Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Valorization of Kitchen Waste and Complementary Organic Biomass into a Liquid Fertilizer: Characterization and Agronomic Validation in Capsicum chinense

H.M.J.K.K. Senanayake
Rajarata University of Sri Lanka
A.N. Kodithuwakku
Rajarata University of Sri Lanka
G.A.S. Ginigaddara
sanjeewanieg@agri.rjt.ac.lk

Rajarata University of Sri Lanka https://orcid.org/0000-0001-5561-1544

Research Article

Keywords: organic waste valorization, liquid fertilizer, nutrient recovery, circular economy, integrated fertilization, Capsicum chinense

Posted Date: November 2nd, 2026

DOI: https://doi.org/10.21203/rs.3.rs-10928060/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Abstract

Purpose

This study developed a multi-component liquid fertilizer by valorizing household kitchen residues together with complementary organic biomass and evaluated its agronomic functionality as a complementary input to mineral fertilizer.

Methods

Banana peels, eggshells, onion peels, fresh *Azolla pinnata*, and cattle manure were processed through a 21-day staged aerobic preparation. The undiluted stock was characterized for pH, electrical conductivity, and nutrient composition. Agronomic validation used container-grown *Capsicum chinense* in a completely randomized design with eight fertilizer treatments and five replications under shade-net conditions.

Results

The stock had a pH of 5.16, an electrical conductivity of 3.57 mS cm^{-1}, and contained total N (0.02%), available P (0.035%), ammonium acetate-extractable K (0.43%), and Ca (0.57%). The liquid fertilizer alone produced no marketable fruits. In contrast, several integrated liquid-fertilizer–mineral-fertilizer treatments produced vegetative growth and fruit yields that were not significantly different from full mineral fertilization. The highest numerical yield was 201 g $plant^{-1}$ with 25% liquid fertilizer + 75% mineral fertilizer.

Conclusion

The developed fertilizer was inadequate as a sole nutrient source but, when combined with mineral fertilizer, supported *Capsicum chinense* yields that were not significantly different from those of full mineral fertilization, indicating its potential as a complementary input at reduced mineral-fertilizer application rates.

1. Introduction

1.1. Organic Waste Valorization and Circular Nutrient Recovery

Biodegradable household and food-related wastes constitute a substantial organic resource stream that is frequently underutilized or disposed of through landfill and other low-value pathways. Such disposal

can contribute to greenhouse gas emissions and other environmental burdens, while many of these residues retain nutrients and organic constituents with potential for recovery [1–3]. Converting these materials into useful agricultural inputs therefore represents a practical route for moving from waste disposal toward resource recovery.

A circular-economy approach seeks to retain the value of materials by recovering nutrients from waste streams and returning them to productive use. Waste-derived fertilizers are one potential pathway because they can simultaneously create an added-value product and recycle plant nutrients that would otherwise be lost from the production-consumption system [4, 5]. Their development is also relevant to efforts to reduce dependence on exclusively mineral nutrient sources and to improve resource-use efficiency in crop production.

For fertilizer valorization to be agronomically meaningful, however, the resulting product must be characterized and its functionality demonstrated under crop-production conditions. Organic waste-derived fertilizers can vary widely in nutrient composition, solubility, stability, and nutrient-release behavior according to feedstock composition and processing method [2, 6]. Product development therefore requires both physicochemical characterization and crop-based validation rather than assuming fertilizer value from feedstock composition alone.

1.2. Kitchen Residues and Complementary Biomass as Fertilizer Feedstocks

Household kitchen residues contain a heterogeneous mixture of plant-derived materials with potential value as fertilizer feedstocks. Fruit and vegetable residues can supply potassium, calcium, magnesium, sulfur, nitrogen, and degradable organic compounds, although the concentrations and chemical forms of these constituents differ markedly among waste types [2, 7]. This variability means that a single kitchen-waste stream may not provide a sufficiently broad nutrient profile for crop production.

Banana peels are particularly associated with potassium-rich biomass and have been valorized into fertilizer materials for crop production [8]. Eggshells provide a concentrated calcium-rich residue and have been evaluated as calcium sources and soil amendments [9, 10]. Onion peels also contain mineral nutrients and biologically active compounds and have shown potential for conversion into useful agricultural inputs [11]. Combining these household residues can therefore broaden the nutrient spectrum of the recovered product compared with relying on a single residue.

Complementary organic biomass can further broaden the formulation. *Azolla pinnata* contributes biologically derived nitrogen and other nutrients through its association with nitrogen-fixing microorganisms, while cattle manure supplies organic matter together with macro- and micronutrients that can be mineralized during decomposition [12, 13]. Their inclusion provides a biological and nutrient complement to the kitchen-residue fraction of a multi-component fertilizer formulation.

Accordingly, combining banana peels, eggshells, onion peels, *A. pinnata*, and cattle manure offers a resource-recovery strategy in which chemically distinct residues and biomass sources are processed into a single liquid product. The value of such a formulation depends not only on the theoretical nutrient contribution of each feedstock but also on the chemical characteristics of the final product and its demonstrated agronomic performance.

1.3. Development of Multi-Component Liquid Fertilizers from Organic Residues

Liquid organic fertilizers can be produced from biodegradable residues through fermentation, aerobic or anaerobic decomposition, extraction, or microbial-assisted processes that transfer part of the nutrient pool into a liquid fraction [2, 6]. Compared with solid amendments, liquid products are easier to apply uniformly in container and intensive horticultural systems, although their nutrient concentrations and release characteristics are highly formulation-dependent [14].

Previous studies have shown that fertilizers derived from fruit, vegetable, and other organic wastes can support plant growth and contribute to waste recycling [15]. Nevertheless, many formulations are based on a single or limited range of feedstocks and may provide an incomplete nutrient supply, requiring integration with mineral fertilizers to meet crop demand [6, 16]. This creates a need for multi-component products in which complementary feedstocks are intentionally combined, and the resulting fertilizer is chemically characterized before agronomic use.

1.4. Research Gap, Hypothesis, and Objectives

Despite increasing interest in converting biodegradable organic wastes into fertilizer products, comparatively limited information is available on multi-component liquid formulations that combine several household kitchen residues with complementary organic biomass, characterize the resulting product, and then validate its agronomic functionality against conventional mineral fertilization. Addressing this gap is important for distinguishing a potentially useful value-added fertilizer from a waste extract whose nutrient contribution has not been demonstrated.

It was hypothesized that a multi-component liquid fertilizer produced from complementary waste and biomass feedstocks would provide measurable plant nutrients and function as a complementary nutrient source capable of supporting *Capsicum chinense* growth and yield when co-applied with reduced rates of mineral fertilizer.

Accordingly, the objectives of this study were to:

1. develop a multi-component liquid fertilizer using banana peels, eggshells, onion peels, *Azolla pinnata*, and cattle manure;
2. characterize its physicochemical and nutrient properties; and
3. validate its agronomic functionality as a complementary input under reduced mineral-fertilizer application rates in container-grown *Capsicum chinense*.

2. Materials and Methods

2.1. Study Location and Experimental Environment

The experiment was conducted at the experimental field of the Faculty of Agriculture, Rajarata University of Sri Lanka, Puliyankulama, Anuradhapura, Sri Lanka (approximately 8.37087° N latitude and 80.42061° E longitude), from May to September 2025. The study site was located in Sri Lanka's dry zone and is characterized by a tropical monsoonal climate with distinct dry and wet seasons. During the experimental period, mean daily temperature ranged from 23–32°C, while average relative humidity ranged from 65.8–77.5%. The site receives approximately 1750 mm annual rainfall, with most precipitation occurring during the Northeast monsoon.

The experimental plants were maintained within a partially enclosed shade-net structure measuring approximately 30 × 4 ft. The roof and sides of the structure were covered with 60% shade net to reduce excessive solar radiation while allowing natural ventilation and exposure to ambient environmental conditions. The structure was not completely enclosed.

UV-stabilized polyethylene grow bags containing the standardized growing medium were arranged within the shade-net structure. All plants were subjected to the same shade, ventilation, irrigation, pest management, and general crop management conditions throughout the experimental period.

2.2. Preparation of the Multi-Component Liquid Fertilizer

The kitchen waste-derived liquid fertilizer (KWLF) was prepared from household kitchen residues; banana peels (1 kg), eggshells (1 kg), and onion peels (1 kg) together with fresh *Azolla pinnata* (3 kg), dried cattle manure (3 kg), sugar (200 g), and water (5 L). Before formulation, banana peels were cut into approximately 1-1.5 cm pieces, while eggshells, onion peels, *A. pinnata*, and cattle manure were reduced to fine pieces to facilitate decomposition.

Initially, the prepared banana peels, eggshells, and onion peels were combined with 5 L of water in a plastic container and maintained under aerobic conditions. The mixture was manually aerated and mixed twice daily for approximately 5–10 min on each occasion. On Day 10, 200 g of sugar was added, after which twice-daily manual aeration and mixing were continued.

On Day 15, fresh *A. pinnata* and dried cattle manure were incorporated into the formulation. The preparation was then transferred to a 50-L plastic container, and aerobic conditions were maintained through twice-daily manual mixing and aeration until Day 21. At the completion of the preparation period, the mixture was first passed through a nylon-mesh strainer to remove coarse residues and subsequently filtered through muslin cloth to obtain the liquid fraction. The undiluted KWLF stock was stored in a cool, shaded location until use. The materials and quantities used in the formulation are summarized in Table 1.

