

Enhancing Yield Performance of Cucumber (Cucumis Sativus) and Soil Properties Using Banana Peel and Carbonized Rice Hull as Foliar Fertilizer

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Abstract: *This study aims to evaluate the effect of utilizing banana peel and rice hull as foliar fertilizer on the growth and yield performance of cucumber. This organic fertilizer helps reduce waste accumulation, lowers greenhouse gas emissions, and supports the shift toward circular and sustainable farming systems. Experimental design was employed involving 160 cucumber seedlings assigned to 4 treatments replicated 4 times: T1 (200 grams of BPP soak in 10 liters of water), T2 (200 grams of CRH powder soak in 10 liters of water), T3 (200 grams of BPP and CRH powder soak in 10 liters of water), T4 – control (no application of organic liquid fertilizer). The organic fertilizer such as banana peel powder and Carbonized rice hull powder underwent a Physicochemical properties and nutrient composition test and were evaluated on their effect on the growth and yield performance of cucumber in terms of Plant height, number of leaves, number of branches, early flowering, and number of fruits. Result showed that the treatment effect on plant height was non-significant, indicating that foliar-applied BPP, CRHP, and the combined application did not affect primary shoot elongation. Individually applied BPP and CRHP each significantly increased lateral branch number relative to the combined treatment and the untreated control, whereas the combined treatment did not differ from the control. Reproductive performance which is the early flowering was unaffected by any treatment, and treatment explained less than 2% of the variance in reproductive timing. For yield parameters, individually applied BPP and individually applied CRHP each produced significantly more fruits, larger fruit diameters, and heavier fruits than the untreated control. BPP was the only treatment that significantly improved fruit length. Across all yield parameters, the combined treatment was statistically equivalent to the untreated control, indicating an antagonistic interaction during co-application attributed to the mismatched pH profiles of BPP and CRHP. Statistical analysis using one-way ANOVA and Tukey's HSD confirmed the significance of these findings. The study concludes that Foliar application of BPP and CRHP, when applied individually it significantly improved lateral branching, fruit number, fruit diameter, and fruit weight of cucumber compared to the untreated control. The combined application of BPP and CRHP produced no significant improvement over the untreated control for any measured parameter, demonstrating an antagonistic interaction attributed to pH incompatibility between BPP and CRHP.*

Keywords: Foliar fertilizer, Yield performance of cucumber, Banana peel, Carbonized rice hull, Experimental design

I. INTRODUCTION

Sustainable agriculture has become an essential approach in addressing one of today's greatest challenges of producing enough food to feed a growing population while protecting the environment. In many developing countries like the Philippines, farmers continue to face serious problems such as the loss of soil nutrients, rising costs of farm inputs, and



heavy dependence on synthetic fertilizers (Gajalakshmi & Abbasi, 2018). These issues threaten both the productivity and long-term health of agricultural lands. To overcome these concerns, researchers and farmers alike are turning to innovative and eco-friendly practices that make better use of natural resources and promote soil regeneration. One practical and sustainable solution is the use of agricultural waste materials—particularly banana peels and carbonized rice hull (CRH) as organic fertilizers and soil enhancers. Result showed that Banana peels, which are often discarded after fresh fruit consumption. These contain valuable nutrients such as potassium (K), phosphorus (P), and calcium (Ca) which are essential for healthy plant growth, flowering, and fruit development (Oyeyinka et al., 2019; Khanyile et al., 2024). When these peels are processed into powder, compost, or liquid extracts, they can enrich the soil, support root and shoot growth, and boost crop yield without causing the environmental problems linked to chemical fertilizers (Hussein et al., 2019). Carbonized rice hull, a by-product of rice milling, has gained attention as a sustainable soil conditioner. It is rich in silica (Si) and has a highly porous, alkaline structure that helps improve soil aeration, water retention, and nutrient-holding capacity (Varela Milla et al., 2013; Karam et al., 2022). In addition, CRH helps neutralize soil acidity and fosters beneficial microbial activity, creating a more balanced and fertile soil environment (Tsai et al., 2020).

In modern farming, cucumber production often relies heavily on inorganic fertilizers to maintain high yields and desirable quality. However, continuous and excessive use of chemical fertilizers can harm the environment by causing soil degradation, increasing production costs, and contributing to pollution (Sallam et al., 2021). These issues highlight the need for more sustainable and affordable alternatives that can enhance soil fertility while promoting eco-friendly farming practices.

Utilizing banana peels and rice hulls as organic fertilizer helps reduce waste accumulation, lowers greenhouse gas emissions, and supports the shift toward circular and sustainable farming systems. By turning what was once considered waste into a valuable farming resource, smallholder farmers can lessen their production costs, reduce their reliance on chemical fertilizers, and contribute to a cleaner, healthier environment (FAO, 2023). Moreover, this initiative supports national and global goals for climate-resilient and sustainable agriculture, including the Department of Agriculture's High-Value Crops Development Program (HVCDP) and the United Nations Sustainable Development Goals (SDGs). Ultimately, transforming agricultural residues such as banana peels and rice hulls into organic fertilizers reflects the true essence of sustainable agriculture—balancing productivity, environmental care, and economic stability for future generations.

Hence, this study titled “Enhancing yield performance of cucumber (*cucumis sativus*) and soil properties using banana peel and carbonized rice hull as foliar fertilizer” aims to evaluate the effects of these organic fertilizer formulations on the growth and yield performance of cucumber. Through this research, the study hopes to contribute to the advancement of sustainable, low-cost, and eco-friendly farming practices that balance productivity with environmental stewardship.

II. CONCEPTUAL FRAMEWORK

The study follows the Input–Process–Output (IPO) model wherein the Inputs include the levels of fertilizer application using banana peel powder and carbonized rice hull powder. The Process involves the preparation and application of different treatments, data collection, and statistical analysis. The Outputs consist of the plant's growth parameters, such as number of leaves, plant height, number of branches, and early flowering, as well as yield parameters including number of fruits, fruit length, fruit diameter, and weight of fruits per plant.’



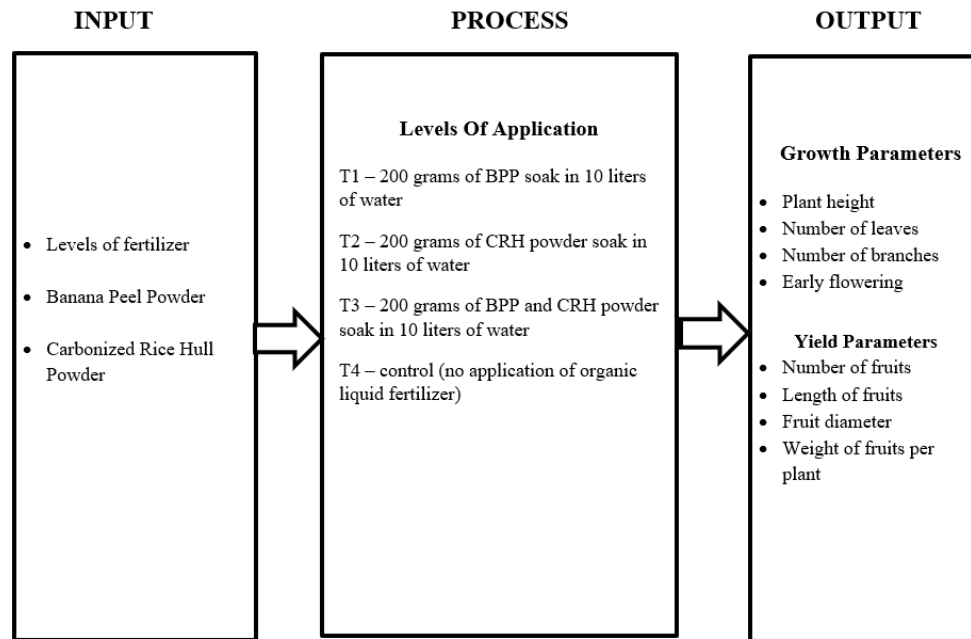


Figure 1: Research Paradigm

III. STATEMENT OF THE PROBLEM

This study seeks to enhance the growth and yield performance of cucumber and its soil properties when applied with banana peel powder and carbonized rice hull powder as foliar fertilizer. Specifically, it sought to answer the following questions:

1. What are the processes and procedures in developing banana peel powder and carbonized rice hull powder as foliar fertilizer?
2. What is the impact on soil health when influenced by the application of banana peel powder, carbonized rice hull powder, and a combination of BPP powder and CRH powder applied as soil enhancer in terms of:
 - 2.1 Soil pH; and
 - 2.2 nutrient content
3. What is the effect of banana peel powder, carbonized rice hull powder, and a combination of BPP powder and CRH powder as foliar fertilizers on the following growth and yield performance of cucumber?
 - a. Plant height
 - b. Number of leaves
 - c. Number of branches
 - d. Early flowering
 - e. Number of fruits
 - f. Length of fruits
 - g. Fruit diameter
 - h. Weight of fruits per plant
4. Which of the treatments shows the best yield performance of cucumber?
5. Is there a significant difference in the growth and yield performance of cucumber with the different fertilizer treatments in terms of plant height, number of branches, early flowering, number of fruits, Length of fruits, fruit diameter, and Weight of fruits per plant?



