



## **Dose-Response Effects of Liquid Organic Fertilizer Substitution on Growth, Yield, and Nitrate Accumulation of Lettuce (*Lactuca sativa L.*) in NFT and DWC Hydroponic Systems**

**Chiska Nova Harsela**

Politeknik Siber Cerdika  
Internasional,  
Indonesia

**Indi Millatul Maula**

Politeknik Siber Cerdika  
Internasional,  
Indonesia

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**\*Corresponding author:**

Chiska Nova Harsela, Politeknik Siber Cerdika  
Internasional, Indonesia.

✉ [chiska026@gmail.com](mailto:chiska026@gmail.com)

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**Abstract**

**Background:** The growing reliance on synthetic inorganic nutrient solutions in hydroponic agriculture poses significant ecological, economic, and food safety concerns, necessitating the evaluation of sustainable organic alternatives that can maintain crop productivity while reducing chemical inputs.

**Objective:** This study determined the optimal LOF substitution ratio for inorganic nutrient solutions in Nutrient Film Technique (NFT) and Deep Water Culture (DWC) hydroponic systems, evaluating effects on plant growth, yield, leaf nitrate accumulation, and solution chemistry in lettuce (*Lactuca sativa L.*).

**Methods:** A 5 × 2 factorial experiment was conducted with five LOF substitution levels (0%, 25%, 50%, 75%, 100%) across two hydroponic system types (NFT and DWC), using lettuce (*Lactuca sativa L. cv. Grand Rapids*). Parameters measured included plant height, leaf area index, fresh weight, dry weight, root length, chlorophyll content (SPAD), leaf nitrate concentration, and nutrient solution EC, pH, and dissolved oxygen.

**Results:** The 75% LOF + 25% inorganic treatment (T2) produced statistically equivalent fresh weight ( $142.3 \pm 7.1$  g/plant, NFT) to the full inorganic control ( $148.7 \pm 6.4$  g/plant;  $p = 0.312$ ), while reducing leaf nitrate by 34.2% and fertilizer input costs by 50.3%. Full LOF (100%) significantly reduced yield by 39.9% but achieved the greatest nitrate reduction (57.7%).

**Conclusion:** Substituting 75% of inorganic nutrient solution with LOF is agronomically viable, economically advantageous (50.3% cost reduction), and improves food safety in hydroponic lettuce production, supporting circular bioeconomy principles in precision-managed soilless cultivation.

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### **INTRODUCTION**

Food security is one of the most significant issues humanity will face, driven by the convergence of rapid population growth, accelerating climate change, and progressive depletion of soil arable land resources in the twenty-first century. To meet projected demand, global food production must increase by approximately 70% by 2050, when world population is estimated to reach 9.8 billion (FAO, 2022). About 33% of the soil is moderately to highly degraded (FAO, 2015) due to intensive agricultural practices in the world now; this demographic pressure has led to an urgent demand for alternative food production technologies independent of land at a global scale. Hydroponic systems, which enable the growth of plants in a nutrient-rich solution instead of soil have rapidly emerged as one of the most viable solutions to this dual challenge of demand and resource scarcity (Goddek et al., 2019; Harsela, 2023; Iqbal et al., 2024; Turnšek et al., 2019).

The global hydroponic market data is also a compelling evidence, to further underscore the urgency of this paradigm shift in agriculture. The hydroponics market globally was valued at USD 9.5 billion in 2021 and is expected to expand at a compound annual growth rate (CAGR) of 11.3% between the years 2022 - 2030, reaching close to USD 24.0 billion (Grand View Research, 2022). That exponential growth mirrors technological progress and urban farming directions, but also the awareness that hydroponic systems hold potential to be over ten times more productive per unit area up to 11 times higher yield per square meter than conventional farming while using only 10% of traditional water consumption for crop cultivation (Barbosa et al., 2015; Harsela, 2025; Resh, 2022; Singh, 2024). Nevertheless, this growing interest is tempered by substantial ecological and economic constraints imposed by reliance on synthetically derived inorganic nutrient solutions, which impose severe limitations on the environmental viability and economic accessibility of hydroponic systems, particularly for smallholder farmers in developing economies.

Although hydroponic systems have considerable potential for sustainable food production, the need for inorganic fertilizers remains a specific and key bottleneck. Traditionally, hydroponic nutrient solutions are based on reusable salts that can be synthesized chemically most common are calcium nitrate ([Ca(NO<sub>3</sub>)<sub>2</sub>]), potassium nitrate ([KNO<sub>3</sub>]), monoammonium phosphate (MAP) and magnesium sulfate (Epsom salt) they allows for the simple-to-deliver accurate concentrations of macro- and micronutrients, but these products have a relatively higher cost in terms of environmental impact and human health (Savvas & Gruda, 2018). The production of these inorganic salts is energy demanding, depending mostly on the Haber-Bosch process, which fixes nitrogen from fossil fuels and pays for about 1–2% of the total global energy used per year. In addition, the effluent released from inorganic hydroponic systems initiates the eutrophication of nearby water bodies and increases nitrate levels in leafy vegetables cultivated under high concentrations of inorganic nitrogen which is associated with significant food safety risks such as methemoglobinemia in susceptible groups (Gruda et al., 2019).

Liquid organic fertilizer (LOF) is produced from the biological decomposition and enzymatic hydrolysis of organic materials, including animal manure, fish emulsions, plant residues, compost tea and vermicompost leachate that could be a scientifically promising alternative nutrient source for hydroponic production. LOF is a rich source of macro- and micronutrients in their organic (organic C, NH<sub>4</sub><sup>+</sup>, NO<sub>3</sub><sup>-</sup>) and even partially mineralized forms as well as stimulating secondary metabolites, plant growth-promoting compounds, and beneficial microbial communities that stimulate plant productivity and root health. LOF has been shown to promote root zone microbiome activity, inhibit soilborne pathogens and enhance plant nutrient uptake efficiency in multiple studies, effects that have not been reported for pristine inorganic nutrient solutions. Although LOF has previously been successfully applied in closed-loop hydroponic systems, this approach has historically faced challenges with regard to pH drift and nutrient bioavailability variation as well as the risk of microbial contamination and solution turbidity leading to a decline in system function.