A representative sample of the undiluted KWLF stock was collected for physicochemical and nutrient characterization before dilution and crop application. The measured properties included pH, electrical conductivity (EC), nitrogen, phosphorus, potassium, calcium, manganese, and zinc, using the analytical procedures described in Section 2.3.

Before crop application, the KWLF stock was diluted with water at a ratio of 1:10 (KWLF: water, v/v) to prepare the working solution. The KWLF application volumes presented in Table 3 therefore refer to the 1:10 diluted working solution applied per plant, rather than to the undiluted KWLF stock. The diluted KWLF was applied to the growing medium according to the treatment-specific combinations and rates described in Tables 2 and 3.

Table 1
Feedstocks and materials used in the multi-component liquid fertilizer formulation

Material	Amount used
Banana peels	1 kg
Eggshells	1 kg
Onion peels	1 kg
Fresh *Azolla pinnata*	3 kg
Dried cattle manure	3 kg
Sugar	200 g
Water	5 L

2.3. Physicochemical and Nutrient Characterization of the Liquid Fertilizer

The undiluted KWLF stock was chemically characterized before dilution and crop application. Representative samples were analyzed in triplicate. The pH and electrical conductivity (EC) were determined using calibrated digital pH and EC meters, respectively. Total nitrogen (N) was determined using the Kjeldahl method. Available phosphorus (P) was determined using the Olsen method, with a 5-mL aliquot of the undiluted KWLF stock used directly for analysis. Potassium (K) was determined by ammonium acetate extraction followed by flame-photometric determination; the undiluted KWLF sample was subjected to ammonium acetate extraction, and K in the resulting extract was quantified using a flame photometer. Calcium (Ca), manganese (Mn), and zinc (Zn) were determined using inductively coupled plasma–optical emission spectrometry (ICP-OES).

All analyses were performed on the undiluted KWLF stock, and the reported values therefore represent the chemical characteristics of the stock fertilizer before its 1:10 dilution for crop application. Results

are presented as the mean of three analytical determinations (n = 3). All laboratory analyses followed standard procedures, and nutrient concentrations were expressed as percentages where applicable.

2.4. Agronomic Validation Design and Treatments

The experiment was conducted using a completely randomized design (CRD) comprising eight fertilizer treatments with five replications per treatment. Each experimental unit consisted of a UV-stabilized polyethylene grow bag containing a single *Capsicum chinense* (Hot Dragon) plant. The grow bags were arranged within a partially enclosed 60% shade-net structure, and their positions were randomly assigned to minimize environmental variation among treatments.

The treatments consisted of different substitution levels of the formulated kitchen waste-derived liquid fertilizer (KWLF) and the recommended mineral fertilizer (RMF) to evaluate the formulated fertilizer's agronomic functionality as a complementary nutrient source under reduced mineral-fertilizer application rates. All treatments received identical crop management practices, including irrigation, weed control, and pest and disease management, throughout the experimental period. The treatment combinations are presented in Table 2.

Table 2
Fertilizer treatments used for agronomic validation of the formulated liquid fertilizer

Treatment	Kitchen waste-derived liquid fertilizer (KWLF)	Recommended mineral fertilizer (RMF)	Description
T_1	0%	0%	0% KWLF + 0% RMF Unfertilized control
T_2	0%	100%	0% KWLF + 100% RMF
T_3	100%	0%	100% KWLF + 0% RMF
T_4	50%	50%	50% KWLF + 50% RMF
T_5	75%	25%	75% KWLF + 25% RMF
T_6	25%	75%	25% KWLF + 75% RMF
T_7	60%	40%	60% KWLF + 40% RMF
T_8	40%	60%	40% KWLF + 60% RMF

2.5. Crop Establishment and Fertilizer Application

Six-week-old *Capsicum chinense* seedlings were transplanted individually into UV-treated polyethylene grow bags measuring 16 × 16 inches, with one plant per grow bag as the experimental unit. Each grow bag was filled with an equal volume of growing medium composed of compost, coir dust, and rice husk biochar at a 2:1:1 (v/v/v) ratio. Although the exact mass or volume of growing medium per bag was not recorded, the bags were filled uniformly to maintain comparable substrate quantities across all experimental units. The grow bags were maintained within the partially enclosed 60% shade-net

structure described in Section 2.1. Irrigation was applied uniformly across all treatments throughout the experimental period.

Fertilizer treatments were applied once weekly from transplanting until 60 days after transplanting (DAT). All fertilizers were applied directly to the growing medium on a per-plant basis, consistent with the media-application method used in the experiment. The unfertilized control (T_1) received no fertilizer; T_2 received 100% recommended mineral fertilizer (RMF); T_3 received 100% kitchen waste-derived liquid fertilizer (KWLF); and T_4–T_8 received the prescribed combinations of KWLF and RMF presented in Tables 2 and 3.

For each integrated treatment, KWLF, Albert Solution, and YaraMila Target were applied according to the treatment-specific weekly combination and growth-stage-specific rates shown in Table 3. During the first 30 DAT, KWLF and/or Albert Solution were applied at progressively adjusted rates according to the predetermined schedule, while YaraMila Target was not included during this period where not specified in Table 3. From 30 to 60 DAT, fixed weekly rates of KWLF, Albert Solution, and YaraMila Target were applied in the prescribed combination for each treatment. The fertilizer quantities in Table 3 are expressed on a per-plant, per-application basis.

The stated KWLF and RMF percentages represent proportional application rates relative to their respective full application rates and do not represent nutrient-equivalent proportions. Thus, the percentages indicate the relative amount of each fertilizer source applied rather than the proportion of total N, P, K, or other nutrients supplied. All treatments were maintained under the same irrigation and general crop-management conditions throughout the experiment.

Table 3
Fertilizer application rates and schedule used for container-grown *Capsicum chinense*

Treatment	Period	Diluted KWLF solution (1:10, v/v) (mL plant^{-1} application^{-1})	RMF (g plant^{-1} application^{-1})		Frequency
			Albert Solution (g plant^{-1} application^{-1})	YaraMila Target (g plant^{-1} application^{-1})	
T_1	0–30 DAT	–	–	–	–
	30–60 DAT	–	–	–	–
T_2	0–30 DAT	–	0.5–0.8	–	Weekly
	30–60 DAT	–	1.0	0.5	Weekly
T_3	0–30 DAT	250–300	–	–	Weekly
	30–60 DAT	350	–	–	Weekly
T_4	0–30 DAT	125–150	0.25–0.40	–	Weekly
	30–60 DAT	175	0.50	0.25	Weekly
T_5	0–30 DAT	187.5–225	0.125–0.20	–	Weekly
	30–60 DAT	262.5	0.25	0.125	Weekly
T_6	0–30 DAT	62.5–75	0.375–0.60	–	Weekly
	30–60 DAT	87.5	0.75	0.375	Weekly
T_7	0–30 DAT	150–180	0.20–0.32	–	Weekly
	30–60 DAT	210	0.40	0.20	Weekly
T_8	0–30 DAT	100–120	0.30–0.48	–	Weekly
	30–60 DAT	140	0.60	0.30	Weekly

Albert Solution (Grow More Inc., USA) contained N 10.5%, P_2O_5 9.1%, K_2O 16.4%, Ca 9.5%, Mg 0.86%, Fe ~ 660 mg kg^{-1}, Mn ~ 130 mg kg^{-1}, Zn ~ 140 mg kg^{-1}, B ~ 35 mg kg^{-1}, Cu ~ 35 mg kg^{-1}, and Mo ~ 20

Treatment	Period	Diluted KWLF solution (1:10, v/v) (mL plant⁻¹ application⁻¹)	RMF (g plant⁻¹ application⁻¹)		Frequency
			Albert Solution (g plant⁻¹ application⁻¹)	YaraMila Target (g plant⁻¹ application⁻¹)	

mg kg⁻¹. YaraMila Target (Yara International, Oslo, Norway) contained N 13%, P_2O_5 13%, and K_2O 21%.

KWLF was diluted with water at a ratio of 1:10 (KWLF: water, v/v) before application. All KWLF volumes shown in Table 3 refer to the diluted working solution applied per plant per application. Albert Solution and YaraMila Target rates are expressed as g plant⁻¹ application⁻¹. Fertilizers were applied weekly to the growing medium according to the prescribed treatment-specific combination. KWLF and RMF percentages represent proportional application rates relative to their respective full application rates and are not nutrient-equivalent proportions.

2.6. Data Collection

The vegetative growth, reproductive, and yield parameters measured during the experiment are summarized in Table 4.

2.6.1. Vegetative Growth Measurements

Vegetative growth was evaluated at regular intervals throughout the experimental period using standardized measurement procedures. Plant height (cm) was measured from the base of the stem at the growing medium surface to the apical growing point using a graduated measuring scale. Internodal length (cm) was measured as the straight-line distance between two adjacent leaf nodes using the measuring scale. The number of fully expanded leaves per plant was counted manually.

