet plants. The significantly highest ear number (13.00±1.00) and finger number (52.67±4.73) was recorded in T4 (50% IF + 50% CLOF). T2 (100% IF) showed the next significantly higher ear number (10.00±1.00) and finger number (39.67±4.73) compared with all other treatments. No notable difference was found in the ear count between T3 (75% IF + 25% CLOF) (8.00±1.00), T5 (25% IF + 75% CLOF) (7.00±1.00) and T8 (50% VC + 50% CLOF) (7.00±1.00). In finger numbers, T3 (33.33±3.79) and T8 (29.67±3.51) also recorded comparable values as T2 (3.67±4.73). The significantly lowest ear number (3.00±1.00) and finger number (11.33±3.51) were recorded in T1 (C).

Yield parameters

The highest fresh (11.48±1.13 g/plant) and dry weight (6.89±1.04 g/plant) of the grain was recorded in T4 (50% IF + 50% CLOF), however, they were not significantly differed from T2 (100% IF) (10.57±0.88 g/plant, 6.34±0.74 g/plant) (Figure 1 (E), (F)). T8 (50% VC+ 50% CLOF) also showed higher fresh (9.64±0.46 g/plant) and dry weight (5.78±0.52 g/plant) of the yield compare with other all treatments, while it was comparable to that of T3 (75% IF + 25% CLOF) (10.04±0.08 g/plant, 6.02±0.44 g/plant) and T2 (100% IF) (10.57±0.88 g/plant, 6.34±0.74 g/plant). The lowest fresh (5.33±0.27 g/plant) and dry weight (3.20±0.31 g/plant) of the yield was observed in T1 (C).

Nutrient levels in plant tissue

Figure 2 (A), (B), and (C) depict the impact of various treatments on the amount of nitrogen (N), phosphorus (P), and potassium (K) in plant tissues in comparison to the control. While T2 (100% IF) exhibited the highest nitrogen content (4.62±0.20 g/plant), the difference between T2 and T4 (50% IF + 50% CLOF) (3.92±0.00 g/plant) was not statistically significant. T3 (3.78±0.20 g/plant) and T8 (3.36±0.20 g/plant) also had similar N content as T4 (3.92±0.00 g/plant). In the case of phosphorous and potassium, T4 (50% IF + 50% CLOF) (0.36±0.01 g/plant, 5.24±0.19 g/plant) outperformed T2 (100% IF) (0.35±0.04 g/plant, 5.19±0.23 g/plant), however, the difference was not significant.