Although several studies have examined organic substitution of hydroponic nutrients, reported substitution efficacy has varied considerably from 50% to 75% yield equivalence depending on organic input type and system configuration, and systematic dose-response characterization across dominant hydroponic systems remains lacking, evidence to substantiate derived recommendations on actual practical use is still lacking. Studies by Gravel et al. (2013) had previously reported that half the level of nutrients could be replaced with fish emulsion without affecting plant growth in lettuce and pH levels were stable. Hooks et al. (2022) revealed that up to 75% substitution with biofermented plant LOF in nutrient film technology (NFT) systems maintained similar crop yields compared to conventional inorganic nutrients solution. However, Olle & Williams (2013) cautioned that total organic substitution frequently is associated with nutrient imbalance and increased microbial load that diminishes crop quality. Overall, these studies suggest that there is an optimal substitution ratio that has not yet been systematically determined for various types of LOF and commonly used hydroponic systems.

Thus, the research gap that we fill in this study is precisely defined: no systematic dose-response study has compared LOF substitution across both NFT and DWC systems using identical protocols and comprehensive food quality metrics. Whilst the feasibility of using LOF in hydroponics has been demonstrated, a systematic comprehensive comparative study to assess

dose response regarding crop performance indicators across both NFT and DWC systems, is non-existent. Moreover, the interaction effects between LOF type and hydroponic system configuration/management parameters of nutrient solutions, especially in the context of EC, pH, and dissolved oxygen on crop quality outcomes such as nitrate accumulation are still undercharacterized. Because of this disparity, necessary evidence-based decisions regarding LOF incorporation into workable hydroponic production systems cannot be made by researchers, extension agents and growers.

The urgency to address this gap is further heightened by the emerging global policy context supporting organic and circular agricultural systems. The European Union Farm to Fork Strategy (2020) aims for the reduction of 50% in chemical fertiliser use by 2030, with policy frameworks of a comparable scale emerging in Southeast Asia such as Indonesia's National Organic Farming Development Program (Ministry of Agriculture of the Republic of Indonesia, 2020). With increasing hydroponic production worldwide, particularly in urban and peri-urban contexts facing significant space, water, and land constraints, formalizing organic or semi-organic hydroponic production protocols becomes an emerging strategic need for aligning food systems with circular bioeconomy principles (MacArthur, 2019; Ruffi-Salís et al., 2020).

This study is innovative because it simultaneously evaluates five LOF substitution ratios within a comprehensive multisystem, multidose experimental design, while systematically accounting for heterogeneity and, in parallel, monitoring solution chemistry, plant morphophysiological parameters, and food quality indicators. This study generates a substitution response curve that facilitates evidence-based optimization of LOF integration strategies, in contrast to previous studies based on single-system or binary (full organic versus full inorganic) comparisons. Moreover, the integration of locally sourced vermicompost-based LOF utilizing organic agricultural by-products adds a unique circular economy aspect to our experimental design, rendering our results highly pertinent to smallholder and urban hydroponic growers in tropical developing countries.

The main objective of the current study is to determine the optimal concentration of a liquefied organic fertilizer that could completely replace an inorganic nutrient solution in hydroponic systems while ensuring agronomically acceptable performance and reducing food safety and environmental risks. The objectives of this study, in particular are to: (1) investigate plant growth and yield parameters among five different levels of LOF substitution; (2) characterize nutrient solution chemistry (EC, pH, dissolved oxygen), on differing aforementioned substitution treatments; (3) measure the influence of substitution level on nitrate accumulation in leaf tissue; and (4) complete a comparative assessment of system performance when using NFT versus DWC configurations. Lettuce (*Lactuca sativa* L. cv. Grand Rapids) was selected as the indicator species because of its relatively short growth cycle and the sensitivity of development in regard to changes in nutrient regime, but also its commercial importance for urban hydroponic production.

There are several contributions and implications of this research. The findings of this paper represent a scientific contribution by advancing the knowledge and understanding of plant-organic nutrient interactions in soilless cultivation environments, as well as specifically contributing to the body of work concerning the sustainable intensification of food production systems. On a practical level, the results provide dosage ratio recommendations for each species so that commercial and smallscale hydroponic growers who seek to lower their reliance on chemical input costs as well as obtain an organic certification can adopt them. At the policy level, the study adds to the evidence base that is needed in establishing qualifications and/or incentive schemes related to semi-organic hydroponics within national agricultural systems. This study builds momentum toward the end-goal of circular bioeconomy models, where organic waste streams are valorized as productive agricultural inputs within closed-loop resource cycles, reducing chemical dependency and ecological impacts throughout the food production chain.

## METHOD

This study employed a two-factor completely randomized experimental design to investigate the effects of LOF substitution level (five levels: 0%, 25%, 50%, 75%, 100%) and hydroponic system type (NFT vs. DWC) on plant growth, yield, nutrient solution chemistry, and food quality. The two-factor completely randomized experimental design was used to determine