Leaf chlorophyll status was estimated using a portable SPAD chlorophyll meter (SPAD-502 Plus, Konica Minolta, Japan). Three fully expanded leaves from the middle canopy of each plant were measured, and the average SPAD value was recorded.

All vegetative growth parameters were assessed at regular intervals from transplanting until the commencement of fruit harvest. Vegetative growth parameters were measured weekly during the crop growth period; however, the final measurements recorded immediately before the commencement of fruit harvest were used for treatment comparison and statistical analysis presented in Table 6.

Table 4
Summary of vegetative growth, reproductive, and yield parameters measured during the experiment

Category	Parameter	Unit	Instrument/Method	Measurement Timing
Vegetative growth	Plant height	cm	Measuring scale	At regular intervals from transplanting to first harvest (Weekly from transplanting until first harvest)
	Internodal length	cm	Measuring Scale	Same as above
	Number of leaves	No. plant^{-1}	Manual count	Same as above
	SPAD chlorophyll value	SPAD units	SPAD-502 Plus chlorophyll meter	Same as above
Reproductive growth and yield	Number of fruits	No. plant^{-1}	Manual count	Cumulative across harvests at 64, 74, and 84 DAT
	Fruit length	cm	Vernier caliper	At harvest
	Fruit girth	cm	Measurement around widest portion of fruit	At harvest
	Fruit diameter	cm	Calculated as D = C/π	At harvest
	Individual fruit weight	g fruit^{-1}	Electronic balance	At harvest
	Total fruit yield	g plant^{-1}	Electronic balance; cumulative fresh weight of marketable fruits	Three successive harvests at 64, 74, and 84 DAT

2.6.2. Reproductive Growth and Yield

Reproductive growth and yield were evaluated using fruit number, fruit dimensions, individual fruit weight, and total fruit yield. The total number of marketable fruits produced by each plant was recorded over the cropping period.

At harvest, fruit length and fruit girth were measured using ten randomly selected marketable fruits from each experimental unit. Fruit length was measured from the fruit base to the distal end using a Vernier caliper and expressed in centimeters. Fruit girth was measured around the widest portion of each fruit and recorded in centimeters. Fruit diameter was subsequently calculated from the measured fruit girth using:

$D = C/\pi$

where *D* represents fruit diameter (cm), *C* represents fruit girth (cm), and π = 3.1416.

Individual fruit weight was determined using a calibrated electronic balance and expressed as g fruit^{-1}. Total fruit yield per plant was determined as the cumulative fresh weight of all marketable fruits harvested from each experimental unit and expressed as g plant^{-1}. Fruits were harvested at commercial maturity in three successive harvests at 64, 74, and 84 days after transplanting (DAT) and were weighed immediately after harvest to minimize moisture loss.

2.6.3. Growing Medium Chemical Properties

Growing-medium samples were collected at 2, 4, 6, and 8 weeks after transplanting from a designated sampling experimental unit (R1) within each treatment. The same R1 grow bag was sampled repeatedly throughout the four sampling occasions. At each sampling time, subsamples were collected from the upper, middle, and lower portions of the grow bag and combined to form a composite sample. Because repeated samples were obtained from a single designated experimental unit per treatment, the growing-medium chemical data were used for descriptive evaluation of temporal and treatment-related patterns rather than for inferential comparison among fertilizer treatments.

Growing medium pH and electrical conductivity (EC) were determined in a 1:2.5 growing medium-to-distilled water suspension using calibrated pH and EC meters. Total nitrogen (N) was analyzed by the Kjeldahl method, available phosphorus (P) by the molybdenum blue method following acid extraction, and exchangeable potassium (K) using a flame photometer. All analyses followed standard laboratory procedures, and results were expressed on a dry-weight basis.

2.7. Statistical Analysis

Experimental data were analyzed using IBM SPSS Statistics version 22 (IBM Corp., Armonk, NY, USA). Agronomic variables were analyzed according to the completely randomized design comprising eight fertilizer treatments. For vegetative growth parameters, the final measurements recorded immediately before the commencement of fruit harvest were used for treatment comparison. Treatment effects were evaluated using one-way analysis of variance (ANOVA), and treatment means were compared using Tukey's Honest Significant Difference (HSD) test at $p < 0.05$. Results are presented as mean ± standard error (SE).

For plant height, internodal length, leaf number, SPAD value, fruit number, and total fruit yield, the analysis included all eight fertilizer treatments (T_1–T_8). However, because the unfertilized control (T_1) and KWLF-only treatment (T_3) produced no marketable fruits, fruit length, fruit diameter, and individual fruit weight were analyzed only among the six fruit-producing treatments (T_2 and T_4–T_8). Missing fruit measurements for T_1 and T_3 were not treated as zero values.

Growing-medium pH, electrical conductivity (EC), total nitrogen (N), available phosphorus (P), and exchangeable potassium (K) were evaluated separately from the agronomic variables. Because samples collected at 2, 4, 6, and 8 weeks after transplanting represented repeated measurements from the same

designated grow bag (R1) within each treatment, these observations were not considered independent biological replicates. Consequently, no inferential treatment comparisons were performed for the growing-medium chemical properties; these data were summarized descriptively to illustrate temporal and treatment-related patterns.

Pearson correlation analysis was performed to assess relationships among final plant height, leaf number, SPAD chlorophyll value, fruit number, and total fruit yield using replicate-level experimental-unit observations (n = 40) rather than treatment means. Principal component analysis (PCA) was subsequently conducted using the same agronomic variables after standardization to a common scale. Principal components with eigenvalues greater than one were retained for interpretation; accordingly, only PC1 was retained for biological interpretation. Statistical significance for ANOVA was assessed at $p < 0.05$.

2.8. Use of Generative AI in Manuscript Preparation

During manuscript preparation, ChatGPT (OpenAI) was used to assist with language refinement and structural editing of author-generated text. The tool was not used to generate experimental data or conduct the statistical analyses reported in this study. All AI-assisted text was critically reviewed and verified by the authors, who take responsibility for the final manuscript.

3. Results

3.1. Physicochemical and Nutrient Characteristics of the Developed Liquid Fertilizer

The formulated kitchen waste-derived liquid fertilizer exhibited a slightly acidic pH of 5.16 and an electrical conductivity (EC) of 3.57 mS cm^{-1} (Table 5). Chemical analysis confirmed the presence of total N (0.02%), available P (0.035%), ammonium acetate-extractable K (0.43%), Ca (0.57%), and Mn (9.03%), while Zn was below the analytical detection limit.

Among the measured macronutrients, calcium occurred at the highest concentration, followed by potassium, phosphorus, and nitrogen. The comparatively low concentrations of N and P, together with the non-detectable Zn concentration, indicate that the formulated KWLF did not provide a nutritionally complete fertilizer when used as the sole nutrient source. Nevertheless, the presence of several essential plant nutrients supports its evaluation as a complementary nutrient source in combination with mineral fertilizer.

Table 5. Chemical characteristics of the undiluted kitchen waste-derived liquid fertilizer stock

Parameter	Unit	Value
pH	–	5.16
EC	mS cm^{-1}	3.57
Total N	%	0.02
Available P	%	0.035
Ammonium acetate-extractable K	%	0.43
Zn	%	<LOD
Mn	%	9.03
Ca	%	0.57
Zn was below the analytical detection limit (LOD). Values for other parameters represent means of triplicate analyses (n = 3).		

3.2. Agronomic Validation: Vegetative Growth Response

Vegetative growth of container-grown *Capsicum chinense* was significantly influenced by fertilizer treatment, as evidenced by differences in plant height, internodal length, leaf number, and SPAD chlorophyll value ($p < 0.001$; Table 6).

Plant height ranged from 14.25 cm in the unfertilized control (T_1) to 36.56 cm in T_4. Treatments T_2, T_4, T_6, T_7, and T_8 produced statistically similar plant heights, whereas T_1 and T_3 recorded significantly lower values. Internodal length followed a similar trend, with the greatest values observed in T_8 (1.78 cm) and T_6 (1.66 cm), while T_1 and T_3 had the shortest internodes.

Leaf production differed significantly among treatments. The highest leaf number was recorded in T_4 (66.60 leaves $plant^{-1}$), followed by T_6 (63.12 leaves $plant^{-1}$) and T_8 (62.62 leaves $plant^{-1}$), whereas the control and T_3 produced significantly fewer leaves.

SPAD values ranged from 13.57 in the control to 44.73 in T_2. Although T_2 recorded the highest chlorophyll value, it did not differ significantly from T_4, T_6, T_7, or T_8. In contrast, T_1 and T_3 exhibited significantly lower SPAD values.

Overall, treatments integrating the kitchen waste-derived liquid fertilizer with mineral fertilizer consistently produced superior vegetative growth compared with the unfertilized control and the liquid fertilizer applied alone.