Research Design

This study was laid out using Randomized Complete Block Design (RCBD) to determine if there was a significant difference of banana peel powder, carbonized rice hull powder, and a combination of BPP powder and CRH powder on the growth and yield performance of cucumber. It consisted of 4 treatments replicated 4 times. The experimental treatments are the following:

- T1 – 200 grams of BPP soak in 10 liters of water
- T2 – 200 grams of CRH powder soak in 10 liters of water
- T3 – 200 grams of BPP and CRH powder soak in 10 liters of water
- T4 – control (no application of organic liquid fertilizer)

Research Environment

This study was conducted at Barangay Paco, Mainit, Surigao del Norte, for a period of 70 days. The study took place in an agricultural area that could support the healthy growth of Cucumis sativus (cucumber). The research was set up using prepared plots in an open field where the plants received natural sunlight, good air circulation, and suitable temperature conditions. Before applying the treatments, the experimental site was carefully prepared so that the soil in all plots was as uniform as possible. Soil analysis was conducted to check for similarities in soil texture, nutrient levels, and pH. Throughout the entire experiment, all cucumber plants were treated in the same manner. Watering schedules, weed removal, and pest management were kept consistent for all groups to avoid influencing the results.

Subject of the Study

In this experimental study, the main subject was cucumber plants. These plants were used to assess how banana peel extract and carbonized rice hull (CRH) functioned as foliar fertilizers. The cucumber seeds were purchased at Kabasakan Farm Supply, and the variety of seeds used in this study was MEGA C F1. Each plot contained 10 hills, with a total of 160 healthy and uniformly grown cucumber seedlings selected for the experiment. The seedlings were randomly assigned to the different treatment groups, which included the control, banana peel extract, CRH foliar application, and a combination of both fertilizers. All experimental plots were kept under similar environmental conditions to ensure consistent exposure to sunlight, water, and soil. Throughout the duration of the study, the cucumber plants served as the biological participants from which data on growth, yield, and soil properties were gathered.

Research Instruments

In this study, several plant growth measurement instruments were utilized to assess how the cucumber plants responded to the different foliar fertilizer treatments. A ruler was employed to measure the length of the cucumber. To obtain precise measurements of fruit diameter, a vernier caliper was utilized to measure the thickness of the cucumber fruit. In addition, a digital weighing scale was used to measure the weight of the harvested fruits. Furthermore, laboratory analyses were conducted to evaluate the properties of the soil, as well as the nutrient content of the organic fertilizers that were applied in this study.

Data Analysis

Vegetative growth, reproductive, and yield parameters of cucumber (*Cucumis sativus* L.) were analyzed using SPSS version 26 for Windows. Plant height, measured weekly over four periods, was analyzed with a repeated-measures GLM to account for correlations among observations on the same experimental unit (Field, 2018). The Greenhouse-Geisser correction was applied when sphericity was violated. Polynomial contrasts examined linear and higher-order trends to characterize growth trajectories beyond the main time effect. Lateral branch number was analyzed using a Kruskal-Wallis test due to non-normality. Pairwise comparisons with Bonferroni correction for treatment comparison. Reproductive timing, including first bud and first flower opening, was analyzed using a multivariate GLM. Pillai's



Trace was used as the MANOVA statistic for robustness against violations of multivariate normality and variance-covariance homogeneity (Tabachnick & Fidell, 2019). Yield parameters such as fruit number, diameter, length, and weight, measured across seven harvesting periods, were analyzed with repeated-measures GLM. Polynomial contrasts examined quadratic and higher-order trends. Tukey HSD post hoc tests determined significant differences among treatments, with Bonferroni correction applied for multiple temporal comparisons. Soil chemical changes were assessed using change scores, calculated as post-harvest minus pre-planting values. Baseline values were identical across experimental units followed by One-way ANOVA, with Levene's test validating homogeneity of variances.

III. RESULTS AND DISCUSSIONS

Processes and procedures in developing banana peel powder and carbonized rice hull powder as foliar fertilizer

Preparation and Collection of Carbonized Rice Hull (CRH) powder

Rice hull was collected at Millenium Rice Mill located at Barangay Magsaysay, Mainit, SDN. Open-type carbonizer, water, long-handled spade/shovel, recycled paper, and sprinklers were gathered. The carbonization process was conducted at Barangay Paco, Mainit, Surigao del Norte in an open and well-ventilated area to ensure safety and proper smoke release. Dry rice hulls were placed loosely into the carbonizer until it was almost full. At the base, small pieces of paper and dry twigs were arranged as kindling material to start the fire. The ignition began through the air holes at the bottom, allowing the flame to gradually move upward through the rice hulls. When the color of the smoke changed from thick white to a thin, bluish hue, it indicated that the rice hulls were nearly done. When the mounds turned completely black, a small amount of water was sprinkled over the surface to put out any remaining embers and to lower the temperature. After 2 days, CRH was bagged, sealed, and stored in a safe, dry place for 1 week. Carbonized rice hull was placed in the electric grinder machine until it became a powder. The carbonized rice hull powder was sieved through a fine mesh to achieve uniform particle size and was stored in a clean, dry, and airtight container to maintain its quality and prevent moisture absorption.

Collection and Preparation of Banana Peel Powder

Cardava banana peels were collected from banana cue and banana turon vendors in Barangay Magpayang, Paco, and other neighboring barangays of Mainit, SDN. The collected peels were carefully washed with clean water to remove adhering dirt and other surface impurities. After washing, the peels were drained and spread on a clean tray to remove excess moisture. The clean banana peels were sliced into smaller pieces to allow even drying. The sliced peels were sun-dried for three to five days, depending on weather conditions, until they became crisp and completely free from moisture. Once the peels were thoroughly dried, they were ground using a clean electric grinder or mortar and pestle until a fine powder was obtained. The banana peel powder was sieved through a fine mesh to achieve uniform particle size and was stored in a clean, dry, and airtight container to maintain its quality and prevent moisture absorption.

Sterilization of organic powder fertilizer

To ensure the cleanliness and safety of the organic materials that were used in the study, appropriate sterilization methods were applied before fertilizer formulation. The banana peel powder underwent the oven-drying method of sterilization at a controlled temperature of 80–90°C for 30–45 minutes. This process was done to eliminate possible pathogenic microorganisms, insect larvae, and fungal spores while preserving essential nutrients such as potassium, calcium, and phosphorus. Carbonized rice hull powder was sun-dried for 2–3 hours before use. It does not require intensive sterilization because the carbonization process itself involved high temperatures.

Fertilizer soaking preparation

Soaking of banana peel powder and carbonized rice hull powder in water was done separately according to treatments using clean and dry bottles. The soaking process was done for 24 hours to allow enough time for nutrient extraction before application.