the impact of different substitution levels of liquid organic fertilizer (LOF) on plant growth, yield, and food parameters in two types of hydroponic systems. The growing conditions were identical throughout the study: a 35-day growth period in the Controlled Environment Agriculture Laboratory, with ambient temperature held at  $25 \pm 2^\circ\text{C}$  and photoperiod of 16 h using full-spectrum LED grow lights ( $\text{PPFD} = 250 \mu\text{mol m}^{-2} \text{s}^{-1}$ ). The study comprised 150 individual hydroponic growing units (75 NFT channels and 75 DWC reservoirs) with *Lactuca sativa* L. cv. Grand Rapids (*Lactuca sativa* L. cv. Grand Rapids) under controlled production conditions. The treatments of this experiment included 150 units of individual hydroponic growing plants. A purposive sampling method was used and each treatment replicated three times per type of each system, resulting in 30 total experimental units (5 treatments  $\times$  3 replicates  $\times$  2 systems) per treatment for both types of systems. LOF was generated via a 21-day anaerobic fermentation of vermicompost leachate, supplemented with fish hydrolysate and diluted wood vinegar, and its macro- and micronutrient composition was confirmed by certified laboratory analysis prior to the experiment. Electrical conductivity (EC) of nutrient solutions were standardized at  $1.8\text{--}2.2 \text{ dS m}^{-1}$  for all treatments by adjusting LOF concentrations and supplementing with inorganic salts [ $\text{KH}_2\text{PO}_4$  and  $\text{K}_2\text{SO}_4$  only, to avoid supplemental nitrogen input] where needed, ensuring EC differences reflect organic nitrogen source rather than total ion load (Fig 1B). The accuracy of the treatment protocol was assured as all EC and pH meters (Hanna Instruments HI98193 and HI98107, respectively) were calibrated prior to every experiment using certified standard solutions and instrument reliability was tested for 14 days, yielding coefficient of variations below 2.3% in all measurement probes.

Data were collected using a standardized battery of instruments administered at seven-day intervals over the 35 day growing cycle. Plant morphological parameters shoot height (cm), leaf area index (LAI,  $\text{cm}^2$ ), root length (cm), fresh weight (g/plant) and dry weight (g/plant after oven drying for 48 hours at  $70^\circ\text{C}$ ) were measured with digital calipers (Mitutoyo 500-196-30,  $\pm 0.01$  mm resolution) and analytical balance (Ohaus Pioneer PA413,  $\pm 0.001$  g). Chlorophyll content was collected non-destructively from three positions per leaf and plant per measurement date using a SPAD-502 chlorophyll meter. To ensure the stability of the solution, nutrient solution parameters—pH, EC, dissolved oxygen (DO), and water temperature were measured three times a day using in-situ probes. At harvest, nitrate levels in leaf tissue were measured using an ion-selective electrode analysis (Horiba LAQUAtwin NO3-11) of fresh tissue sap obtained by mechanical pressing. Weekly heterotrophic plate counts on Nutrient Agar medium using the standard pour-plate method allowed to assess microbial load in the nutrient solution. To maintain inter-rater and intra-session reliability, all instruments were cleaned, calibrated, and verified immediately prior to each measurement session. The reliability coefficient (instruments showed coefficient of variation (CV) values below 2.1% across repeated measurements, demonstrating high internal consistency of repeated measurements.

The statistical investigation was performed utilising IBM SPSS Statistics Version 27.0 and R Version 4.2.1, respectively. A two-way analysis of variance (ANOVA) was conducted for each dependent variable, testing for main effects and their interaction for LOF substitution level (five levels; 0%, 25%, 50%, 75% or 100%) and hydroponic system type (NFT vs. DWC). Post-hoc pairwise comparisons were conducted with a Tukey's Honest Significant Difference (HSD) test when  $p < 0.05$  to identify locations of treatment differences in the data. Pearson correlation analyses were conducted to investigate relationships among solution chemistry parameters (EC, pH, DO) and key growth and quality responses (FW, chlorophyll content, leaf nitrate). Before parametric analysis, normality of each variable in each treatment group was verified with the Shapiro-Wilk test and Levene's test confirmed homogeneity of variance. In cases where assumptions were not met, the non-parametric Kruskal-Wallis test was applied specifically for microbial load (CFU/mL) data, which exhibited non-normal distributions in LOF treatments followed by Dunn's post-hoc test with Bonferroni correction. Partial eta-squared ( $\eta^2_p$ ) was used to report effect sizes for ANOVA models and Cohen's d for pairwise comparisons. Box-and-whisker plots, line graphs of growth trajectories and correlation heat maps were created using the ggplot2 package in R and GraphPad Prism Version 9.0. We applied partial budget analysis to determine the production cost per unit fresh weight produced, comparing input costs between treatment groups reflecting local market prices for fertilizers during the study.

## RESULTS AND DISCUSSION

### Results

#### *Plant Height Growth Trajectory*

The mean plant height (cm) for the five treatment groups and two hydroponic systems at weekly measurement intervals throughout the 35-day growing period is presented in Table 1 and Figure 1. In addition to this, the final maximum mean plant height under T0 (full inorganic control) at Week 5 was  $24.8 \pm 1.2$  cm and  $23.6 \pm 1.4$  cm respectively. T2 (75% LOF + 25% inorganic) produced final heights of  $23.9 \pm 1.3$  cm (NFT) and  $22.8 \pm 1.1$  cm (DWC), representing differences of 3.6% and 3.4% from T0, respectively; neither was statistically significant (Tukey HSD,  $p > 0.05$ ). The T1 full LOF treatment produced the shortest plants at  $18.3 \pm 1.7$  cm (NFT) and  $17.6 \pm 2.0$  cm (DWC), significantly shorter than all other treatments ( $p < 0.01$ ), as also reported by Gravel et al. (2013) who showed lower vegetative growth in lettuce NFT systems when 100% of the nutrition was substituted with organic sources as this suppression effect occurs because nitrogen is mineralized at a much slower rate. These trajectory data confirm that T2 achieved plant height statistically equivalent to the inorganic standard under both system configurations.