Table 6. Effect of different fertilizer treatments on vegetative growth of container-grown *Capsicum chinense*

Treatment	Plant height (cm)	Internodal length (cm)	Leaf number (plant^{-1})	SPAD value
T_1	14.25 ± 0.80 c	0.85 ± 0.11 d	4.96 ± 0.45 c	13.57 ± 1.19 d
T_2	32.60 ± 1.72 a	1.53 ± 0.11 b	54.84 ± 10.52 ab	44.73 ± 1.03 a
T_3	16.55 ± 0.89 c	0.86 ± 0.11 d	8.17 ± 1.02 c	25.64 ± 1.03 c
T_4	36.56 ± 0.89 a	1.56 ± 0.10 b	66.60 ± 4.48 a	41.34 ± 0.92 ab
T_5	28.31 ± 1.79 b	1.27 ± 0.10 c	34.34 ± 5.89 b	38.79 ± 0.92 b
T_6	35.02 ± 0.62 ab	1.66 ± 0.10 a	63.12 ± 3.24 a	43.23 ± 0.92 ab
T_7	34.44 ± 0.99 ab	1.44 ± 0.10 b	54.46 ± 5.42 ab	41.16 ± 0.92 ab
T_8	33.79 ± 0.20 ab	1.78 ± 0.10 a	62.62 ± 1.81 a	41.94 ± 0.92 ab
F-value	58.40	10.78	23.68	98.13
p-value	<0.001	<0.001	<0.001	<0.001

Values are presented as mean ± standard error (SE). Means within a column followed by different letters are significantly different according to Tukey's Honest Significant Difference (HSD) test at $p < 0.05$.

3.3. Agronomic Validation: Reproductive Growth and Yield

Fertilizer treatments significantly affected fruit number, fruit diameter, individual fruit weight, and total fruit yield of container-grown *Capsicum chinense*, whereas fruit length did not differ significantly among treatments ($p = 0.077$; Table 7). No fruits were produced by the unfertilized control (T_1) or the KWLF-only treatment (T_3).

Fruit number differed significantly among treatments ($p < 0.001$). The highest mean fruit number was recorded in T_6 (40.80 fruits plant^{-1}), followed by T_4 (36.20), T_8 (34.80), T_7 (33.20), and T_2 (25.40). T_5 produced 21.00 fruits plant^{-1} and was significantly lower than T_2, T_6, T_7, and T_8, but did not differ significantly from T_4. Fruit length ranged from 4.60 cm in T_5 to 5.71 cm in T_4, with no significant differences among the fruit-producing treatments.

Fruit diameter was significantly affected by fertilizer treatment ($p = 0.019$). The largest mean fruit diameter was recorded in T_2 (2.84 cm), although it did not differ significantly from T_4 (2.30 cm), T_6 (2.32 cm), or T_7 (2.38 cm). Smaller mean fruit diameters were recorded in T_5 (2.14 cm) and T_8 (2.19 cm). Individual fruit weight also differed significantly among treatments ($p = 0.043$), with the highest mean value recorded in T_2 (5.14 g fruit^{-1}) and the lowest in T_6 (4.94 g fruit^{-1}); the remaining integrated treatments were intermediate.

Total fruit yield differed significantly across all treatments ($p < 0.001$), largely reflecting the absence of yield in T_1 and T_3. Among the fertilized treatments, however, no significant differences in total yield were detected, as all shared the same Tukey grouping. Numerically, T_6 produced the highest yield (201 g plant^{-1}), followed by T_4 (182 g plant^{-1}), T_8 (173 g plant^{-1}), T_7 (169 g plant^{-1}), T_2 (131 g plant^{-1}), and T_5 (106 g plant^{-1}). These results indicate that combined KWLF–RMF treatments supported fruit production and yields that were not significantly different from full mineral fertilization under the conditions of this study.

Table 7. Effect of different fertilizer treatments on reproductive growth and yield of container-grown *Capsicum chinense*

Treatment	Number of fruits (plant^{-1})	Fruit length (cm)	Fruit diameter (cm)*	Fruit weight (g fruit^{-1})	Total yield (g plant^{-1})
T_1	0.00 ± 0.00 c	–	–	–	0.00 ± 0.00 b
T_2	25.40 ± 6.82 a	4.83 ± 0.55 a	2.84 ± 0.26 a	5.14 ± 0.06 a	131.00 ± 35.51 a
T_3	0.00 ± 0.00 c	–	–	–	0.00 ± 0.00 b
T_4	36.20 ± 4.42 ab	5.71 ± 0.12 a	2.30 ± 0.08 a	5.03 ± 0.03 ab	182.00 ± 22.06 a
T_5	21.00 ± 5.51 b	4.60 ± 0.24 a	2.14 ± 0.13 b	5.04 ± 0.04 ab	106.00 ± 27.99 a
T_6	40.80 ± 4.03 a	5.11 ± 0.20 a	2.32 ± 0.07 a	4.94 ± 0.04 b	201.00 ± 19.07 a
T_7	33.20 ± 2.65 a	4.80 ± 0.17 a	2.38 ± 0.10 a	5.09 ± 0.06 ab	169.00 ± 13.73 a
T_8	34.80 ± 3.89 a	4.95 ± 0.19 a	2.19 ± 0.08 b	4.97 ± 0.03 ab	173.00 ± 19.72 a
F-value	15.22	2.33	3.46	2.77	14.72
p-value	<0.001	0.077 (n.s)	0.019	0.043	<0.001

*Fruit diameter was calculated from measured fruit girth using $D = C/\pi$.

Values are presented as mean ± standard error (SE). Means within a column followed by different letters are significantly different according to Tukey's Honest Significant Difference (HSD) test at $p < 0.05$.

3.4. Temporal Variation in Growing-Medium Chemical Properties

Growing-medium pH, electrical conductivity (EC), total nitrogen (N), available phosphorus (P), and exchangeable potassium (K) were monitored at 2, 4, 6, and 8 weeks after transplanting using the

designated sampling grow bag (R1) within each treatment (Figure 1). The measurements showed temporal and numerical variation among fertilizer treatments during the cultivation period.

Across treatments, growing-medium pH remained within a relatively narrow range, indicating limited variation in substrate acidity during the experimental period. In contrast, EC showed more pronounced numerical differences among treatments and sampling times. Treatments receiving mineral fertilizer generally exhibited higher EC values than the KWLF-only treatment, although the magnitude of this pattern varied over time.

Total N, available P, and exchangeable K also varied across treatments and sampling occasions. Higher numerical values of some nutrients were observed in selected integrated KWLF–RMF treatments, particularly for exchangeable K, while other treatments showed lower or fluctuating concentrations during the crop cycle. These temporal patterns indicate that nutrient concentrations in the growing medium changed during cultivation and differed numerically according to fertilizer treatment.

Because growing-medium samples were repeatedly collected from the same designated grow bag within each treatment, the observations were treated as descriptive rather than independent biological replicates. Consequently, no inferential statistical comparisons among treatments were performed for the growing-medium chemical properties.

3.5. Pearson Correlation Analysis

Pearson correlation analysis showed predominantly positive relationships among the measured variables (Figure 2). Plant height was strongly correlated with leaf number (r = 0.90), fruit number (r = 0.88), fruit yield (r = 0.88), and SPAD value (r = 0.84). Likewise, fruit yield exhibited strong positive correlations with fruit number (r = 1.00), SPAD value (r = 0.73), and leaf number (r = 0.88).

Overall, the correlation analysis indicated strong positive associations among vegetative growth, chlorophyll status, fruit number, and fruit yield.

3.6. Principal Component Analysis (PCA)

Principal component analysis (PCA) was performed using plant height, leaf number, SPAD value, fruit number, and total fruit yield to summarize the major patterns of variation among the measured agronomic variables. PC1 was the only principal component with an eigenvalue greater than one, with an eigenvalue of 4.414 and explaining 88.28% of the total variance (Table 8). Accordingly, PC1 was retained for interpretation, while the remaining components, which had eigenvalues below one, were not considered further.

Table 8. Eigenvalues and percentage of variance explained by principal component analysis of agronomic variables of container-grown *Capsicum chinense*

Principal Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)
PC1	4.414	88.28	88.28
PC2	0.361	7.21	95.49
PC3	0.136	2.71	98.21
PC4	0.089	1.78	99.98
PC5	0.0007	0.015	100

Table 9. Principal component loadings for agronomic variables of container-grown *Capsicum chinense*

Variable	PC1 loading
Plant height (PH)	0.958
Leaf number (LN)	0.952
SPAD chlorophyll value (SPAD)	0.868
Fruit number (FN)	0.958
Fruit yield (FY)	0.959

As shown in Table 9, PC1 had strong positive loadings for plant height (0.958), leaf number (0.952), SPAD value (0.868), fruit number (0.958), and fruit yield (0.959). The consistently high positive loadings indicate that PC1 represented an integrated growth and productivity dimension, in which greater vegetative development and chlorophyll status were associated with increased reproductive performance. Because all remaining components had eigenvalues below one, they were not retained for biological interpretation.

Discussion

4.1. Waste Valorization and Characteristics of the Developed Liquid Fertilizer

The present study valorized three household kitchen residues: banana peels, eggshells, and onion peels together with *A. pinnata* and cattle manure as complementary organic biomass to produce a multi-component liquid fertilizer. This approach converted heterogeneous biodegradable materials into a recoverable liquid product with measurable physicochemical and nutrient characteristics. The undiluted stock had a slightly acidic pH of 5.16 and an electrical conductivity of 3.57 mS cm^{-1} and contained total N (0.02%), available P (0.035%), ammonium acetate-extractable K (0.43%), Ca (0.57%), and Mn (9.03%), while Zn was below the analytical detection limit. The product therefore demonstrated nutrient-recovery potential, although its relatively low N and P concentrations indicated that it was not nutritionally complete as a stand-alone fertilizer.