Impact on soil health when influenced by the application of banana peel powder, carbonized rice hull powder, and a combination of BP powder and CRH powder applied as soil enhancer

Banana peel powder (BPP) exhibited an alkaline pH of 9.28, with phosphorus content of 0.971%, potassium of 5.05%, and nitrogen of 1.44%. In contrast, carbonized rice hull powder (CRHP) had a neutral pH of 6.75, with phosphorus at 1.18%, potassium at 0.374%, and nitrogen at 0.807%. pH was measured using electrometry, phosphorus by the colorimetric method, potassium by flame atomic emission spectrometry (Flame AES), and nitrogen by the Kjeldahl method, all in accordance with the Official Methods of Analysis of AOAC International (2019).

Table 1: Physicochemical properties and nutrient composition of banana peel powder (BPP) and carbonized rice hull powder (CRHP)

Nutrient	Banana Peel Powder (BPP)	Carbonized Rice Hull Powder (CRHP)	Test Method
pH	9.28	6.75	Electrometry
Nitrogen	1.44	0.81	Kjeldahl Method
Phosphorus	0.97	1.18	Colorimetric
Potassium	5.05	0.37	Flame AES

Note: Nutrient values for banana peel powder and carbonized rice hull were not statistically run

Islam et al. (2019) and Raj et al. (2021) identified potassium as the dominant macronutrient in banana peel preparations. The present findings are consistent with these studies, as potassium (5.05%) was the most abundant macronutrient detected in BPP. Raj et al. (2021) reported nitrogen at 0.95% and phosphorus at 0.34% in banana peel powder. The present study differs from Raj et al. (2021) regarding nitrogen and phosphorus, as BPP had higher nitrogen (1.44%) and markedly higher phosphorus (0.971%) levels. These elevated nitrogen and phosphorus levels indicate that BPP is comparatively nutrient-rich, which is favorable for foliar application. The lower potassium content in BPP relative to biochar-derived values reported in the literature likely reflects the air-drying method used, which preserves moisture and yields lower mineral concentrations than pyrolysis.

Carbonized rice-derived materials typically exhibit a pH range of 8–9, as reported in previous studies. The present findings partially diverge from this expectation, as CRHP registered a lower pH of 6.75, suggesting incomplete or low-temperature carbonization during its production. Sabes et al. (2020) noted that the agronomic value of rice hulls derives primarily from silicon rather than from NPK. The present findings are consistent with this, as nitrogen (0.807%) and potassium (0.374%) contents of CRHP remained low. Notably, the phosphorus content of CRHP (1.18%) exceeded that of BPP (0.971%), possibly due to phytate compounds or inorganic phosphates within the rice hull matrix.

Effect of banana peel powder, carbonized rice hull powder, and a combination of BPP powder and CRH powder as foliar fertilizers

Plant height

A repeated-measures analysis of variance showed that plant height differed significantly across measurement periods ($p < 0.001$, partial $\eta^2 = 0.839$; Greenhouse–Geisser correction applied because the assumption of sphericity was violated, $p < 0.001$). The main effect of treatment was not significant, $p = 0.139$, partial $\eta^2 = .034$. The measurement period \times treatment interaction was not significant ($p = 0.108$, partial $\eta^2 = 0.036$).

Table 2: Weekly plant height (cm) of plants under different treatments across four measurement periods with repeated-measures ANOVA summary

Treatment	Week 1	Week 2	Week 3	Week 4	Overall Mean
Treatment 1	8.05	14.45	30.57	51.6	26.17
Treatment 2	7.30	11.95	25.08	49.18	23.38
Treatment 3	7.57	12.93	26.37	46.80	23.42



Treatment 4	7.35	11.55	22.68	43.08	21.17
Within-measurement effect	p-Value	η^2	Linear	Quadratic	Cubic
Mauchly's Test of Sphericity	<0.001***				
Measurement periods	<0.001***	0.839	<0.001***	<0.001***	0.80 ^{ns}
Measurement periods * Treatment	0.108 ^{ns}	0.036	0.137 ^{ns}	0.11 ^{ns}	0.05 ^{ns}
Between-treatment effect	p-Value	η^2			
Treatment	0.139 ^{ns}	0.034			

Note:*** - very highly significant p-value; ns - not significant p-value; η^2 - partial eta squared (effect size)

Plant height increased significantly over weeks 1–4, indicating continuous stem elongation throughout the experimental period. Liu and Zhang (2021) described cucumber (*Cucumis sativus*) as an indeterminate vining species that continuously produces vegetative nodes from the shoot apical meristem while simultaneously forming flowers in leaf axils. The week-to-week increases in plant height, which remained fully separated under Bonferroni correction, are consistent with the indeterminate growth pattern described by Liu and Zhang (2021).

The dominant linear trend indicated a unidirectional increase in plant height across measurement periods, consistent with continuous indeterminate vining (Liu & Zhang, 2021). A significant quadratic trend reflected deceleration in height gain during later periods, likely due to the establishment of reproductive sinks that shift resources away from vegetative growth (Marshall & Watson, 1992). This quadratic pattern aligns with Kozłowski and Ziółko (1988), who showed that the shift from vegetative to reproductive energy allocation occurs gradually, producing a smooth sigmoidal growth pattern. The non-significant cubic component confirmed the absence of irregular oscillations.

The non-significant treatment effect suggests that foliar applications of BPP, CRHP, or their combination did not affect primary shoot elongation. Maboko et al. (2017) reported similar results in hydroponically grown mini-cucumber plants. The non-significant interaction polynomials across all three components indicate that the temporal shape of the plant height curve was consistent across treatment groups, supporting the idea that vegetative height gain is controlled by endogenous developmental processes rather than exogenous foliar nutrient inputs (Liu & Zhang, 2021; Marshall & Watson, 1992; Kozłowski & Ziółko, 1988).

Number of Leaves

A repeated-measures analysis of variance showed that leaf count differed significantly across measurement periods ($p < 0.001$, partial $\eta^2 = 0.843$). The Greenhouse–Geisser correction was applied because the assumption of sphericity was violated. The main effect of treatment was not significant ($p = 0.221$, partial $\eta^2 = 0.028$), and the measurement period \times treatment interaction was also non-significant ($p = 0.126$, partial $\eta^2 = 0.034$).

Table 3: Weekly number of leaves of plants under different treatments across four measurement periods with repeated-measures ANOVA summary

Treatment	Week 1	Week 2	Week 3	Week 4	Overall Mean
Treatment 1	3.18	4.95	9.20	13.75	7.77
Treatment 2	2.80	4.42	8.45	13.02	7.17
Treatment 3	3.15	4.78	8.85	12.93	7.43
Treatment 4	3.05	4.78	7.75	11.80	6.85
Within-measurement effect	p-Value	η^2	Linear	Quadratic	Cubic
Mauchly's Test of Sphericity	<0.001***				
Measurement periods	<0.001***	0.843	<0.001***	<0.001***	<0.001***
Measurement periods * Treatment	0.126 ^{ns}	0.034	0.129 ^{ns}	0.607 ^{ns}	0.024*
Between-treatment effect					
Treatment	0.221 ^{ns}	0.028			

Note:*** - very highly significant p-value; ns - not significant p-value; η^2 - partial eta squared (effect size)



The strong effect of measurement period on leaf count reflects the ontogenetic program of cucumber, in which each node initiated by the shoot apical meristem produces a new leaf primordium. Luo et al. (2021) showed that cytokinins sustain the meristematic activity of the shoot apical meristem required for leaf primordium initiation and promote subsequent cell division and expansion during leaf development. This measurement period effect is consistent with Luo et al. (2021), as leaf production progressed predictably at each node throughout the experimental period.

The non-significant treatment effect indicates that foliar BPP and CRHP did not influence leaf initiation rate. Savvides et al. (2016) demonstrated that leaf initiation rate in cucumber is determined by apical bud temperature, independent of other plant organ temperatures. Baker and Reddy (2001) identified temperature-driven plastochron intervals as the primary determinant of leaf appearance rate in cucurbits. Horie et al. (1979) showed that leaf development rate in cucumber is governed by radiation and temperature on a plastochron basis. The non-significant treatment effect is consistent with Savvides et al. (2016), Baker and Reddy (2001), and Horie et al. (1979), confirming that leaf number is controlled by temperature-driven plastochron intervals rather than by foliar nutrient inputs.