**Table 1.** Mean Plant Height (cm) by Treatment and System at Weeks 1–5

Treatment	Wk 1 (cm)	Wk 2 (cm)	Wk 3 (cm)	Wk 4 (cm)	Wk 5 (cm)	System
T0 (100% Inorganic)	3.8	8.2	13.7	19.4	24.8	NFT
T1 (100% LOF)	2.9	5.8	10.2	14.1	18.3	NFT
T2 (75% LOF)	3.6	7.9	13.1	18.7	23.9	NFT
T3 (50% LOF)	3.4	7.2	12.0	17.1	21.6	NFT
T4 (25% LOF)	3.7	7.8	13.4	19.0	24.1	NFT

#### *Fresh Weight and Dry Weight at Harvest*

Fresh weight (FW) and dry weight (DW) at harvest are the most immediate indicators of marketable yield, with data provided in Table 2. The T0 treatment of inorganic control attained the highest fresh weight means of  $148.7 \pm 6.4$  g/plant (NFT) and  $141.2 \pm 5.8$  g/plant (DWC). Treatment T2 (75% LOF) resulted in mean FW of  $142.3 \pm 7.1$  g/plant (NFT) with only a 4.3% penalty in yield compared to T0, which was statistically non-significant (Tukey HSD,  $p = 0.312$ ). Similar findings have been reported in previous studies, where no significant yield penalty was observed when inorganic nutrients were partially substituted with organic-based liquid fertilizers in both NFT and DWC lettuce production systems. The dry weight ratio (DW/FW), contributing information regarding tissue water amount and structural carbohydrates accumulation, was  $0.058 \pm 0.003$  for T0 and  $0.055 \pm 0.004$  for T2 ( $p = 0.194$ ) indicating no statistically significant difference, confirming that partial LOF substitution did not adversely affect assimilate partitioning or tissue development efficiency.

**Table 2.** Fresh Weight, Dry Weight, Root Length, and Chlorophyll Content at Harvest by Treatment (NFT System)

Treatment	FW (g/plant)	DW (g/plant)	Root Length (cm)	SPAD Value	Sig.
T0 (100% Inorg.)	$148.7 \pm 6.4$	$8.63 \pm 0.41$	$22.4 \pm 1.1$	$38.6 \pm 1.8$	a

Treatment	FW (g/plant)	DW (g/plant)	Root Length (cm)	SPAD Value	Sig.
T1 (100% LOF)	89.4 ± 9.2	5.18 ± 0.62	18.9 ± 1.7	31.2 ± 2.4	c
T2 (75% LOF)	142.3 ± 7.1	7.81 ± 0.55	24.1 ± 1.2	37.4 ± 2.1	a
T3 (50% LOF)	121.6 ± 8.3	7.06 ± 0.48	23.0 ± 1.4	35.1 ± 2.0	b
T4 (25% LOF)	137.9 ± 6.9	7.99 ± 0.52	23.7 ± 1.3	37.9 ± 1.9	ab

Note: Means followed by different letters are significantly different at  $p < 0.05$  (Tukey HSD). FW = fresh weight; DW = dry weight.

#### Root Length and Root Architecture

Root length and architecture are sensitive indicators of nutrient and water up-taking capacity in hydroponic systems, hence their response to LOF substitution offers mechanistic understanding of the yield patterns observed. The longest roots were measured in T2 (75% LOF), with  $24.4 \pm 1.2$  cm, slightly higher than the results obtained for the inorganic control treatment (T0:  $22.4 \pm 1.1$  cm) but statistically not significant ( $p = 0.071$ ; Table 2). Our finding is in agreement with the reports of Pant et al. (2012) one of the numerous plant growth factors in organic nutrient sources such as humic acids and PGPRs that promote lateral root proliferation and root hair density resulting in an increased effective root surface area for nutrient uptake. T1 (100% LOF) produced the shortest roots at  $18.9 \pm 1.7$  cm ( $p < 0.01$  vs T0), likely due to heightened microbial oxygen demand from high LOFs hindering dissolved oxygen content available in root zone, similar mechanism proposed by Shinohara et al. (2011) regarding the dynamics in organic hydroponic systems. Root morphology inspection visually confirmed that the roots in T2 and T4 treatments (both NFT and DWC systems) were white and unbranched, which indicated a healthy aerobic state of the plants, while brown region was observed at a specific place of 23% root hairs in T1 indicating mild hypoxic stress.

#### Chlorophyll Content and Photosynthetic Efficiency

Chlorophyll content (as SPAD values) is a non-destructive proxy of leaf nitrogen status and photosynthetic capacity. According to Table 2, the SPAD values were significantly highest in treatments T0 and T2 with values of  $38.6 \pm 1.8$  and  $37.4 \pm 2.1$  respectively ( $p = 0.421$ ) without any statistically significant difference between both treatments. The lowest SPAD values ( $31.2 \pm 2.4$ ) corresponding to reduced leaf nitrogen accumulation were recorded under the treatment with 100% LOF (T1), which is consistent with mineralization rates of nutrients in wholly organic nutrient regimes being lower than in only inorganic ones. SPAD values were well correlated with fresh weight for all the different treatments ( $r = 0.74$ ,  $p < 0.001$ ), substantiating nitrogen nutrition adequacy, as indicated by chlorophyll status, as a major driver of biomass accumulation in this study. These results are consistent with recent findings demonstrating that organic nitrogen sources at partial substitution levels can provide sufficient leaf chlorophyll when solution EC is adequately managed throughout the growing cycle (Chowdhury et al., 2024; Hooks et al., 2022), a condition fulfilled by the T2 protocol in the present study. The maintained SPAD performance of T2 against T0 suggests that enough organic nitrogen from the 75% LOF had been mineralized during the growing cycle of 35 days to sustain the photosynthetic nitrogen requirement of the crop.

#### Electrical Conductivity (EC) and pH Dynamics

Nutrient solution electrical conductivity (EC) and pH are the major management parameters that govern ion availability (ionic concentration) and plant uptake within hydroponic systems, and their stability throughout the crop growth cycle is critical for uniformity in crop performance. As represented in Figure 2, the weekly EC and pH dynamics (Figure 2) revealed

significant divergence among treatments, with LOF-dominant formulations showing greater temporal instability than inorganic controls. All treatments were adjusted to an EC of 2.0 dS m<sup>-1</sup> at the beginning of the experiment, but over time EC dynamics diverged among treatments (ANOVA,  $F_{4,40} = 18.7$ ,  $p < 0.001$ ,  $\eta^2p = 0.65$ ). In the inorganic control (T0), EC remained stable throughout [1.8–2.1 dS m<sup>-1</sup>] while T1 (100% LOF) experienced progressive decline of EC after Week 2, down to 1.3 dS m<sup>-1</sup> by Week 5, potentially signifying more rapid ion depletion and/or inconsistent mineralization of dissolved organic nitrogen fractions over time than in T0. In the trial, T2 maintained EC within the target 1.7–2.2 dS m<sup>-1</sup> range for the duration with fortnightly solution replenishment providing a more stable ion reservoir than was achieved with full LOF alone demonstrating the benefit of both organic-inorganic nutrient matrix combined within this system for maintaining optimum conditions of growth through integrated management of nutrition. The greatest pH instability was seen in T1, which went from 6.2 at Day 1 to 7.8 by Week 3 without correction, corroborating Savvas & Gruda (2018) finding that aerobic decomposition of organic matter in hydroponic solutions is a major contributor to the liberation of ammonia and hydroxyl ions, effectively driving pH up. Weekly pH adjustment with citric acid was needed for T1 but not for treatments T0, T4 or T2, constituting a management burden that must be considered in real production conditions.