The nutrient composition of the formulation can reasonably be related to the complementary characteristics of its constituent materials, although the contribution of individual ingredients was not quantified separately. Banana peels are recognized as a relatively rich source of K and have been successfully valorized into fertilizer materials capable of contributing to plant nutrient supply [8]. Eggshell-derived materials provide substantial amounts of Ca and have been evaluated as Ca sources and soil amendments in crop production [9, 10]. Onion-peel residues also contain mineral nutrients and biologically active compounds and have demonstrated potential for conversion into useful agricultural inputs [11]. In addition, *A. pinnata* can contribute biologically derived N and other nutrients through its association with N-fixing microorganisms, while cattle manure provides organic matter together with macro- and micronutrients that can undergo mineralization during decomposition [12, 13]. The use of these complementary feedstocks therefore provides a reasonable basis for the broad nutrient spectrum detected in the formulated KWLF.

The slightly acidic pH of the KWLF may favor the solubility of several plant nutrients; however, nutrient availability ultimately depends on the interaction between fertilizer chemistry, substrate properties, microbial transformations, and plant uptake. Huang et al. [17] demonstrated that nutrient solubility in soilless substrates can respond strongly to pH, with effects varying according to both nutrient and substrate composition. The EC of the undiluted KWLF stock indicates the presence of soluble ionic constituents, although EC alone does not indicate whether individual nutrients occur in forms immediately available for plant uptake. Furthermore, organic nutrient sources commonly contain a substantial proportion of nutrients in forms that require decomposition or mineralization before becoming plant available, resulting in nutrient-release patterns that differ from those of highly soluble mineral fertilizers [14].

In the present experiment, the undiluted KWLF stock was diluted 1:10 (KWLF:water, v/v) before application. Consequently, the nutrient concentrations measured in the stock should not be interpreted as the concentrations directly supplied to the root zone at each application. The relatively low N and P concentrations of the stock, together with the superior crop performance observed when KWLF was combined with mineral fertilizer, support its interpretation as a complementary nutrient source rather than a complete replacement for mineral fertilizer. Integrated use of organic and mineral nutrient sources can combine the rapid nutrient availability associated with mineral fertilizers with the more gradual nutrient release and nutrient-recycling benefits of organically derived materials [18]. Accordingly, the chemical characteristics of the formulated KWLF provide a scientific basis for its use in partial mineral-fertilizer substitution, while also indicating the need for further optimization of nutrient balance and application rate.

4.2. Agronomic Validation: Vegetative Growth and Chlorophyll Response

Fertilizer treatment significantly affected plant height, internodal length, leaf number, and SPAD chlorophyll value of *Capsicum chinense*. The integrated KWLF–mineral fertilizer treatments generally maintained vegetative growth at levels comparable with full mineral fertilization, whereas the unfertilized

control (T_1) and the KWLF-only treatment (T_3) showed markedly poorer growth. T_4 produced the greatest plant height and leaf number, while T_6 and T_8 recorded comparatively greater internodal lengths. Similarly, SPAD values in several integrated treatments were statistically comparable with those obtained under full mineral fertilization. These results indicate that partial integration of KWLF with mineral fertilizer was more effective in supporting vegetative development than application of KWLF alone.

The generally stronger vegetative response of the integrated treatments may be associated with complementary nutrient-supply characteristics of organic and mineral fertilizer sources. Mineral fertilizers provide readily soluble nutrients that can rapidly support early plant establishment and canopy development, whereas organically derived nutrients may become available more gradually through decomposition and mineralization. Combining these nutrient sources can therefore provide both immediately available nutrients and a more gradual nutrient contribution during crop development [18, 19]. Such complementary nutrient release provides a plausible explanation for the comparable plant height, leaf development, and chlorophyll status observed between several integrated treatments and the full mineral-fertilizer treatment.

In contrast, the relatively poor performance of T_3 suggests that the nutrient supply provided by KWLF alone was insufficient to meet the nutritional requirements of *C. chinense* during vegetative development. This interpretation is consistent with the low N concentration measured in the undiluted KWLF stock. Nitrogen plays a central role in chlorophyll synthesis, protein formation, photosynthetic activity, and canopy development, and insufficient N availability can therefore restrict both leaf production and overall vegetative growth [20]. Although the KWLF contained several essential nutrients, its low N and P concentrations may have limited its ability to support vigorous plant development when applied without supplementary mineral fertilizer. The response of T_3 therefore supports the interpretation of KWLF as a complementary nutrient source rather than a complete fertilizer replacement.

Potassium and calcium present in the KWLF may also have contributed to the vegetative performance of the integrated treatments. Potassium is involved in enzyme activation, stomatal regulation, assimilate transport, and plant water relations [21], while calcium plays important structural and regulatory roles in cell-wall stability and membrane function [22]. However, plant tissue nutrient concentrations and nutrient uptake were not measured in the present study. Consequently, the improved growth observed under integrated fertilization cannot be attributed directly to the uptake of individual nutrients. Rather, the results indicate that combining KWLF with mineral fertilizer provided a nutrient-supply regime that was more compatible with the vegetative requirements of *C. chinense* than KWLF applied alone.

4.3. Agronomic Validation: Reproductive Growth, Fruit Development, and Yield

Reproductive performance of *Capsicum chinense* was strongly influenced by fertilizer treatment. The unfertilized control (T_1) and the KWLF-only treatment (T_3) produced no marketable fruits, whereas the full mineral-fertilizer treatment (T_2) and all integrated KWLF–RMF treatments supported fruit production. Fruit number, fruit diameter, individual fruit weight, and total fruit yield were significantly affected by fertilizer treatment, while fruit length did not differ significantly among the fruit-producing treatments. T_2

produced the largest numerical fruit diameter and individual fruit weight, whereas T_6 (25% KWLF + 75% RMF) produced the highest numerical fruit number and total yield. These results indicate that sufficient nutrient availability was particularly important for successful fruit development and yield formation.

The absence of fruit production in T_3, despite application of KWLF at the full prescribed rate, suggests that KWLF alone did not supply nutrients in sufficient amounts or at a rate synchronized with crop demand during reproductive development. This interpretation is consistent with the relatively low N and P concentrations measured in the formulated KWLF. Reproductive development in pepper is particularly sensitive to limitations in assimilate and nutrient supply because flowering, fruit retention, and fruit growth impose substantial demands on plant resources. Wubs et al. [23] reported that reproductive-organ abortion in pepper is closely associated with competition for assimilates as well as environmental and nutritional constraints. Similarly, Y.-F. Yang et al. [24] demonstrated that appropriate nutrient supply and distribution are important for maintaining pepper growth and productivity. Thus, the failure of T_3 to produce fruits is consistent with the interpretation that the nutrient contribution from KWLF alone was inadequate to sustain both vegetative and reproductive requirements.

In contrast, all integrated KWLF–RMF treatments produced marketable fruits, suggesting that the mineral-fertilizer component compensated for limitations in nutrient availability from KWLF. Mineral fertilizers provide nutrients in readily available forms, whereas nutrients from organic materials are generally released more gradually through decomposition and mineralization. Combining the two sources may therefore improve synchronization between nutrient availability and crop demand during fruit set and development. This interpretation is consistent with evidence that integrated organic–mineral fertilization can enhance nutrient availability and crop performance [18], while a broader meta-analysis by Yang et al. [25] showed that combined organic and inorganic fertilization can maintain crop productivity while reducing reliance on mineral fertilizer inputs.

Although total fruit yield differed significantly when all eight treatments were considered, this overall effect was largely associated with the zero yields recorded for T_1 and T_3. Among the six fruit-producing treatments, total yield did not differ significantly according to Tukey's HSD test. T_6 produced the highest numerical yield at 201 g plant^{-1}, followed by T_4 (182 g plant^{-1}), T_8 (173 g plant^{-1}), T_7 (169 g plant^{-1}), T_2 (131 g plant^{-1}), and T_5 (106 g plant^{-1}), but all six treatments belonged to the same statistical group. Therefore, T_6 should be described as producing the highest numerical yield, rather than as being statistically superior to full mineral fertilization or the other integrated treatments.

Of particular relevance to partial mineral-fertilizer substitution, treatments containing substantial proportions of KWLF maintained yields within the same statistical group as full mineral fertilization. For example, T_7 (60% KWLF + 40% RMF) produced 169 g plant^{-1}, while T_5 (75% KWLF + 25% RMF) produced 106 g plant^{-1}. These findings indicate that KWLF has potential to replace a proportion of the mineral-fertilizer application rate when used as a complementary nutrient source. However, the absence of significant differences among fertilized treatments does not establish formal agronomic equivalence or non-inferiority. Consequently, the present results should be interpreted as evidence of potential for

partial mineral-fertilizer substitution, rather than as proof of an optimum replacement rate. Further multi-season and multi-location experiments, together with nutrient-use-efficiency and economic assessments, are required before a specific KWLF–RMF combination can be recommended.