Bonferroni-adjusted pairwise comparisons showed that all measurement periods differed significantly, whereas no significant differences were observed among treatments. The complete separation among measurement periods reflects the cumulative and irreversible nature of leaf production in indeterminate vines. Liu and Zhang (2021) described cucumber as a species that continuously produces vegetative nodes from the shoot apical meristem. This temporal separation is consistent with Liu and Zhang (2021), as each week's leaf count necessarily exceeds that of the preceding week. Singh et al. (2018) developed non-destructive methods for estimating leaf area and leaf area index in cucumber, confirming the predictable progression of leaf development. The absence of treatment-level differences is consistent with Singh et al. (2018), reinforcing the interpretation that foliar nutrient supplementation at 200g L⁻¹ did not alter the phyllotactic program controlling leaf emergence.

The dominant linear trend confirmed steady leaf accrual across measurement periods. The significant quadratic component indicated a gradual slowing in leaf production rate. Marshall and Watson (1992) argued that resource allocation shifts from vegetative growth toward reproduction as reproductive sinks are established. Egli et al. (1985) showed that partitioning coefficients in soybeans increase during reproductive development as assimilate allocation shifts toward fruit growth. The quadratic deceleration in leaf count is consistent with Marshall and Watson (1992) and Egli et al. (1985), as cucumber plants approached the reproductive phase and assimilate partitioning shifted toward flowering and fruiting. The significant cubic component captured mid-season fluctuations in leaf production rate. The significant cubic interaction indicates that treatments differentially influenced mid-season leaf production. Islam et al. (2019) demonstrated that banana peel-derived potassium is biologically active in cucurbit systems. He et al. (2015) and Sabes et al. (2020) confirmed the biological availability of silicon derived from carbonized rice hull. This cubic interaction is consistent with Islam et al. (2019), He et al. (2015), and Sabes et al. (2020), as potassium from BPP and silicon from CRHP may have modestly affected cytokinin–auxin ratios governing axillary bud outgrowth, resulting in treatment-specific transient changes in leaf number during mid-season growth.

Number of Branches

A Kruskal-Wallis's test showed that the number of lateral branches differed significantly among treatments ($H(3) = 34.97, p < 0.001$). Pairwise comparisons with Bonferroni correction indicated that T1 (200 g BPP with 10 L of water) and T2 (200 g CRHP with 10 L of water) each differed significantly from T3 (200 g BPP and CRHP with 10 L of water) and T4 (no application) (all adjusted $p \leq 0.005$). However, the difference between T1 and T2 was not significant (adjusted $p = 1.000$), and the difference between T3 and T4 was also not significant (adjusted $p = 1.000$).

Table 4: **Number of branches per plant as affected by different treatments (Kruskal–Walli's test with pairwise comparisons)**

Treatment	Number of branches
Treatment 1	1.49 ± 0.51a
Treatment 2	1.56 ± 0.50a



Treatment 3	1.13 ± 0.34b
Treatment 4	1.03 ± 0.17b
p-Value	< 0.001***

Note: Column means and standard deviations with the same letter are not statistically significant; *** Very highly significant p-value

The treatment effect on lateral branch number was highly significant. Individually applied BPP (T1) and CRH (T2) each increased branching relative to the combined treatment (T3) and the untreated control (T4). Shimizu-Sato et al. (2009) showed that auxin from the shoot apex suppresses axillary bud outgrowth, whereas cytokinin signaling at the node releases lateral buds from dormancy by shifting the local auxin–cytokinin balance toward cytokinin dominance. The finding that BPP alone promoted lateral branching is consistent with Shimizu-Sato et al. (2009), suggesting that the high potassium content of BPP may have shifted the auxin–cytokinin balance at axillary nodes toward cytokinin dominance. This interpretation remains tentative, as hormone concentrations were not measured in the present study.

Su et al. (2024) reported that in cucumber cultivar LZ1, the exogenous strigolactone analog GR24 suppresses lateral branch development by decreasing auxin content and inhibiting cytokinin synthesis in axillary regions. The promotion of branching under BPP aligns with the opposite pattern described by Su et al. (2024). Foliar-applied potassium may have increased cytokinin accumulation or reduced strigolactone sensitivity at axillary nodes, producing the observed lateral bud release under T1; however, the mechanism cannot be confirmed directly without hormone measurements.

He et al. (2015) demonstrated that silicon forms covalent crosslinks with hemicellulose polysaccharides in rice cell walls, improving wall stiffness and regenerative capacity. The effect of CRH on lateral branching is consistent with He et al. (2015), as silicon-strengthened cell walls in axillary buds could enhance the ability of emerging buds to expand against surrounding tissue resistance. This agreement is indirect because He et al. (2015) studied rice, and silicon deposition in cucumber buds was not measured.

The non-significant difference between T3 (BPP + CRH combined) and T4 (untreated control) indicates that co-application eliminated the branching benefits observed with individual applications. Fernández and Eichert (2009) established that the plant cuticle carries pH-dependent fixed negative charges and that foliar solution pH influences nutrient penetration via cuticular polar pathways. The antagonistic outcome is consistent with this mechanism: the alkaline pH of BPP (9.28) and near-neutral pH of CRH (6.75) likely produced a combined solution outside the slightly acidic range (pH 5.0–6.5) that favors macronutrient absorption.

Reproductive Performance/Early Flowering

Pillai's Trace was selected as the MANOVA test statistic because it is robust to violations of multivariate normality and homogeneity of variance–covariance matrices. The non-significant multivariate effect ($p = 0.579$, partial $\eta^2 = 0.015$) indicates that foliar treatments exerted minimal influence on the joint distribution of reproductive timing variables.

Table 5: Multivariate (MANOVA) and univariate (ANOVA) analysis of reproductive performance variables as influenced by treatments

Source of variations	Pillai's Trace	p-value	η^2
MANOVA	0.031	0.579 ^{ns}	0.015
ANOVA	Days to first bud	Days of first flower fully open	
Treatment 1	23.24 ± 3.87	25.68 ± 3.89	
Treatment 2	23.49 ± 3.43	31.46 ± 32.57	
Treatment 3	24.03 ± 3.59	26.85 ± 3.33	
Treatment 4	23.95 ± 2.91	26.41 ± 2.94	
Significance	p – value	η^2	p – value
	0.708 ^{ns}	0.009	0.408 ^{ns}
			η^2
			0.019

Note: ns – not significant MANOVA and ANOVA p-Values; η^2 - partial eta squared (effect size)



Liu and Zhang (2021) described cucumber as a species that undergoes vegetative and reproductive growth simultaneously, with leaves produced from the shoot apical meristem and flowers formed in leaf axils throughout most of the life cycle. The non-significant multivariate effect is consistent with Liu and Zhang (2021), as floral primordia are initiated continuously at leaf axils as part of an endogenous developmental program governed by meristem identity rather than by exogenous nutrient supply.

Lai et al. (2018) demonstrated that photoperiod decreased the cucumber female flower ratio by 17.7–52.9% under long-day conditions and influenced MADS-box gene expression in shoot apices. The non-significant treatment effect is consistent with Lai et al. (2018), indicating that reproductive timing is regulated by light-mediated gene expression rather than by foliar mineral inputs. Ikram et al. (2017) similarly showed that CsACS2, CsETR1, and CsCaN expression was positively correlated with female flower number under different photoperiods. The non-significant treatment effect on first bud appearance and first open flower is consistent with Ikram et al. (2017), as ethylene-mediated regulation of floral sex differentiation responds to photoperiod rather than foliar nutrient application.

Wen et al. (2019) demonstrated that a non-synonymous SNP in CsTFL1 causes determinate growth in cucumber and that CsTFL1 competes with CsFT for interaction with CsNOT2a–CsFDP to inhibit terminal flower formation. The non-significant treatment effect is consistent with Wen et al. (2019), as the vegetative-to-reproductive transition is governed by FT–TFL1 interactions rather than nutrient-responsive signaling. Sato et al. (2009) similarly identified FT and TFL1 homologs in cucumber and reported distinct expression patterns between determinate and indeterminate cultivars. The present finding is consistent with Sato et al. (2009), indicating that reproductive timing is under genetic control mediated by FT–TFL1 regulatory networks that are not responsive to foliar potassium or silicon inputs.