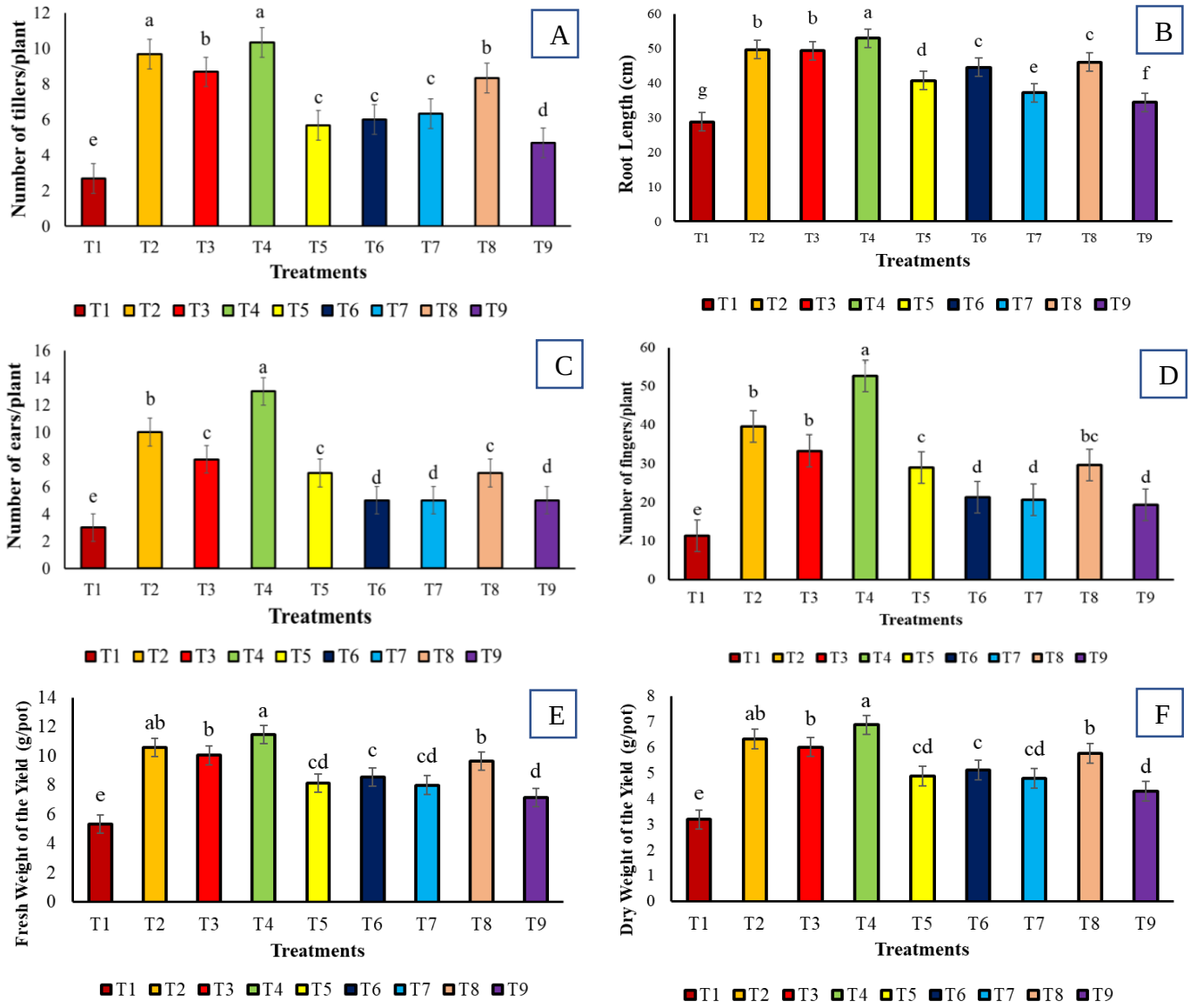


Figure 1. Effect of different treatments on A) number of tillers B) root length C) number of ears D) number of fingers E) fresh weight of the yield F) dry weight of the yield
Means (±SD) denoted by the same letter indicate no significant difference according to Duncan's test at $p<0.05$

Discussion

The T4 treatment (50% IF + 50% CLOF) produced the best results for all plant growth and reproductive parameters ($p < 0.05$). This suggests that microalgae grown in dairy wastewater could partially substitute inorganic fertilizer requirements of finger millet. In addition, T4 (50% IF + 50% CLOF), T3 (75% IF + 25% CLOF), and T8 (50% VC + 50% CLOF) demonstrated either similar or higher grain yields compared to T2 (100% IF). Previous studies have explored the application liquid organic fertilizers having *Chlorella* sp. grown in standard medium: improved growth of parameters of different plants such as green gram (Dineshkumar et al., 2020), tomato (Garcia-Gonzalez and Sommerfeld, 2016) and okra (Tiamiyu et al., 2012) have been reported. Replacing 50% of inorganic nitrogen fertilizer with microalgal biofertilizer grown in different types of wastewaters without yield reduction, has also been reported in other crops such as basil (Álvarez-González et al., 2022) and brinjal (Kariyawasam Hetti Gamage et al., 2023). In addition to nutrient contributions and efficient foliar delivery, the presence of phytohormones, particularly auxin, cytokinin, gibberellin as well as secondary metabolites in *Chlorella* biomass may have positively influenced various aspects of plant growth and development (Kholssi et al., 2018; Plaza et al., 2018; Bayona-Morcillo et al., 2020; Chookalaii et al., 2020; Loganathan et al., 2021). Foliar application enables direct absorption of nutrients through stomata, trichomes, cuticular cracks, and lenticels, allowing for rapid uptake and targeted translocation to metabolically active tissues. This combined nutrient and hormonal stimulation likely contributed to the observed improvements in plant growth and yield (Fernández et al., 2013; Battacharyya et al., 2015; Dias et al., 2016; Plaza et al., 2018).