4.4. Temporal Patterns in Growing-Medium Chemical Properties

Growing-medium chemical properties showed temporal and numerical variation among fertilizer treatments during the cultivation period. However, because samples were collected repeatedly from the same designated grow bag within each treatment at 2, 4, 6, and 8 weeks after transplanting, these measurements did not represent independent biological replicates. The observed patterns in pH, electrical conductivity (EC), total N, available P, and exchangeable K should therefore be interpreted descriptively rather than as statistically demonstrated treatment effects.

Growing-medium pH remained within a relatively narrow range across treatments and sampling times, suggesting that none of the fertilizer combinations produced pronounced numerical changes in substrate acidity during the experimental period. Maintenance of a relatively stable pH is important in container cultivation because substrate pH strongly influences nutrient solubility and potential availability to plant roots. Huang et al. [17] demonstrated that changes in the pH of soilless container substrates can substantially alter macronutrient solubility, including that of N, P, and K. Differences between organic and mineral fertilizer sources may also influence root-zone nutrient dynamics because the chemical form and transformation of nutrients differ between fertilizer types [14].

Electrical conductivity exhibited greater numerical variation than pH, particularly in treatments receiving mineral fertilizer. This pattern may reflect the rapid addition of soluble ions from mineral fertilizer sources, whereas nutrients contained in organically derived materials may become soluble more gradually. EC is widely used as an indicator of soluble salt concentration in container media, and excessive EC can adversely affect plant water relations and nutrient acquisition [26]. Fertilizer management has similarly been shown to influence substrate EC and nutrient conditions in pepper production systems [27]. Consequently, the relatively higher EC values observed in some RMF-containing treatments are consistent with a greater immediate contribution of soluble fertilizer-derived ions; however, because the root-zone measurements were not independently replicated, these differences cannot be attributed statistically to fertilizer treatment.

Total N, available P, and exchangeable K also fluctuated numerically over the four sampling occasions. Such temporal patterns may result from several simultaneous processes, including fertilizer addition, decomposition and mineralization of organic materials, plant nutrient uptake, immobilization, adsorption or precipitation, and nutrient losses from the growing medium. Organic nutrient sources generally differ from highly soluble mineral fertilizers because a proportion of their nutrients must undergo transformation before becoming available for plant uptake. Martínez-Alcántara et al. [14] reported differences in nutrient-release characteristics between liquid organic and mineral fertilizers, supporting the possibility that the temporal variation observed among KWLF, RMF, and integrated treatments reflected differences in nutrient-release dynamics.

The comparatively high numerical exchangeable K concentrations observed at some sampling times in integrated treatments may also be related partly to the composition of the KWLF. Banana peel, one of the major components of the formulation, is recognized as a substantial source of K, and banana-peel-derived fertilizers have been reported to contribute K to crop-production systems [8]. Nevertheless, the present study did not measure plant tissue K concentrations or nutrient uptake. Therefore, higher numerical K concentrations in the growing medium cannot be interpreted as evidence of greater K uptake or as a direct explanation for the improved growth and yield observed in some integrated treatments.

Overall, the observed root-zone patterns are consistent with the general concept of integrated organic-mineral nutrient management, in which mineral fertilizers provide a relatively rapid nutrient supply while organically derived materials may contribute nutrients more gradually through decomposition and mineralization. Integrated organic and inorganic fertilization has been associated with improved nutrient availability and crop productivity in other production systems [18]. Nevertheless, the present growing-medium data provide exploratory evidence only, because a single designated grow bag per treatment was repeatedly sampled. Future experiments should use independently replicated growing-medium sampling units and repeated measurements to determine statistically whether KWLF–RMF combinations influence root-zone pH, EC, nutrient-release patterns, and nutrient availability during crop development.

4.5. Integrated Agronomic Response

Pearson correlation analysis revealed strong positive associations among plant height, leaf number, SPAD chlorophyll value, fruit number, and total fruit yield. Plant height was strongly associated with leaf number (r = 0.90), fruit number (r = 0.88), fruit yield (r = 0.88), and SPAD value (r = 0.84), while fruit yield was positively associated with leaf number (r = 0.88) and SPAD value (r = 0.73). Fruit number and total fruit yield showed an exceptionally strong association (r = 1.00). These relationships indicate that vegetative development, chlorophyll status, and reproductive productivity responded in a coordinated manner to fertilizer treatment rather than as independent agronomic traits.

The positive relationships between plant height, leaf number, SPAD value, and yield are biologically plausible because adequate vegetative development provides the photosynthetic surface required to support reproductive growth. SPAD measurements provide an indirect indication of leaf chlorophyll status, which is influenced by plant N nutrition and is commonly associated with photosynthetic capacity. Nitrogen plays a major role in chlorophyll formation, leaf development, photosynthesis, and biomass production [20]. In pepper, adequate nutrient availability during vegetative and reproductive development is particularly important because restricted nutrient supply can limit canopy development and subsequently constrain fruit retention and productivity [23, 24]. However, plant tissue nutrient concentrations and photosynthetic rates were not measured in the present study. Consequently, the observed associations involving SPAD should not be interpreted as direct evidence of enhanced nutrient uptake or photosynthetic activity.

The very strong relationship between fruit number and total yield requires particularly cautious interpretation. Fruit number is itself a direct component of cumulative fruit yield, together with individual fruit weight; therefore, a strong correlation between these variables is partly expected mathematically rather than representing an independent physiological relationship. Wubs et al. [23] emphasized the importance of reproductive-organ retention in determining pepper productivity, while Yang et al. [25] reported that responses to organic and combined organic–inorganic fertilization can involve coordinated changes in vegetative growth and reproductive performance. Thus, the r = 1.00 relationship observed between fruit number and yield should be interpreted primarily as evidence that variation in fruit number was a major contributor to variation in total yield in this experiment, rather than as evidence of a separate causal mechanism.

Principal component analysis further supported this coordinated response. PC1 explained 88.28% of the total variance and showed high positive loadings for plant height (0.958), leaf number (0.952), SPAD value (0.868), fruit number (0.958), and fruit yield (0.959). The uniformly positive and relatively high loadings indicate that PC1 represented an integrated growth–productivity dimension, in which greater vegetative development and chlorophyll status occurred together with stronger reproductive performance. Comparable coordinated responses to fertilizer management have been reported in pepper, where nutrient supply can simultaneously influence vegetative growth, nutrient acquisition, and crop productivity [24, 27].

Taken together, the correlation and PCA results indicate that fertilizer effects on *C. chinense* were expressed through interconnected changes in vegetative growth, chlorophyll status, fruit production, and yield. This pattern is consistent with the broader concept that balanced nutrient management can support several interdependent physiological and agronomic processes contributing to crop productivity [18]. Nevertheless, both correlation and PCA describe patterns of association and do not establish causality. Future studies incorporating plant tissue nutrient analysis, direct photosynthetic measurements, nutrient-use-efficiency indices, and independently replicated root-zone nutrient measurements would be required to determine the physiological mechanisms underlying these relationships.

4.6. Implications for Waste Valorization, Product Development, and Study Limitations

The present findings demonstrate that selected household kitchen residues can be incorporated with complementary organic biomass into a liquid product with measurable nutrient content and agronomic functionality. The agronomic validation also defined an important limitation of the product: KWLF applied alone did not support satisfactory growth or marketable fruit production, whereas its co-application with mineral fertilizer maintained vegetative growth and fruit yield at levels not significantly different from full mineral fertilization under the conditions evaluated. The developed fertilizer should therefore be regarded as a complementary value-added nutrient input rather than a complete mineral-fertilizer replacement.

From a product-functionality perspective, the absence of significant yield differences among the fruit-producing fertilized treatments provides preliminary evidence that the developed liquid fertilizer can be used alongside reduced mineral-fertilizer application rates without an obvious yield penalty under the specific experimental conditions. However, the treatment percentages represented proportional application rates rather than nutrient-equivalent substitution. Consequently, the study does not establish agronomic equivalence, nutrient-equivalent replacement, or an optimum substitution rate.

Valorization of kitchen residues into a usable fertilizer product can contribute to nutrient recycling by redirecting biodegradable materials toward productive use. The approach may be particularly relevant to household, peri-urban, and smallholder horticultural systems in which such residues are locally available and container cultivation is practiced. Nevertheless, the present study did not quantify waste diversion, mass recovery, life-cycle environmental benefits, or economic savings. Claims regarding circular-economy performance, environmental sustainability, or cost-effectiveness should therefore be treated as potential benefits requiring direct evaluation rather than demonstrated outcomes.

Several limitations should be considered when interpreting the findings. First, the experiment was conducted during a single crop cycle at one location under shade-net cultivation conditions, which limits the extent to which the results can be generalized to other seasons, environments, substrates, or production systems. Second, growing-medium chemical properties were monitored by repeatedly sampling only one designated grow bag per treatment. Consequently, these observations were descriptive and cannot be used to infer statistically significant fertilizer effects on root-zone nutrient dynamics. Third, plant tissue nutrient concentrations, nutrient uptake, nutrient-use efficiency, photosynthetic activity, organic matter dynamics, and microbial processes were not measured. Therefore, the physiological and biogeochemical mechanisms responsible for the observed plant responses could not be directly established.

In addition, fertilizer safety, microbial quality, storage stability, shelf life, nutrient-release kinetics, and batch-to-batch consistency of the KWLF were not evaluated. Economic feasibility, labour requirements, and the costs associated with preparation and application were also beyond the scope of the study. These factors are important if the formulation is to progress from experimental evaluation to practical farm or household use.