Li et al. (2025) found that far-red light and gibberellin decreased IAA, cytokinin, and jasmonate levels in cucumber internodes and concluded that elongation responses were mediated through hormone metabolism and signaling pathways. The non-significant treatment effect is consistent with Li et al. (2025), indicating that developmental transitions are regulated by light–hormone interactions rather than by exogenous mineral nutrition.

For individual reproductive parameters, univariate tests supported the MANOVA results. Treatment had no significant effect on the date of first bud appearance ($p = 0.708$, partial $\eta^2 = 0.009$) or on the date of first flower opening ($p = 0.408$, partial $\eta^2 = 0.019$). These effect sizes indicate that treatment explained less than 2% of the variance in reproductive timing.

Wu et al. (2014) conducted a genome-wide analysis of auxin-response gene families in cucumber and demonstrated that ARF, Aux/IAA, GH3, SAUR, and LBD genes exhibit diverse expression patterns across organs and developmental stages. The non-significant univariate effects are consistent with Wu et al. (2014). Bud initiation depends on the transition of the apical meristem from vegetative to floral primordia, mediated by auxin-responsive transcriptional cascades. The interval from bud initiation to anthesis is governed by cell expansion in floral tissues, driven by internal auxin and carbohydrate fluxes regulated by whole-plant carbon balance. The finding that foliar BPP and CRHP did not alter reproductive timing indicates that these treatments influenced mineral nutrition rather than phytohormone pathways regulating floral development.

Number of Fruits

A repeated-measures analysis of variance for the number of fruits across seven harvesting periods revealed a significant effect of harvesting period ($p < 0.001$, partial $\eta^2 = 0.392$) and a significant main effect of treatment ($p = 0.012$, partial $\eta^2 = 0.586$). The treatment \times harvesting period interaction was not significant ($p = 0.921$, partial $\eta^2 = 0.121$). Mauchly's test indicated that the assumption of sphericity was met ($p = 0.383$).

Table 6: Number of fruits per plant across seven harvesting periods under different treatments with repeated-measures ANOVA results

Treatment	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Overall Mean
Treatment 1	0.50	1.33	1.33	0.75	1.48	1.17	1.21	1.11 ^a



Treatment 2	0.50	1.13	1.18	1.30	1.27	1.13	0.75	1.04 ^{ab}
Treatment 3	0.00	1.33	1.06	1.00	1.00	1.00	0.75	0.87 ^b
Treatment 4	0.25	1.00	1.13	1.00	1.25	0.75	0.75	0.88 ^b
Within-measurement	p-Value	η^2	Linear	Quadratic	Cubic	Order 4	Order 5	Order 6
Mauchly's Test of Sphericity	0.383	0.634						
Measurement periods	<0.001** *	0.392	0.05 ^{ns}	<0.001** *	0.11 ^{ns}	0.018*	0.12 ^{ns}	0.18 ^{ns}
Measurement periods * Treatment	0.921 ^{ns}	0.121	0.92 ^{ns}	0.46 ^{ns}	0.85 ^{ns}	0.43 ^{ns}	0.95 ^{ns}	0.21 ^{ns}
Between-treatment Treatment	0.012*	0.586						

Note: Overall column mean with the same letter are not statistically significant; *** - very highly significant p-value; * - significant p-value; ns - not significant p-value; η^2 - partial eta squared (effect size)

The treatment effect on cumulative fruit number was significant, with a large effect size, representing the first yield-related response to foliar fertilization in this study. Individually applied BPP (T1) and CRHP (T2) each produced significantly more fruits than untreated control (T4). T1 and T2 were statistically equivalent and both superior to the combined treatment (T3). Islam et al. (2019) demonstrated that banana peel-derived materials function as potassium-rich amendments, alleviating potassium deficiency in *Cucurbita moschata* seedlings and promoting vigorous cucurbit growth. The higher fruit number under T1 agrees with Islam et al. (2019) and extends their findings from vegetative biomass to cumulative fruit number. The potassium-mediated mechanism, in which K^+ supplied by BPP enhanced sucrose phloem loading to developing ovaries and supported fruitlet retention across harvests, is consistent with the biological activity of banana peel-derived potassium reported by Islam et al. (2019).

The comparable fruit number under CRHP and BPP, despite lower potassium in CRHP, can be interpreted through silicon-mediated mechanisms. He et al. (2015) demonstrated that silicon forms covalent crosslinks with hemicellulose in rice cell walls, improving mechanical stiffness and regenerative capacity. The effect of CRHP on fruit number is consistent with He et al. (2015), as silicon may reinforce pedicel and ovary tissues, reduce premature fruitlet abscission and support fruit retention comparable to the potassium effect of BPP. This interpretation is indirect, as He et al. (2015) studied rice and silicon deposition in cucumber fruit tissues was not measured. Sabes et al. (2020) showed that CRH at 3.0 t ha⁻¹ increased rice plant silicon content by ~9% and confirmed bioavailability. The present findings align with Sabes et al. (2020) and extend silicon-related effects to cucumber fruit retention.

Maboko et al. (2017) found that foliar fertilizer did not significantly affect fruit number in hydroponically grown mini-cucumber supplied with a complete nutrient solution. The present results partially disagree with Maboko et al. (2017), likely due to differences in nutrient context. In the soil-based system without background fertilization, foliar BPP or CRHP provided sufficient nutrients to produce detectable differences in fruit number. This suggests that foliar nutrient efficacy depends on baseline nutrient availability.

The non-significant treatment \times harvesting period interaction indicates that the fruit-number advantage under T1 and T2 remained consistent across all seven harvests. This pattern is consistent with sustained nutrient delivery (Islam et al., 2019) and continuous cell expansion supporting developing fruits (Marcelis et al., 1993).

The harvesting period effect was significant (harvests 1–7), with the first harvest producing fewer fruits than harvests 2–5. This temporal pattern aligns with Marshall and Watson (1992), who argued that early investment in vegetative growth establishes resource-acquisition capacity before shifting to reproductive allocation. The dominant quadratic trend described a rise-and-fall pattern across harvests. Kozłowski and Ziółko (1988) showed that gradual shifts from



vegetative to reproductive energy allocation produce an initial increase in reproductive output that later plateaus and declines as assimilate availability decreases, consistent with the observed quadratic pattern. The significant fourth-order component captured secondary oscillations, reflecting temporary flush-and-rest cycles. Kozłowski and Ziółko (1988) also demonstrated that brief reductions in fruit set occur when fruit load temporarily exceeds assimilate supply, explaining the oscillatory signal detected in the present data. Non-significant interaction polynomials indicate that temporal dynamics were consistent across treatments, with BPP and CRHP affecting overall fruit number magnitude but not the temporal pattern of cucurbit fruit production.

Fruit Diameter

A repeated-measures analysis of variance showed that fruit diameter differed significantly across harvesting periods ($p < 0.001$, partial $\eta^2 = 0.364$). The main effect of treatment was also significant ($p = 0.001$, partial $\eta^2 = 0.711$). However, the treatment \times harvesting period interaction was not significant ($p = 0.874$, partial $\eta^2 = 0.134$). Mauchly's test indicated that the assumption of sphericity was met ($p = 0.225$).