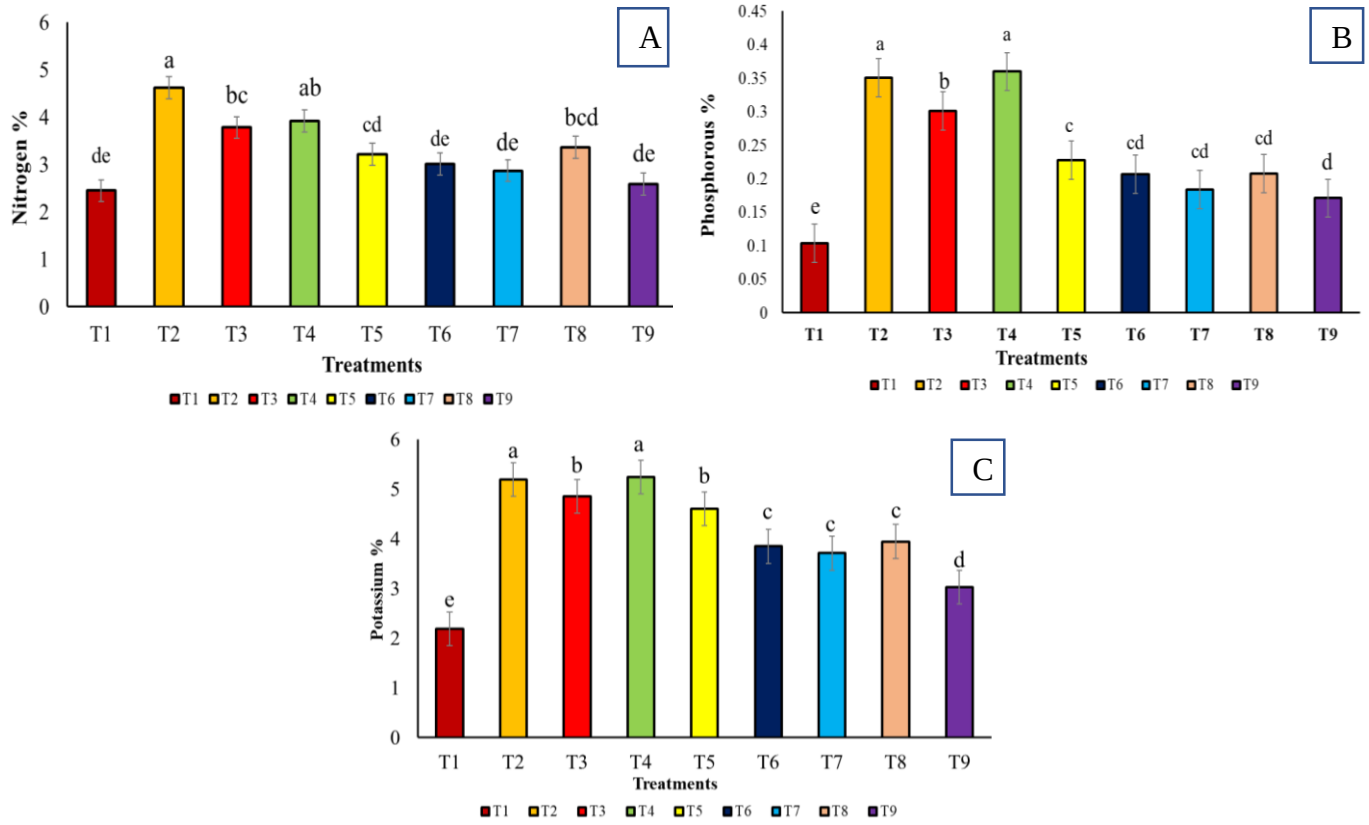


Figure 2. Leaf nutrient content A) nitrogen B) phosphorous C) potassium in finger millet plants grown with different fertilizer treatments

Means (±SD) denoted by the same letter indicate no significant difference according to Duncan's test at $p<0.05$

Similar nutrient content of plant tissue in T2 (100% inorganic fertilizers) and T4 (50% IF + 50% CLOF) indicate that 50% of the nutrient could be supplemented by foliar spray which is evident in comparable grain yield of these two treatments. In a previous study, foliar application of extracts of microalgae, showed an elevation in N-content in the tissues of shoots and roots in Chinese chives and spinach (Kim et al., 2018), indicating the positive response.

This study demonstrates that replacing half the synthetic fertilizer with CLOF maintained comparable finger millet growth and grain yield, suggesting cost-saving potential for farmers. Notably, the combination of 50% vermicompost and 50% CLOF also achieved similar dry grain yields of T2, offering an alternative for farmers preferring organic sources. However, this study was conducted under greenhouse conditions, which may not fully reflect field dynamics such as environmental variability, soil heterogeneity, and pest pressure. Therefore, further field-based trials are essential to validate these findings and evaluate the long-term agronomic, economic, and environmental impacts of CLOF use under real-world conditions. Additionally, the advantages of using microalgae as fertilizer extend beyond economic gains, offering significant environmental benefits (Arashiro et al., 2022). By transforming waste into value-added inputs, this strategy mitigates the ecological drawbacks of synthetic fertilizers; such as high energy requirements for production and pollution from nitrogen leaching, thereby contributing to more sustainable and circular agricultural systems.

Conclusion

This study shows the potential to use dairy industry wastewater as a least cost growing medium of the microalgae *Chlorella* sp. The formulated CLOF fulfilled the chemical requirements and trace metal requirements of Sri Lankan Standards Institution (SLSI) recommendations. The highest dry grain yield was recorded in T4 (50% IF + 50% CLOF), which was not significantly different from T2 (100% IF), indicating that CLOF can effectively substitute 50% of inorganic fertilizer without compromising productivity. Similarly, combinations such as T8 (50% VC + 50% CLOF) and T3 (75% IF + 25% CLOF) also yielded comparably to the inorganic fertilizer treatment, T2. This highlights the potential of CLOF as a sustainable and effective nutrient source. The novelty of this research lies in repurposing dairy wastewater into a productive resource, applying circular bioeconomy principles to agriculture by converting nutrient-rich effluent into a value-added product through microalgae cultivation. CLOF offers a dual environmental benefit

by reducing fertilizer-related pollution and minimizing nutrient discharge from dairy industries, while also providing a locally producible, low-cost alternative for synthetic fertilizers. This study therefore concludes that the microalgae *Chlorella* cultivated in dairy wastewater boosted finger millet growth and yield when combined with either inorganic fertilizers or vermicompost. While the greenhouse results are promising, field-scale validation under diverse agro-climatic conditions is needed, to evaluate the cost-benefit for large-scale adoption. Additionally, research into optimizing large-scale microalgae cultivation in different industrial wastewater types could enhance the scalability of this sustainable approach.

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