Future research should therefore evaluate the KWLF across multiple seasons, locations, crops, and growing-media conditions using independently replicated root-zone sampling. Studies should also quantify plant nutrient uptake and nutrient-use efficiency, characterize nutrient-release patterns, determine microbiological and chemical safety, assess shelf life and formulation stability, and conduct economic analyses. Such work would allow the optimum KWLF-mineral fertilizer combination and application schedule to be identified and would provide a stronger basis for determining whether the formulation can reliably reduce mineral-fertilizer inputs in horticultural production.

Conclusion

This study demonstrated the feasibility of valorizing selected household kitchen residues, together with complementary organic biomass, into a multi-component liquid fertilizer with measurable nutrient content and agronomic functionality. The developed fertilizer contained total N, available P, ammonium acetate-extractable K, Ca, and Mn; however, its relatively low N and P concentrations limited its effectiveness as a sole nutrient source. Accordingly, the liquid fertilizer alone did not support satisfactory vegetative growth or marketable fruit production in container-grown *Capsicum chinense*.

Co-application of the developed liquid fertilizer with mineral fertilizer substantially improved crop performance. Several integrated treatments produced vegetative growth and fruit yields that were not significantly different from full mineral fertilization. The treatment receiving 25% of the full liquid-fertilizer application rate together with 75% of the recommended mineral-fertilizer rate produced the highest numerical yield (201 g plant^{-1}), although yield did not differ significantly among the fruit-producing fertilized treatments. These findings demonstrate the agronomic functionality of the developed product as a complementary nutrient input and indicate its potential to reduce mineral-fertilizer application rates under the conditions evaluated.

The findings provide a strong basis for further optimization of the developed liquid fertilizer as a complementary nutrient input. Future studies incorporating nutrient-equivalent formulations, product safety and stability, batch consistency, nutrient recovery and mass balance, plant nutrient-use efficiency, economic feasibility, and environmental performance will help identify an effective substitution rate and support the development of a scalable waste-valorization pathway.

Declarations

Disclosure statement

The authors declare that they have no competing interests.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data Availability

The datasets generated and/or analyzed during the current study are available from the corresponding author on reasonable request.

References

1. UNEP (United Nations Environment Programme): Food waste index report 2021. United Nations Environment Programme (2021). https://www.unep.org/resources/report/unep-food-waste-index-report-2021

2. Kulikowska, D., and K. Bernat: Conversion of kitchen waste into sustainable fertilizers: Comparative effectiveness of biological, microbial, and thermal treatments in a ryegrass growth trial. Applied Sciences 15: 5281 (2025). https://doi.org/10.3390/app15105281
3. Rex, P., N. Meenakshisundaram, and P. Barmavatu: Sustainable valorisation of kitchen waste through greenhouse solar drying and microwave pyrolysis: Technology readiness level for the production of biochar. Journal of Environmental Health Science and Engineering 22: 381–395 (2024). https://doi.org/10.1007/s40201-024-00909-x
4. Aborisade, M. A., H. Long, H. Rong, A. Kumar, B. Cui, O. A. Oladeji, O. P. Okimiji, B. T. Oba, and D. Guo: Bio-based fertilizers from waste: Nutrient recovery, soil health, and circular economy impacts. Toxics 14: 90 (2026). https://doi.org/10.3390/toxics14010090
5. Rizwan, D., S. B. R. Kirmani, and F. A. Masoodi: Circular economy in the food systems: A review. Environmental Quality Management 34 (2025). https://doi.org/10.1002/tqem.70096
6. Chand, J., R. Reza, M. Chowdhury, J. V. Hager, P. K. Dash, N. Akter, and L. Cammarisano: Liquid organic fertilizers in soilless cultivation: A systematic review of production, performance, challenges, and future prospects. Frontiers in Sustainability 7: 1775182 (2026). https://doi.org/10.3389/frsus.2026.1775182
7. Khanyile, N., N. Dlamini, A. Masenya, N. C. Madlala, and S. Shezi: Preparation of biofertilizers from banana peels: Their impact on soil and crop enhancement. Agriculture 14: 1894 (2024). https://doi.org/10.3390/agriculture14111894
8. Ma'mor, A. S., N. H. Wahida, and A. R. Nur Firdaus: The application of eggshell and fruit peels as soil amendment on the growth performance and yield of corn (*Zea mays* L.). IOP Conference Series: Earth and Environmental Science 1182: 012040 (2023). https://doi.org/10.1088/1755-1315/1182/1/012040
9. Vu, N.-T., T.-H. Dinh, T.-T.-C. Le, T.-T.-H. Vu, T.-T.-T. Nguyen, T.-A. Pham, N.-L. Vu, et al: Eggshell powder as calcium source on growth and yield of groundnut (*Arachis hypogaea* L.). Plant Production Science 25: 413–420 (2022). https://doi.org/10.1080/1343943X.2022.2120506
10. Zhang, Q., Y. Kong, J. Masabni, and G. Niu: Onion peel waste has the potential to be converted into a useful agricultural product to improve vegetable crop growth. HortScience 59: 578–586 (2024). https://doi.org/10.21273/HORTSCI17694-24
11. Eghball, B., D. Ginting, and J. E. Gilley: Residual effects of manure and compost applications on corn production and soil properties. Agronomy Journal 96: 442–447 (2004). https://doi.org/10.2134/agronj2004.4420
12. Yang, Y., Y. Yang, S. Deng, and Z. Ying: Role of Azolla in sustainable agriculture and climate resilience: A comprehensive review. Frontiers in Plant Science 16: 1661720 (2025). https://doi.org/10.3389/fpls.2025.1661720
13. Martínez-Alcántara, B., M.-R. Martínez-Cuenca, A. Bermejo, F. Legaz, and A. Quiñones: Liquid organic fertilizers for sustainable agriculture: Nutrient uptake of organic versus mineral fertilizers in citrus trees. PLOS ONE 11: e0161619 (2016). https://doi.org/10.1371/journal.pone.0161619

14. Ramamoorthy, K., R. Dhanraj, N. Vijayakumar, Y. Ma, S. Al Obaid, and M. Narayanan: Vegetable and fruit wastes: Valuable source for organic fertilizer for effective growth of short-term crops: *Solanum lycopersicum* and Capsicum annum. Environmental Research 251: 118727 (2024). https://doi.org/10.1016/j.envres.2024.118727
15. Sande, T. J., H. J. Tindwa, A. M. T. Alovisi, M. J. Shitindi, and J. M. Semoka: Enhancing sustainable crop production through integrated nutrient management: A focus on vermicompost, bio-enriched rock phosphate, and
16. inorganic fertilisers—a systematic review. Frontiers in Agronomy 6: 1422876 (2024). https://doi.org/10.3389/fagro.2024.1422876
17. Huang, J., P. R. Fisher, W. R. Argo, K. Y. Jeong, and J. Altland: Macronutrient solubility in response to the pH of soilless container substrates. Journal of Soil Science and Plant Nutrition 25: 3224–3240 (2025). https://doi.org/10.1007/s42729-025-02331-0
18. Sharma, S., T. Ghosh, N. Gupta, and S. S. Walia: Long-term effects of integrated organic and inorganic fertilization on soil properties, nutrient use efficiency, and crop yield in a rice–wheat system. Frontiers in Soil Science 6: 1869636 (2026). https://doi.org/10.3389/fsoil.2026.1869636
19. Sicignano, M., R. Beleggia, L. del Piano, T. Enotrio, S. Suriano, F. Raimo, and D. Trono: Effect of combining organic and inorganic fertilizers on the growth of hemp (*Cannabis sativa* L.) plants and the accumulation of phytochemicals in their inflorescence. Plants 14: 1519 (2025). https://doi.org/10.3390/plants14101519
20. Fathi, A: Role of nitrogen (N) in plant growth, photosynthesis pigments, and N use efficiency: A review. Agrisost 28: 1–8 (2022). https://doi.org/10.5281/zenodo.7143588
21. Oosterhuis, D. M., D. A. Loka, E. M. Kawakami, and W. T. Pettigrew: The physiology of potassium in crop production. In Advances in agronomy, vol. 126, ed. D. L. Sparks, 203–233. Academic Press (2014). https://doi.org/10.1016/B978-0-12-800132-5.00003-1
22. Thor, K: Calcium—Nutrient and messenger. Frontiers in Plant Science 10: 440 (2019). https://doi.org/10.3389/fpls.2019.00440
23. Wubs, A. M., E. Heuvelink, and L. F. M. Marcelis: Abortion of reproductive organs in sweet pepper (*Capsicum annuum* L.): A review. Journal of Horticultural Science and Biotechnology 84: 467–475 (2009). https://doi.org/10.1080/14620316.2009.11512550
24. Yang, Y.-F., F.-B. Liu, W.-K. Yang, Y.-K. Xi, T. Liang, T. Zhang, and X.-Z. Wang: Effects of optimized fertilizer and water management on nutrient uptake and distribution in open-field peppers in Southwest China. Journal of Plant Nutrition and Fertilizers 31 (12): 2517–2527 (2025). https://doi.org/10.11674/zwyf.2025057
25. Yang, J., A. K. Mattoo, Y. Liu, F. Zvomuya, and H. He: Trade-offs of organic and organic-inorganic fertilizer combinations in tomato quality and yield: A global meta-analysis (1992–2021). European Journal of Agronomy 151: 126985 (2023). https://doi.org/10.1016/j.eja.2023.126985
26. Hanlon, E. A., B. L. McNeal, and G. Kidder: Soil and container media electrical conductivity interpretations (CIR1092/SS117). UF/IFAS Extension, University of Florida (2017).