Table 7: Fruit diameter (inches) across seven harvesting periods as affected by different treatments with repeated-measures ANOVA results

Treatment	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Overall Mean
Treatment 1	1.05	2.56	2.36	1.41	2.66	2.18	2.37	2.08 ^a
Treatment 2	1.08	2.17	2.23	2.49	2.42	2.03	1.41	1.97 ^a
Treatment 3	0.00	2.51	2.07	1.91	1.87	1.78	1.28	1.63 ^b
Treatment 4	0.49	1.85	2.06	1.80	2.52	1.28	1.30	1.61 ^b
Within-measurement	p-Value	η^2	Linear	Quadratic	Cubic	Order 4	Order 5	Order 6
Mauchly's Test of Sphericity	0.225	0.59						
Measurement periods	<0.001** *	0.364	0.10 ^{ns}	<0.001** *	0.16 ^{ns}	0.02*	0.07 ^{ns}	0.18 ^{ns}
Measurement periods * Treatment	0.874 ^{ns}	0.134	0.88 ^{ns}	0.30 ^{ns}	0.85 ^{ns}	0.34 ^{ns}	0.92 ^{ns}	0.29 ^{ns}
Between-treatment								
Treatment	0.001**	0.711						

Note: Overall column mean with the same letter are not statistically significant; *** - very highly significant p-value; ** - highly significant p-value; ns - not significant p-value; η^2 - partial eta squared (effect size)

The treatment effect on fruit diameter was the strongest among all yield parameters in this study. Individually applied BPP (T1) and CRHP (T2) each produced significantly larger fruits than the combined treatment (T3) and the untreated control (T4), whereas T3 was not statistically different from T4. Marcelis et al. (1993) showed that cell division in parthenocarpic cucumber fruit occurs only during early growth, with later increases in fruit size resulting entirely from continuous cell expansion in the pericarp and placenta. The conclusion of Marcelis et al. (1993) that per-cell expansion capacity determines final fruit diameter is consistent with the present treatment effect. Foliar-applied potassium from BPP may have enhanced the osmotic gradient driving water influx into expanding pericarp cells during the post-division phase, increasing radial expansion and producing the larger fruit diameters observed under T1.

The statistical equivalence between T3 and T4 provides evidence for an antagonistic interaction during co-application, suggesting impaired nutrient delivery rather than biological incompatibility. Fernández and Eichert (2009) established that spray solution pH governs nutrient penetration through cuticular polar pathways. The T3 = T4 outcome aligns with Fernández and Eichert (2009), as the alkaline pH of BPP (9.28) and near-neutral pH of CRHP (6.75) likely produced a



combined solution outside the slightly acidic optimal range for uptake, reducing cuticular penetration of potassium and silicon. Fernández and Brown (2013) further demonstrated that ionic composition and solution pH affect foliar absorption, with nutrient ions showing reduced affinity for cuticular pathways exhibiting diminished uptake. The antagonistic outcome aligns with Fernández and Brown (2013), as the contrasting pH profiles of BPP and CRHP may have altered nutrient ionization states, reducing compatibility with cuticular penetration. This antagonism is a novel finding for organic-derived foliar amendments, as He et al. (2015) and Sabes et al. (2020) did not investigate mixed-material applications. The result warrants further investigation through chemical characterization of the combined spray solution.

The non-significant treatment \times harvesting period interaction confirmed that the fruit diameter advantage under T1 and T2 remained stable across all seven harvests, consistent with the continuous cell-expansion model of Marcelis et al. (1993). Sustained foliar nutrient delivery across the cropping season may maintain osmotic and structural conditions for radial expansion.

The harvesting period effect was significant, with the first harvest producing smaller fruits than harvests 2–5. This result agrees with Trouwborst et al. (2010), who demonstrated that early canopy underdevelopment limits light interception and constrains fruit expansion. The dominant quadratic trend described a rise-and-decline pattern, consistent with Trouwborst et al. (2010) and Parvathi et al. (2022), who showed that accumulated stress during later growth stages reduces plant capacity to sustain dry matter production. The significant fourth-order component captured secondary oscillations in fruit diameter across harvests, consistent with Marshall and Watson (1992), who described alternating dilution and recovery of assimilate per fruit generating oscillatory patterns. Non-significant polynomial contrasts for the interaction confirmed that temporal dynamics remained consistent across treatments, indicating that BPP and CRHP affected overall fruit diameter magnitude without altering the inherent temporal pattern of fruit-size development in cucumber.

Length of Fruits

A repeated-measures analysis of variance showed that fruit length differed significantly across harvesting periods ($p < 0.001$, partial $\eta^2 = 0.330$). The main effect of treatment was also significant ($p = 0.011$, partial $\eta^2 = 0.595$). The treatment \times harvesting period interaction was not significant ($p = 0.924$, partial $\eta^2 = 0.120$). Mauchly's test indicated that the assumption of sphericity was met ($p = 0.239$).

Table 8: Fruit length (cm) across seven harvesting periods as affected by different treatments with repeated-measures ANOVA results

Treatment	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Overall Mean
Treatment 1	9.25	24.19	19.78	12.13	23.65	19.48	22.38	18.69 ^a
Treatment 2	9.63	20.63	19.68	21.84	21.99	19.48	12.31	17.94 ^{ab}
Treatment 3	0.00	23.27	17.89	16.40	17.59	15.24	11.54	14.56 ^b
Treatment 4	4.50	16.50	17.38	15.66	20.94	11.34	11.54	13.98 ^b
Within-measurement	p-Value	η^2	Linear	Quadratic	0	Order 4	Order 5	Order 6
Mauchly's Test of Sphericity	0.239	0.617						
Measurement periods	<0.001** *	0.33	0.15 ^{ns}	<0.001** *	0.16 ^{ns}	0.01*	0.07 ^{ns}	0.24 ^{ns}
Measurement periods * Treatment	0.92 ^{ns}	0.12	0.89 ^{ns}	0.25 ^{ns}	0.84 ^{ns}	0.38 ^{ns}	0.94 ^{ns}	0.41 ^{ns}
Between-treatment	p-Value	η^2						
Treatment	0.01*	0.595						



Note: Overall column mean with the same letter are not statistically significant; *** - very highly significant p-value; ** - highly significant p-value; * - significant p-value; ns - not significant p-value; η^2 - partial eta squared (effect size). The treatment effect on fruit length was significant, although smaller than the effect on fruit diameter, indicating that longitudinal growth was less responsive than radial growth to foliar nutrient inputs. Marcelis et al. (1993) established that cell division in parthenocarpic cucumber fruit is restricted to the early growth period, with subsequent growth resulting from cell expansion occurring throughout most parts of the fruit, except at the fruit ends where growth slows earlier. The present finding that the treatment effect on fruit length was smaller than that on fruit diameter is consistent with Marcelis et al. (1993). Fruit diameter depends on later-phase expansion and responds directly to osmotic solute supply through K^+ , whereas fruit length is partly determined during early cell division, limiting the magnitude of the treatment response.

Pairwise comparisons showed that only T1 (BPP) differed significantly from T4 (no application), whereas T2 (CRHP), T3 (combined treatment), and T4 were statistically equivalent. He et al. (2015) demonstrated that silicon forms covalent crosslinks with hemicellulose polysaccharides in rice cell walls, improving mechanical stiffness. The observation that CRHP increased fruit diameter but not fruit length aligns with He et al. (2015), as silicon primarily increases rigidity rather than plasticity required for longitudinal elongation. Taylor et al. (1989) found that GA_3 -stimulated elongation in cucumber hypocotyls increased cell wall plastic extensibility by up to 35% without significant changes in osmotic pressure, concluding that elongation is governed by cell wall yielding. The finding that BPP (K_2O at 5.05%) significantly improved fruit length aligns with Taylor et al. (1989). Potassium from BPP may have supported ATPase-driven proton transport, maintaining apoplastic acidification and wall loosening during longitudinal elongation, whereas silicon from CRHP would improve wall stiffness rather than extensibility.

The smaller treatment effect on fruit length than on fruit diameter also reflects stronger hormonal regulation of longitudinal growth. Wu et al. (2014) demonstrated that auxin-response gene families are expressed in stage-specific patterns and that the ARF and Aux/IAA repressor system regulates the transition from cell division to elongation. The present findings are consistent with Wu et al. (2014), suggesting that endogenous IAA limits longitudinal expansion and that foliar K^+ and Si applications without gibberellins or auxin have limited capacity to enhance fruit length relative to diameter.

The non-significant treatment \times harvesting period interaction confirmed that the fruit length advantage under BPP remained stable across all seven harvests, consistent with continuous cell expansion (Marcelis et al., 1993).