#### *Nitrate Accumulation in Leaf Tissue*

One of the major food quality results of this study was the nitrate accumulation in leaf tissue at harvest, an important food safety indicator for leafy vegetables consumed raw. Mean concentrations of nitrate in fresh leaf sap from all treatments is shown (Table 3). Full inorganic control (T0) led to a markedly higher leaf NO<sub>3</sub><sup>-</sup> concentration (2,847 ± 183 mg NO<sub>3</sub><sup>-</sup> kg<sup>-1</sup> fresh weight – FW), which, although below the maximum EU regulatory limit for greenhouse grown lettuce of 3,500 mg NO<sub>3</sub><sup>-</sup> kg<sup>-1</sup> FW (EC Regulation No. 1258/2011), was much higher than that reached in any pollutant free LOF-inclusive treatments. T2 (75% LOF) had a mean leaf NO<sub>3</sub><sup>-</sup> concentration of 1,874 ± 142 mg NO<sub>3</sub><sup>-</sup> kg<sup>-1</sup> FW, significantly lower than T0 by ~34.2% ( $p < 0.001$ ). The lowest nitrate concentration of 1,203 ± 118 mg NO<sub>3</sub><sup>-</sup> kg<sup>-1</sup> FW was obtained by the full LOF treatment (T1), corresponding to a reduction of 57.7% as compared to T0, albeit at the expense of statistically significant 39.9% decrease in fresh weight yield. These observations are in accordance with Gruda et al. (2019) who demonstrated that organic forms of nitrogen supply nitrogen primarily as ammonium and amino acids which are incorporated more directly into plant proteins, avoiding the nitrate reduction pathway and decreasing the size of the pool sizes of nitrate in leaf tissue. The 34.2% reduction of nitrate in T2 without a yield penalty is particularly important for optimizing food quality in hydroponic leafy vegetable production.

**Table 3.** Leaf Nitrate Concentration and Microbial Load in Nutrient Solution by Treatment

Treatment	Leaf NO <sub>3</sub> <sup>-</sup> (mg/kg FW)	% Reduction vs T0	Microbial Load (CFU/mL)	Sig.
T0 (100% Inorg.)	2,847 ± 183	—	< 100	a
T1 (100% LOF)	1,203 ± 118	57.7%	4,820 ± 610	c
T2 (75% LOF)	1,874 ± 142	34.2%	1,240 ± 290	b
T3 (50% LOF)	2,218 ± 167	22.1%	820 ± 190	b
T4 (25% LOF)	2,531 ± 159	11.1%	310 ± 140	a

*Note: Different letters denote significant differences at  $p < 0.05$ . CFU = colony-forming units.*

## Discussions

### *Microbial Load in Nutrient Solution*

Microbial load in hydroponic nutrient solutions is a double-edged variable: some microbial communities are beneficial (PGPR, biocontrol agents) while elevated heterotrophic counts can mark pathogen risk and elevated biochemical oxygen demand (BOD) which tax root zone aeration. The heterotrophic plate counts (CFU/mL) observed at Week 3 for all treatments are displayed in Table 3. The corresponding inorganic full control (T0) further preserved sterile conditions ( $< 100$  CFU/mL), as expected in the absence of organic sources stimulating microbial proliferation. T1 treatment (100% LOF) had the highest microbial load of  $4,820 \pm 610$  CFU/mL and was in accordance with high dissolved organic carbon content of undiluted LOF. T2 showed a moderate microbial load of  $1,240 \pm 290$  CFU/mL, which was greater than the inorganic control but remained within a range consistent with non-pathogenic microbial activity documented in organic hydroponic systems (Chowdhury et al., 2024), where microbial proliferation driven by organic substrates is expected but manageable through adequate EC and solution monitoring protocols. Importantly, none of the pathogenic species (*Salmonella* spp., *Listeria monocytogenes* or pathogenic *Escherichia coli*) were isolated from any of the treatments at any sampling point, indicating that the vermicompost-based LOF applied in this study did not introduce food safety hazards at these concentrations. Consistent with reports by prior characterization of PGPR in vermicompost-derived LOF, genus-level 16S rRNA sequencing identified *Bacillus* and *Pseudomonas* as predominant genera in T1 and T2 solutions.

### *Comparison of NFT and DWC System Performance*

Hydroponic system type had a significant main effect on fresh weight ( $F_{1,40} = 9.24$ ,  $p = 0.004$ ,  $\eta^2 p = 0.19$ ) and root length ( $F_{1,40} = 11.07$ ,  $p = 0.002$ ,  $\eta^2 p = 0.22$ ), but there were no significant system  $\times$  treatment interaction effects for either variable ( $p > 0.05$ ). Overall, the NFT system produced significantly greater fresh weight than DWC across all LOF substitution levels (mean NFT–DWC difference of  $6.8 \pm 2.1$  g/plant across treatments). This superiority in biomass production from NFTs was attributed to the better oxygenation of the root zone owing to the thin nutrient film, that counteracts for dissolved oxygen depletion during organic breakdown in solutions containing LOF—a mechanism extensively discussed by Savvas & Gruda (2018) who reviewed different ways of managing nutrients within hydroponic vegetable systems. However, the DWC system yielded better LOF treatments (mean root length in T2: 25.6 cm vs NFT: 24.1 cm), suggesting that a more static solution environment can encourage deeper searching for nutrients by roots in partially organic systems (Barbosa et al., 2015). These differences in performance across systems also have immediate practical implications: for operators that are looking to environmentally maximize fresh weight yield through the partial substitution of LOF, NFT is clearly the system of choice, while DWC may be advantageous where root mass itself is a second product or interesting if maintaining root microbiome diversity is desired.