https://edis.ifas.ufl.edu/publication/SS117

27. Liu, J., J. Masabni, and G. Niu: Organic fertilizer optimization for enhanced growth and nutrient uptake in bell pepper transplants (*Capsicum annuum* L.). Horticulturae 11: 1066 (2025). https://doi.org/10.3390/horticulturae11091066

Figures

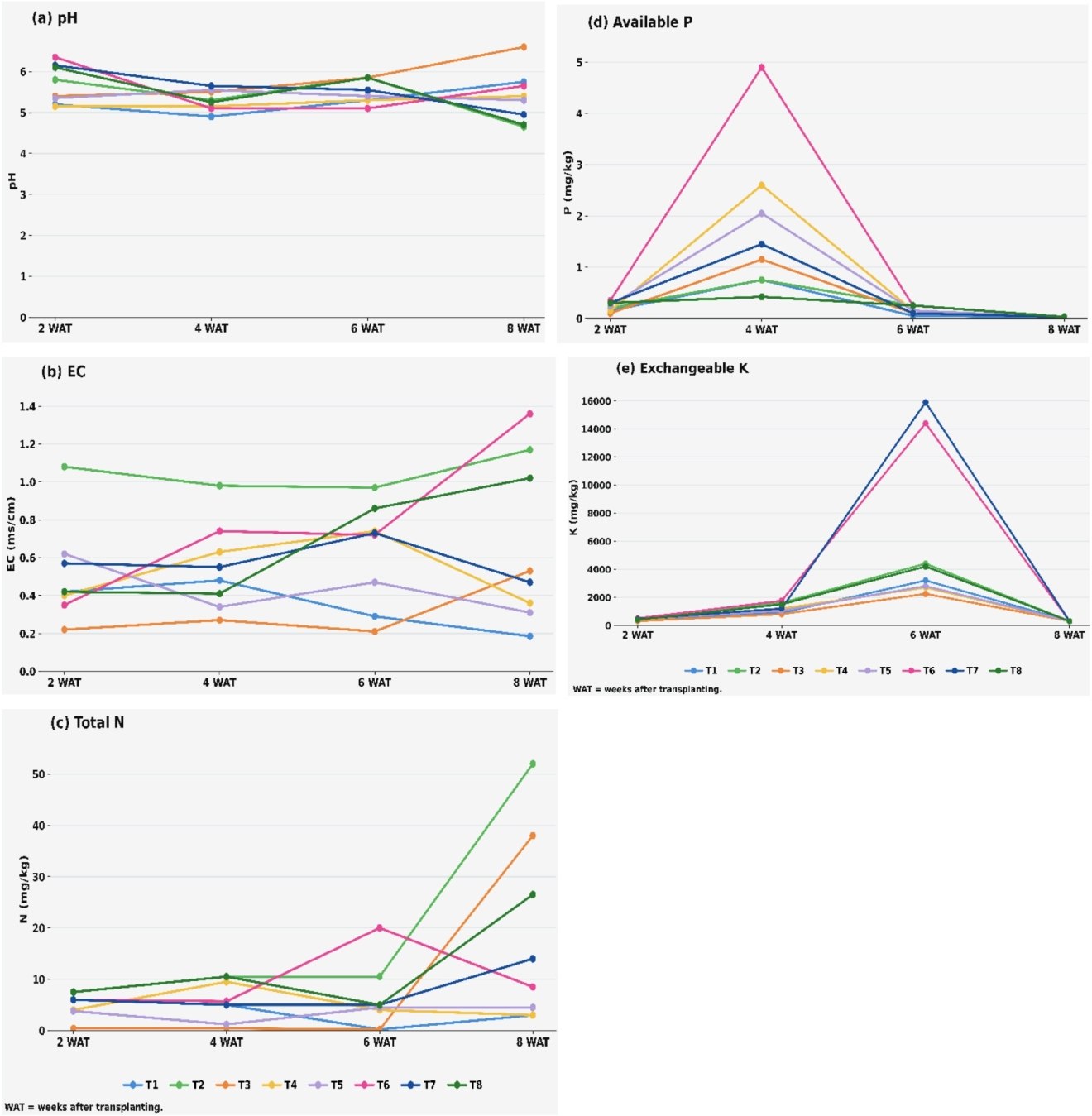


Figure 1

Temporal variation in growing-medium (a) pH, (b) electrical conductivity (EC), (c) total N, (d) available P, and (e) exchangeable K under different fertilizer treatments during cultivation of *Capsicum chinense*. (Values represent repeated measurements from one designated grow bag per treatment and are presented descriptively; no inferential treatment comparisons were performed).

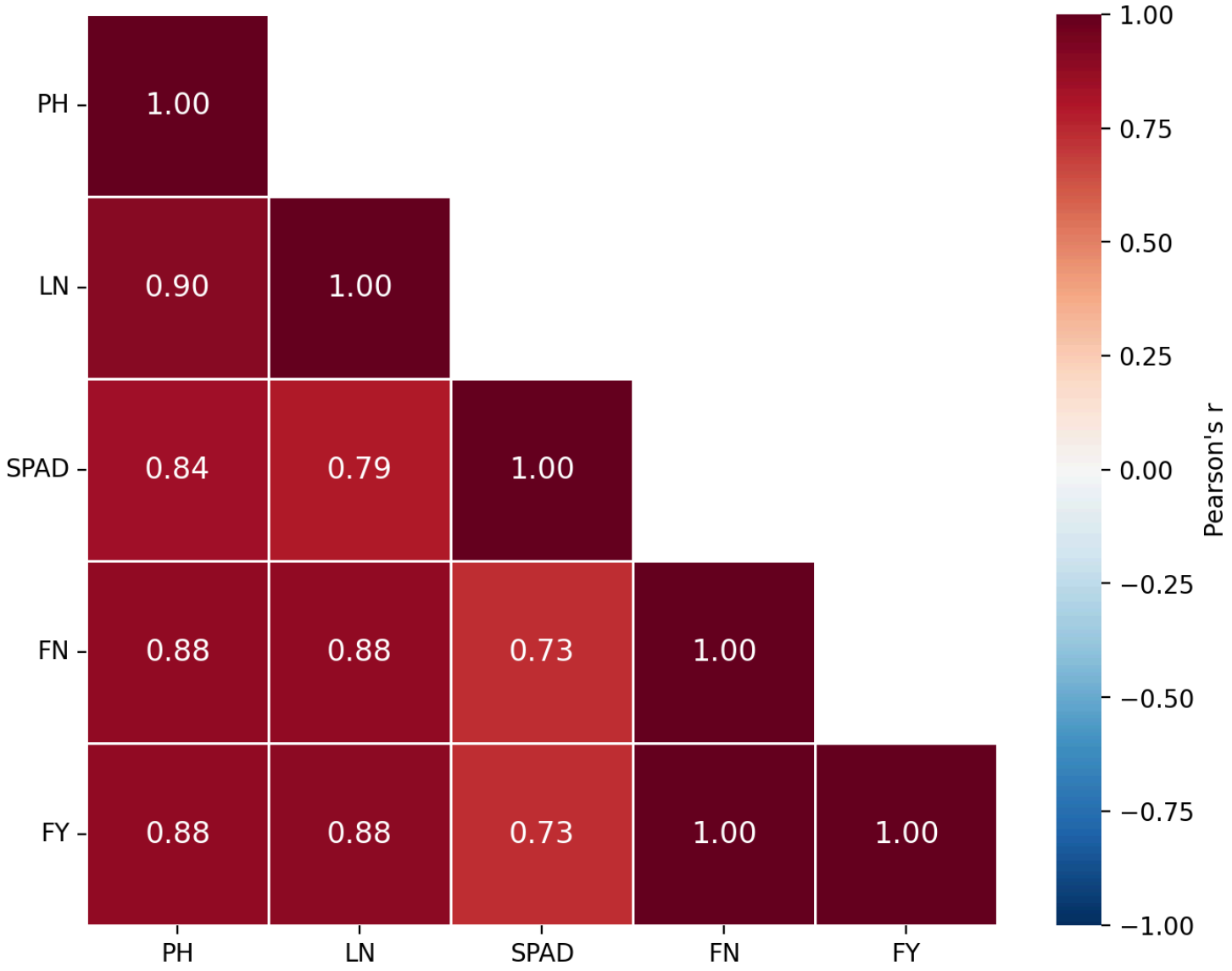


Figure 2

Pearson correlation heat map of vegetative and reproductive variables based on replicate-level experimental-unit observations (n = 40).

Abbreviations: PH = Plant height; LN = Leaf number; SPAD = SPAD chlorophyll value; FN = Fruit number; FY = Fruit yield

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- KWLFGraphicalAbstract.png
- KWLFKeyhighlights.docx