The harvesting period effect followed the same temporal pattern as fruit number and diameter. The significant quadratic trend described a rise-and-decline pattern, consistent with Parvathi et al. (2022), who reported that accumulated biotic and abiotic stress reduces productive capacity during later growth stages. The significant fourth-order trend, the strongest oscillatory signal among all yield parameters, captured pronounced harvest-to-harvest fluctuations in fruit length. This agrees with Kozłowski and Ziólko (1988), who showed that temporary excess fruit load over assimilate supply can briefly reduce individual fruit growth. The larger effect size of the fourth-order component for fruit length compared with fruit diameter is consistent with Marcelis et al. (1993), indicating that fruit ends are especially sensitive to phloem import timing and magnitude, making longitudinal expansion more vulnerable to temporary assimilate shortages. Non-significant polynomial contrasts for the interaction confirmed that temporal dynamics remained consistent across all treatments, indicating that BPP and CRHP altered the overall magnitude of fruit length without changing the inherent temporal pattern of fruit development.

Weight of Fruits

A repeated-measures analysis of variance showed that fruit weight differed significantly across harvesting periods ($p < 0.001$, partial $\eta^2 = 0.313$). The main effect of treatment was also significant ($p = 0.016$, partial $\eta^2 = 0.563$). The treatment \times harvesting period interaction was not significant ($p = 0.486$, partial $\eta^2 = 0.198$). Mauchly's test indicated that the assumption of sphericity was met ($p = 0.312$).



Table 9: Fruit weight (g) across seven harvesting periods as affected by different treatments with repeated-measures ANOVA results

Treatment	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Overall Mean
Treatment 1	149.08	193.32	240.26	154.27	243.56	224.67	231.50	205.24 ^a
Treatment 2	160.75	221.95	223.02	250.25	233.77	216.54	122.75	204.15 ^a
Treatment 3	0.00	277.00	242.41	198.46	183.19	161.95	153.73	173.82 ^b
Treatment 4	0.00	215.75	213.35	176.06	224.88	132.00	151.75	159.11 ^b
Within-measurement	p-Value	η^2	Linear	Quadratic	Cubic	Order 4	Order 5	Order 6
Mauchly's Test of Sphericity	0.312 ^{ns}	0.623						
Measurement periods	<0.001** *	0.31	0.28 ^{ns}	<0.001** *	0.06 ^{ns}	0.07 ^{ns}	0.25 ^{ns}	0.22 ^{ns}
Measurement periods * Treatment	0.486 ^{ns}	0.20	0.72 ^{ns}	0.24 ^{ns}	0.24 ^{ns}	0.77 ^{ns}	0.67 ^{ns}	0.32 ^{ns}
Between-treatment Treatment	p-Value	η^2						
	0.016*	0.563						

Note: Overall column mean with the same letter are not statistically significant; *** - very highly significant p-value; ** - highly significant p-value; * - significant p-value; ns - not significant p-value; η^2 - partial eta squared (effect size)

The treatment effect on fruit weight was significant. Individually applied BPP (T1) and CRHP (T2) produced significantly heavier fruits than the untreated control (T4), while the combined treatment (T3) did not differ significantly from T4, replicating the antagonistic co-application pattern observed for fruit diameter and fruit number. Marcelis et al. (1993) demonstrated that cucumber fruit weight is determined by continuous cell expansion in the pericarp and placenta during the post-division growth phase, with the duration and rate of expansion as the primary determinants of final fruit mass. The present finding is consistent with Marcelis et al. (1993). Foliar-applied potassium from BPP may have enhanced osmotic solute supply and maintained turgor-driven cell expansion throughout the season, producing heavier fruits under T1.

He et al. (2015) demonstrated that silicon forms covalent crosslinks with hemicellulose polysaccharides in rice cell walls, improving mechanical stiffness and regenerative capacity. The finding that CRHP increased fruit weight compared with T4, despite not affecting fruit length, agrees indirectly with He et al. (2015). Silicon-strengthened pericarp cell walls could resist turgor-induced volume loss during maturation, allowing cells to retain the expanded state longer and accumulate more dry matter per unit length. The directional pattern, in which silicon enhanced mass per unit length rather than elongation, is consistent with He et al. (2015), whose study did not examine cucumber tissues, so the agreement remains indirect. Fahimi et al. (2016) compared soil and foliar application of NPK and organic fertilizers in greenhouse cucumber and found that soil treatments produced greater fruit yield and dry weight than foliar applications, due to sustained nutrient delivery via the root-phloem pathway. The present results partially agree with Fahimi et al. (2016), confirming that potassium-rich organic materials improve cucumber fruit biomass. However, the present study differs in that foliar application at 20 g L⁻¹ significantly increased fruit weight under conditions without base fertilization, which Fahimi et al. (2016) did not test. Similarly, Maboko et al. (2017) reported no significant effect of foliar fertilizer on fruit yield in hydroponic mini-cucumber with sufficient background nutrients. The fruit weight advantage under T1 and T2 in the present soil-based study reflects the importance of nutrient context, demonstrating that foliar K⁺ or silicon is effective when no alternative nutrient source is available.

The harvesting period effect produced a narrower range of significant pairwise differences compared with other yield parameters, limited to contrasts between the first harvest and the second and third harvests. Ando et al. (2012) showed that cucumber fruit size stabilizes rapidly after the exponential growth phase, with most dimensional increases



occurring between 4 and 12 days post-pollination and remaining constant from ~16 days onward. The narrower window of significant differences aligns with Ando et al. (2012). Fruit weight integrates assimilate supply over ~10–30 days of maturation, buffering mid-season fluctuations and limiting significant temporal contrasts to early-season harvests. Marcelis et al. (1993) reinforced this interpretation, showing that continuous cell expansion allows fruits to continue growing despite temporary reductions in assimilate supply.

The exclusive significance of the quadratic component, without the fourth-order oscillations observed for fruit number, diameter, and length, aligns with Ando et al. (2012). Temporal averaging across the maturation window dampens flush-and-rest oscillations. The ascending phase reflects canopy photosynthetic capacity establishment, while the descending phase aligns with Parvathi et al. (2022), who reported that accumulating stress reduces the plant's ability to sustain dry matter production. The near-significant cubic ($p = 0.059$) and fourth-order ($p = 0.066$) components suggest subtle oscillations predicted by Kozłowski and Ziólko (1988) may be present but undetectable with the current sample size. Non-significant polynomial contrasts for the interaction indicate that all treatments followed similar trajectories, differing only in overall elevation, suggesting that temporal dynamics in fruit weight were governed by developmental architecture and progressive stress accumulation rather than by foliar nutrient inputs.

Soil Chemical Properties

To assess treatment effects on soil chemical properties, change scores were computed for each replicate by subtracting the uniform pre-planting baseline value from the corresponding post-harvest measurement. A composite soil sample was analyzed before planting to establish the initial soil chemical condition of the experimental area. The before-planting baseline soil-test values were obtained from the composite soil sample, whereas the after-harvest soil-test values were obtained from each treatment replicate and pooled. Baseline soil values were identical across all 12 experimental units (pH = 4.96, N = 0.848%, P = 2.6 ppm, K = 272 ppm). Because baseline values exhibited zero variance across treatments, analysis of covariance was inapplicable, and one-way analysis of variance (ANOVA) was performed on change scores for each soil parameter. Levene's test confirmed homogeneity of variances for all four parameters (all $F = 0.000$, $p = 1.000$), satisfying the equal-variance assumption of ANOVA.

Table 10: Changes in soil chemical properties (pH, nitrogen, phosphorus, and potassium) after harvest as influenced by different treatments

Treatment	pH	Nitrogen	Phosphorus	Potassium
Treatment 1	-0.43 ^a	-0.02 ^c	0.10 ^a	-173.00 ^c
Treatment 2	-0.16 ^b	0.04 ^{ab}	0.10 ^a	-29.00 ^a
Treatment 3	-0.20 ^{ab}	0.35 ^a	-0.36 ^b	-59.00 ^b
Treatment 4	-0.39 ^{ab}	0.12 ^b	0.10 ^a	-74.00 ^b
p-Value	0.025*	<0.001***	0.001**	<0.001***

Note: Column mean with the same letter are not statistically significant; *** - Very highly significant; ** - highly significant; * - significant p-values.