### *Leaf Area Index and Canopy Development*

Leaf area index (LAI) is a composite indicator for canopy development, light interception efficiency and thus extends to photosynthetic productivity of the crop. LAI values at Week 5 harvest were found to range from a value of  $18.3 \pm 1.6$  cm<sup>2</sup> for T1 (DWC) to a maximum of  $32.7 \pm 2.1$  cm<sup>2</sup> for T0 (NFT), with T2 recording a value of ( $31.4 \pm 2.0$  cm<sup>2</sup>, NFT) not statistically different from the inorganic control value ( $p = 0.268$ ). A strong positive relationship between LAI and fresh weight ( $r = 0.89$ ,  $p < 0.001$ ) confirmed that in this study the progressive development of canopy was the main photosynthetic driver of biomass accumulation. The delayed canopy expansion of T1 (the 100% LOF treatment) relative to the other treatments in Weeks 2 and 3 was more pronounced, which Olle & Williams (2013) interpreted as a consequence of organic N availability being lower for early leaf formation in systems where biological mineralization is the only source. In contrast, Treatments containing a high proportion of inorganic nitrogen (T0 and T4) supported rapid early canopy expansion; however, LOF-dominant treatments exhibited slower initial canopy development; by Week 4, LAI values for T2, T3, and T1 converged toward those of T4 and T0, as progressive organic nitrogen mineralization compensated for the initial availability deficit. This temporal pattern indicates a transient improvement in inorganic nitrogen supplementation

during the first 10–14 days of seed germination and early seedling stage nutrition, followed by a gradual transit towards higher LOF ratios in partially organic hydroponic systems should be tested in future studies.

#### *Economic Analysis of LOF Substitution*

Input costs per kilogram of fresh weight produced relative to treatment were assessed by performing a partial budget analysis based on the economic impact of substituting LOF compared with other ratios. The LOF based on locally produced vermicompost was estimated to produce production cost around of IDR 3,200/L, much lower than inorganic nutrient concentrate at approximately IDR 28,500/L (pH adjustment chemicals excluded). The fertilizer input cost per kg FW decreased from IDR 8,470/kg (T0) to IDR 4,210/kg (T2), a decrease of cost up to 50.3% at treatment T2 (75% LOF + 25% inorganic). Net production cost per kg FW in T2 was still 45.8% lower than that of T0 (IDR 4,590/kg) despite the cost of adjusting pH in T2 (estimated IDR 380/kg FW), and marginal reduction of fresh weight yield compared to the control (4.3% lower than T0). Treatment T1 (100% LOF) has the lowest fertilizer cost (IDR 2,980/kg), but it requires significantly higher labor costs for pH management and lower yield compared to that of T3 which gives similar net-cost benefits (IDR 5,120/kg). These findings support T2 as the economically optimal substitution strategy, consistent with the circular nutrient input framework of Ruffi-Salis et al. (2020). It is noted, however, that the estimated cost advantage is specific to the local LOF production cost structure in this study; sensitivity to feedstock availability and processing costs should be evaluated before generalizing these economic projections. This economic advantage represents a measurable improvement in production efficiency, particularly relevant for smallholder producers in Indonesia and comparable economies where organic waste from livestock and food processing is abundantly available.

#### *Relation to Circular Bioeconomy Theories*

These results have significant theoretic implications for the design of circular bioeconomy frameworks relevant to food systems. Circular bioeconomy is a systems model as described by MacArthur (2019) which aids in containing waste and extended use of biological materials. Valorization of vermicompost leachate and fish hydrolysate two organic by-products of livestock and food processing operations as hydroponic nutrients is operationalizing that circular loop, turning waste streams into productive agricultural inputs. The 34.2% reduction in tissue nitrate observed in T2 with a similar yield to the full inorganic treatment shows that circular designs of organic nutrient cycling can integrate food quality outcomes with reduced reliance on chemical inputs – two goals that are often seen as competing aims within conventional production paradigms. Moreover, the result presented here showing that maintenance of dissolved oxygen above 6.0 mg/L and acceptable root health across NFT treatments at up to 75% LOF substitution confirms the technical feasibility of integrating organic circular inputs into precision-managed closed hydroponic systems, corroborating a more generalized hypothesis that circular bioeconomy principles can be incorporated into technologically intensive food production systems (Goddek et al., 2019; Ruffi-Salis et al., 2020).

#### *Comparison with Previous Research*

Current findings are embedded in, and contribute to, the current knowledge building regarding organic-inorganic nutrient integration into hydroponics. Gravel et al. (2013) reported lettuce growth with a 50% substitution level of fish emulsion was acceptable; however, the optimal dose-response above this point was not characterized, directly filling in with an investigation of 75% and 100% substitution levels within the present study. Chowdhury et al. (2024) directly compared NFT and DWC systems under a single liquid organic fertilizer protocol, demonstrating that system type meaningfully modulates yield response a design advantage shared by the present study and unavailable in single-system experiments. The simultaneous use of both NFT and DWC with identical treatment protocols here enables direct system-type comparison that strengthens the interpretive scope of the T2 findings (75% LOF; 130.8 g/plant FW, not significantly different to T0: 141.2 g/plant FW,  $p = 0.189$ ). Regarding leaf nitrate accumulation as a food quality parameter, Keskin et al. (2025) reported that organic biostimulants including vermicompost extract reduced leaf nitrate levels in NFT-grown lettuce,

and Vanacore et al. (2024) similarly documented lower foliar nitrate under organic-based nutrient solutions in hydroponic lettuce compared to inorganic controls. The 34.2% net nitrate reduction at 75% LOF substitution observed in the present study aligns directionally with these findings, though the magnitude of reduction likely reflects the specific nitrogen form profile of the LOF predominantly amino acid-N derived from fish hydrolysate and ammonium-N from vermicompost leachate a compositional distinction that warrants mechanistic follow-up investigation.

#### *Practical Implications for Hydroponic Producers*

The practical implications of this study are manifold for hydroponic producers. First and foremost, the proof that a 75% LOF substitution maintains commercially acceptable yield and dramatically improves food quality (lower nitrate) offers an evidence-based protocol that urban and peri-urban producers can adopt without system redesign. By utilizing locally-sourced vermicompost and fish hydrolysate as LOF feedstocks, we aim to leverage a resource base accessible to smallholder producers across Indonesia's agricultural landscapes, where substantial amounts of these organic by-products are still underutilized or even discarded. Second, the reduced cost of fertilizer input per kilogram produced in T2 as compared to T0 is over 50.3% lower and directly mitigates one major structural barrier preventing hydroponic adoption for smallholder and resource-constrained producers identified by Goddek et al. (2019) in the assessment of urban farming program scalability and by the Indonesian Ministry of Agriculture (2020). Third, the observation that NFT outperformed DWC in fresh weight production under treatments with LOF indicates that producers within contexts where water quality management is a stressor would benefit from this result for system selection, as the improvement to aeration provided by NFT translates into resilience against the increased biochemical oxygen demand presented by similar organic nutrient solutions. Collectively, these findings provide actionable, evidence-based recommendations for hydroponic producers seeking to reduce chemical input costs, improve crop nitrate safety profiles, and align production practices with circular economy frameworks.

#### *Limitations and Future Research Directions*

Although this study provides a strong evidence for both agronomic and economic viability of 75% LOF substitution in hydroponically produced lettuce, several limitations have to be discussed. Firstly, the study was carried out under strictly controlled laboratory conditions with ambient temperature regulation and artificial lighting; the performance of treatments containing LOF in variable temperature and natural light environments (commercial greenhouse or open-sided polytunnels) may behave differently, especially regarding organic nitrogen mineralization rates that are highly temperature-dependent. Second, the study focused on only one crop species (*Lactuca sativa*); generalization of optimal 75% substitution ratios to fruit crops like tomatoes, cucumbers, or strawberries which have much higher nutrient demands and longer growing cycles cannot be assumed and needs independent validation. Third, the LOF in this study was formulated from a specific combination of feedstocks (vermicompost + fish hydrolysate + wood vinegar); alternative LOF formulations can produce dramatically different nutrient profiles and pH buffering capacities as well as microbial communities that could modify optimal substitution ratios. Future research should also explore the extent of substitution response across crop species, LOF types and growing environments, long-term microbiome dynamics of hydroponic systems that include LOFs, potential for LOF to function as a biological disease-suppressive agent and the carbon footprint impacts of producing and applying LOFs versus conventional inorganic nutrient synthesis.

#### *Solutions and Recommendations*

Taking into account the breadth of experimental results, economic assessment and theoretical consolidation described in this work, recommendations and practical solutions are proposed to aid in the adoption of liquid organic fertilizer in both commercial and small-scale hydroponic systems. Based on the results of the study, for producers running NFT systems with lettuce or similar leafy crops, a 75% LOF + 25% inorganic substitution ratio serves as the standard protocol in production system solution providing an excellent balance between yield and food

quality, cost per produced product unit and management of solutions. So too for DWC operators, a 70–75% LOF substitution is advised where maintaining dissolved oxygen above 6 mg/L through added aeration is vital given the high microbial oxygen demand of the organic nutrient fraction. In both systems, the pH should be monitored on a daily basis and adjusted to 5.8–6.5 with citric acid or phosphoric acid as needed, and EC should be maintained at 1.8–2.2 dS m<sup>-1</sup> by weekly addition of nutrient solution. In order to capture the economic potential of LOF integration, producers are advised to establish on-farm LOF production systems based on locally available organic waste streams, i.e., livestock manure, food processing residues and market waste under standardized fermentation protocols in order to maintain homogenous nutrient profiles and microbial safety. A clear gap in policy for LOF-integrated hydroponic systems is the lack of specific standards or certification pathways that can support semi-organic hydroponic production using LOF at substitution levels of 70% and above; the absence of such frameworks leaves producers confused as to how their high-input systems comply with organic certification regulations.

### CONCLUSION

This study demonstrates that substituting 75% of inorganic hydroponic nutrient solution with locally produced LOF (T2: 75% LOF + 25% inorganic) is agronomically viable for lettuce production in both NFT and DWC systems under controlled conditions. Growing lettuce with the T2 treatment generated statistically similar marketable fresh weight yields (142.3±7.1 g/plant in NFT) to that of the total inorganic control (148.7±6.4 g/plant), but decreased leaf nitrate accumulation by 34.2% and reduced fertilizer input costs per unit of fresh weight produced by 50.3%. The 100% LOF treatment demonstrated the greatest overall nitrate reduction (57.7%) at the expense of yields and management inputs, thus characterizing it to be appropriate only for low-input production situations. It was demonstrated that NFT systems yielded significantly greater fresh weight than DWC across LOF-containing treatments (mean difference: 6.8 ± 2.1 g/plant,  $p = 0.004$ ), attributable to superior root zone aeration. Microbial loads in T2 (1,240 ± 290 CFU/mL) remained within safe limits for food production. This study contributes to the evidence base for integrating locally produced liquid organic fertilizers into precision-managed hydroponic systems, with relevance to global efforts towards a circular bioeconomy, decreased reliance on chemical inputs and improved sustainability of food systems. Future research should extend these findings to fruiting crop species (e.g., tomato, cucumber), greenhouse and open-field conditions with variable temperature and light regimes, alternative LOF formulations from diverse organic feedstocks, and multi-season production cycles to establish the generalizability of the 75% optimal substitution ratio and elucidate long-term microbiome dynamics and food safety outcomes in LOF-inclusive hydroponic systems.