Soil pH

The one-way ANOVA revealed a significant treatment effect on soil pH change ($p = 0.025$). Mean changes ranged from +0.16 in T2 (CRHP) to +0.43 in T1 (BPP). All treatments increased soil pH relative to baseline. T1 (BPP) produced a significantly greater increase than T2 (CRHP; $p = 0.043$). T3 (BPP + CRHP) and T4 (control) recorded intermediate changes of +0.20 and +0.39, respectively. Tukey HSD homogeneous subset analysis indicated that only the T1–T2 contrast reached significance.

The significant pH increases under T1 (BPP; +0.43) is consistent with Naramabuye and Haynes (2006), who reported that organic amendments with high ash alkalinity raise soil pH and reduce exchangeable aluminum in acidic soils. The alkaline nature of BPP (pH 9.28) provides a mechanistic basis, as decarboxylation of organic acids during



decomposition consumes protons, elevating soil pH (Naramabuye & Haynes, 2006). This result also aligns with Topoliantz et al. (2005), who observed that organic amendments, including charcoal, reduce soil acidity in tropical soils. The smaller pH increases under T2 (CRHP; +0.16) reflects its near-neutral pH (6.75), consistent with Locke and Altland (2013), who reported minimal pH effects from rice hull biochar. Intermediate changes under T4 (control; +0.39) likely reflect natural buffering and organic matter decomposition from root residues.

Soil Nitrogen

The treatment effect on soil nitrogen change was highly significant ($p < 0.001$). T1 (BPP) showed the smallest decline (-0.016%), indicating near-baseline nitrogen levels. T2 (CRHP) declined slightly (-0.045%), T4 (control) declined moderately (-0.123%), and T3 (BPP + CRHP) declined most (-0.352%). Tukey HSD post hoc comparisons indicated that T3 differed significantly from T1 ($p < 0.001$), T2 ($p < 0.001$), and T4 ($p = 0.002$). T1 also differed from T4 ($p = 0.038$). Differences between T1 and T2 ($p = 0.483$) and between T2 and T4 ($p = 0.296$) were not significant.

The nitrogen results reveal a gradient of nitrogen conservation corresponding to amendment properties. T1 (BPP) maintained soil nitrogen near baseline, consistent with Makhaye et al. (2024), who reported moderate nitrogen contributions from banana peel amendments. The largest decline under T3 (-0.352%) reflects microbial nitrogen immobilization induced by high-carbon organic amendments, consistent with Xu et al. (2022). The high carbon content of CRHP, combined with BPP's alkalinity, may have enhanced ammonia volatilization and microbial immobilization. This antagonistic pattern corresponds with the reduced vegetative and reproductive performance observed under T3. The moderate nitrogen declines under T4 reflect crop uptake without supplementation, while the slight decline under T2 aligns with Islam et al. (2024), who reported nitrogen retention by carbon-rich biochars.

Soil Phosphorus

The treatment effect on soil phosphorus change was significant ($p = 0.001$). Only T3 (BPP + CRHP) increased soil phosphorus (+0.36 ppm), while T1, T2, and T4 exhibited identical decreases (-0.10 ppm). Tukey HSD post hoc comparisons confirmed T3 differed significantly from T1, T2, and T4 ($p = 0.002$). No differences existed among T1, T2, and T4 ($p = 1.000$).

This result agrees with Haynes and Mokolobate (2001), who reported that combined organic amendments solubilize native phosphorus via low-molecular-weight organic acids released during decomposition. Topoliantz et al. (2005) similarly demonstrated improved phosphorus availability when combining organic peel materials with charcoal. The absence of phosphorus increases under individual BPP or CRHP applications indicates that only the combined decomposition produced sufficient organic acids to mobilize fixed soil phosphorus.

Soil Potassium

The treatment effect on soil potassium change was highly significant ($p < 0.001$). T1 (BPP) produced the largest increase (+173 ppm), T4 (control) +74 ppm, T3 (BPP + CRHP) +59 ppm, and T2 (CRHP) +29 ppm. Tukey HSD comparisons showed T1 differed from T2 ($p < 0.001$), T3 ($p < 0.001$), and T4 ($p < 0.001$); T2 differed from T3 ($p = 0.026$) and T4 ($p = 0.003$); T3 and T4 were not significantly different.

The large potassium increase under T1 aligns with Islam et al. (2019), reflecting BPP's high K content (5.05%) measured in this study, and with Makhaye et al. (2024), who reported substantial potassium enrichment from banana peel amendments. The lower increases under T2 reflect CRHP's lower K content (0.374%) and are consistent with Locke and Altland (2013). The lack of potassium increase in T3 relative to T4 supports the antagonistic interaction between BPP and CRHP, suggesting BPP potassium may have been immobilized or rendered unavailable by CRHP's high-carbon matrix.

IV. CONCLUSIONS

This study demonstrates the effects of foliar application of banana peel powder (BPP), carbonized rice hull powder (CRHP), and their combination on cucumber growth, yield, and post-harvest soil fertility, highlighting both beneficial and antagonistic outcomes.



Banana peel powder was prepared by sun-drying the banana peels followed by milling into a fine powder, resulting in an alkaline amendment rich in potassium. Carbonized rice hull powder was produced via low-temperature carbonization of rice hulls, yielding a near-neutral amendment with moderate phosphorus and low potassium. These procedures preserved nutrient content while producing materials suitable for foliar application.

Application of BPP individually improved soil pH, conserved nitrogen, and enhanced potassium accumulation. CRHP alone moderately increased soil potassium and minimized nitrogen losses, but had limited impact on pH adjustment. The combined application produced a unique increase in phosphorus while causing the most severe nitrogen depletion and lowest potassium accumulation, reflecting antagonistic interactions. These results indicate that individually applied BPP contributes most favorably to post-harvest soil fertility.

Foliar application of BPP or CRHP individually improved lateral branching, fruit number, fruit diameter, and fruit weight compared to the untreated control. BPP was uniquely effective in increasing fruit length, attributable to potassium-mediated cell wall loosening during longitudinal elongation. CRHP enhanced fruit diameter and weight, consistent with the structural reinforcement role of silicon. The combined application did not improve any growth or yield parameter, demonstrating an antagonistic interaction likely due to mismatched pH profiles reducing cuticular nutrient penetration. Plant height and reproductive timing were not affected by any treatment, indicating that these traits are primarily governed by endogenous and environmental cues rather than by foliar nutrient supply.

Individually applied BPP provided the best overall yield performance. CRHP performed comparably for certain yield parameters but was less effective for fruit length. The combination of BPP and CRHP underperformed relative to individual applications.

Significant differences were observed among treatments for lateral branching, fruit number, fruit diameter, fruit length, and fruit weight. Plant height and reproductive timing showed no significant differences. Overall, individually applied BPP and CRHP were superior to the control, whereas the combined treatment did not differ from the control, confirming antagonistic interactions in co-application.

V. RECOMMENDATIONS

BPP at 200g with 10L of water is recommended for cucumber production when improvement across all yield parameters is desired, as it produced the greatest lateral branching, fruit number, fruit diameter, fruit weight, and fruit length, while also delivering the largest post-harvest increases in soil pH and potassium and the best nitrogen conservation among all treatments. CRHP at 200g with 10L of water is recommended as an alternative when BPP is unavailable, as it produced comparable fruit number, fruit diameter, and fruit weight to BPP while moderating post-harvest soil nitrogen losses.

The combined application of BPP and CRHP should be avoided, as it produced no significant improvement over the untreated control for any yield parameter and caused the most severe post-harvest soil nitrogen depletion among all treatments, despite uniquely increasing soil phosphorus availability. Both amendments should be applied individually rather than in combination until the mechanisms underlying their antagonistic interaction across plant performance and soil nitrogen outcomes are better understood.

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