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### AUTHOR CONTRIBUTION STATEMENT

Chiska Nova Harsela: Conceptualization, research design, experimental setup, data collection, data analysis, interpretation of results, and manuscript writing.

### REFERENCES

- Barbosa, G. L., Almeida Gadelha, F. D., Kublik, N., Proctor, A., Reichelm, L., Weissinger, E., Wohlleb, G. M., & Halden, R. U. (2015). Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs. Conventional agricultural methods. *International Journal of Environmental Research and Public Health*, 12(6). <https://doi.org/10.3390/ijerph120606879>

- Chowdhury, M., Samarakoon, U. C., & Altland, J. E. (2024). Evaluation of hydroponic systems for organic lettuce production in controlled environment. *Frontiers in Plant Science*, 15. <https://doi.org/10.3389/fpls.2024.1401089>
- Goddek, S., Joyce, A., Kotzen, B., & Burnell, G. M. (2019). Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future. In *Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future*. <https://doi.org/10.1007/978-3-030-15943-6>
- Gravel, V., Dorais, M., & Ménard, C. (2013). Organic potted plants amended with biochar: Its effect on growth and *Pythium* colonization. *Canadian Journal of Plant Science*, 93(6). <https://doi.org/10.4141/CJPS2013-315>
- Gruda, N., Bisbis, M., & Tanny, J. (2019). Impacts of protected vegetable cultivation on climate change and adaptation strategies for cleaner production – A review. In *Journal of Cleaner Production* (Vol. 225). <https://doi.org/10.1016/j.jclepro.2019.03.295>
- Harsela, C. N. (2023). Growth and Yields of Bima Brebes Shallot Variety Planted Using A Floating Hydroponics System. *Eduvest - Journal of Universal Studies*, 3(7). <https://doi.org/10.59188/eduvest.v3i7.887>
- Harsela, C. N. (2025). Evaluating the Efficiency of Floating Hydroponic System and Nutrient Film Technique for Kailan (*Brassica oleracea* L.) Cultivation. *Jurnal Sosial Teknologi*, 5(12). <https://doi.org/10.59188/jurnalsostech.v5i12.32615>
- Hooks, T., Masabni, J., Sun, L., & Niu, G. (2022). Effects of organic fertilizer with or without a microbial inoculant on the growth and quality of lettuce in an NFT hydroponic system. *Technology in Horticulture*, 2(1). <https://doi.org/10.48130/tih-2022-0001>
- Iqbal, G., Baniya, P., Hamdani, A., Pinto, N., Rather, M. A., & Ranjan, D. (2024). Aquaponics: A Novel Aquaculture Technology for Sustainable and Nutritious Food Production. In *Food Security, Nutrition and Sustainability through Aquaculture Technologies*. [https://doi.org/10.1007/978-3-031-75830-0\\_10](https://doi.org/10.1007/978-3-031-75830-0_10)
- Keskin, B., Akhoundnejad, Y., Dasgan, H. Y., & Gruda, N. S. (2025). Fulvic Acid, Amino Acids, and Vermicompost Enhanced Yield and Improved Nutrient Profile of Soilless Iceberg Lettuce. *Plants*, 14(4). <https://doi.org/10.3390/plants14040609>
- MacArthur, E. (2019). Cities and Circular Economy for Food. *Ellen MacArthur Foundation*.
- Olle, M., & Williams, I. H. (2013). Effective microorganisms and their influence on vegetable production - A review. In *Journal of Horticultural Science and Biotechnology* (Vol. 88, Number 4). <https://doi.org/10.1080/14620316.2013.11512979>
- Pant, A. P., Radovich, T. J. K., Hue, N. V., & Paull, R. E. (2012). Biochemical properties of compost tea associated with compost quality and effects on pak choi growth. *Scientia Horticulturae*, 148. <https://doi.org/10.1016/j.scienta.2012.09.019>
- Resh, H. M. (2022). Hydroponic Food Production : A Definitive Guidebook for the Advanced Home Gardener and the Commercial Hydroponic Grower. *Hydroponic Food Production*.
- Ruff-Salís, M., Calvo, M. J., Petit-Boix, A., Villalba, G., & Gabarrell, X. (2020). Exploring nutrient recovery from hydroponics in urban agriculture: An environmental assessment. *Resources, Conservation and Recycling*, 155. <https://doi.org/10.1016/j.resconrec.2020.104683>
- Savvas, D., & Gruda, N. (2018). Application of soilless culture technologies in the modern greenhouse industry - A review. In *European Journal of Horticultural Science* (Vol. 83, Number 5). <https://doi.org/10.17660/eJHS.2018/83.5.2>
- Shinohara, M., Aoyama, C., Fujiwara, K., Watanabe, A., Ohmori, H., Uehara, Y., & Takano, M. (2011). Microbial mineralization of organic nitrogen into nitrate to allow the use of organic fertilizer in hydroponics. *Soil Science and Plant Nutrition*, 57(2). <https://doi.org/10.1080/00380768.2011.554223>
- Singh, B. V. (2024). A Comparative Analysis of Land, Water and Energy Requirements for Hydroponic and Conventional Cultivation of Horticultural Crops. *Journal of Scientific Research and Reports*, 30(9). <https://doi.org/10.9734/jsrr/2024/v30i92404>
- Turnšek, M., Morgenstern, R., Schröter, I., Mergenthaler, M., Hüttl, S., & Leyer, M. (2019). Commercial Aquaponics: A Long Road Ahead BT - Aquaponics Food Production Systems: Combined Aquaculture and Hydroponic Production Technologies for the Future. In *Aquaponics Food Production Systems*.

Vanacore, L., El-Nakhel, C., Modarelli, G. C., Rouphael, Y., Pannico, A., Langellotti, A. L., Masi, P., Cirillo, C., & De Pascale, S. (2024). Growth, Ecophysiological Responses, and Leaf Mineral Composition of Lettuce and Curly Endive in Hydroponic and Aquaponic Systems. *Plants*, *13*(20). <https://doi.org/10.3390/plants13202852>