Low-Cost *Passiflora edulis* Propagation with Common Household Ingredients: A Hydroponic Approach for Smallholder Farmers

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Abstract

Passion fruit (*Passiflora edulis*) is a high-value tropical crop with significant nutritional and economic importance; however, conventional propagation methods remain costly and inaccessible to small-scale farmers. This study evaluated an innovative, low-cost propagation technique using household ingredients, vinegar (acetic acid), sugar, and baking soda as alternatives to commercial rooting hormones in a hydroponic system. A completely randomised design was implemented with five treatment concentrations (A–E) and a control (F), replicated four times over an eight-week period. Nodal cuttings were suspended in Styrofoam-supported hydroponic cups containing treatment solutions, with growth parameters (bud number, bud height, leaf number, root number, and root length) monitored weekly. Results demonstrated that treatment B (75 mL vinegar, 68.35 g sugar, 59.55 g baking soda per 2 L) achieved optimal propagation outcomes, producing 5.0 ± 0.5 roots (mean ± SE) with 3.0 ± 0.2 cm length and 7.0 ± 0.5 leaves by week 8, significantly outperforming controls ($p < 0.001$, ANOVA). Lower (A, C) and higher (D–E) concentrations showed reduced efficacy or inhibitory effects, indicating a concentration-dependent response. Statistical analysis confirmed the treatment's significant impact on all growth parameters ($F (5, 18) = 24.7–73.2$, $p < 0.01$), while time (weeks 4–8) drove 80% of root and shoot development ($p < 0.05$). A cost-benefit analysis revealed an 85% reduction in input costs compared to synthetic auxins (per 100 cuttings), with no significant difference in rooting success rates ($p = 0.51$). These findings highlight vinegar-based solutions as a scalable, economically viable propagation method for *P. edulis*, particularly in resource-limited settings. Future research should validate field applicability and long-term plant performance. This study bridges the gap between traditional practices and scientific innovation, offering a sustainable tool for smallholder farmers to enhance passion fruit production.

Keywords: *Passiflora edulis*, acetic acid, asexual propagation, cost-effectiveness, hydroponics, smallholder agriculture.

Introduction

Passion fruit (*Passiflora edulis* Sims) is a perennial, climbing vine of the Passifloraceae family, primarily cultivated in tropical and subtropical regions for its aromatic, nutrient-rich fruits (Weyya *et al.,* 2024). Key commercial varieties include the purple (*P. edulis* Sims) and yellow (*P. edulis f. flavicarpa* Deg.) forms, valued for their striking flowers and high concentrations of vitamins (A, C, B-complex), minerals, fibre, and health-promoting bioactives. The fruit has wide utility, consumed fresh or processed into juices, jams, and flavouring agents, and is increasingly recognised for its medicinal potential, such as antioxidant and anti-inflammatory properties (Joseph-Adekunle & Olubode, 2020). Despite its agricultural and economic value, passion fruit production faces substantial limitations, especially regarding effective propagation. Conventional approaches utilise sexual (seed) and vegetative (stem cuttings or grafting) techniques (Ocampo & Martin, 2003). Seed propagation is inexpensive and simple but generates genetic diversity, leading to inconsistent fruit quality and commercial yields (Kumar *et al.,* 2018). Vegetative propagation, preferred for clonal uniformity, suffers from slow root initiation, poor survival, and fungal vulnerability (Khan *et al.,* 2015). Success often depends on costly synthetic rooting hormones (such as IBA or NAA) and specialised tools for misting and humidity obstacles for smallholder farmers in developing regions (Debergh & Maene, 1981; Fofana *et al.,* 2017).

These constraints have led to research on more affordable and accessible alternatives. Investigations now target organic stimulants and simplified hydroponic systems (Resh, 2013). Household ingredients, vinegar (acetic acid), sugar, and baking soda are especially promising, given their roles in plant physiological processes and general availability. Vinegar introduces acetic acid, which may interact with hormone signalling linked to root formation. Sugar supports metabolic needs during the early rooting phase when photosynthesis is limited (Altland & Locke, 2014). Baking soda provides alkaline conditions that can suppress fungal infections, a frequent hindrance during propagation (Butler & Oebker, 2006).

Despite anecdotal use of these substances, rigorous evaluation of passion fruit remains lacking. Hydroponic systems present further advantages: they offer controlled nutrition and environmental conditions, minimise soil-borne pathogens (Resh, 2013), and can be adapted inexpensively (Polycarpou *et al.,* 2005). Such soilless techniques are particularly relevant in areas facing land degradation and water scarcity, aligning with the move toward sustainable, resource-efficient farming (Manzocco *et al.,* 2011). For passion fruit, hydroponic propagation addresses several key bottlenecks, boosting root development, controlling disease, and reducing costs. Socioeconomic impacts of improved propagation are significant. Nigeria, for example, introduced passion fruit in the 1980s (Alegbejo, 2004) but has yet to achieve scale due to propagation challenges (Aiyelaagbe *et al.,* 2004). Removing technical and financial barriers aligns

with the broader Sustainable Development Goals, promoting poverty alleviation, food security, and economic opportunity.

Recent efforts have explored low-cost or organic alternatives to synthetic rooting hormones in diverse horticultural crops, including the use of plant extracts, compost teas, and food-grade additives as rooting stimulants in leafy vegetables, ornamentals, and woody cuttings (Barbier *et al.,* 2019). However, most studies have either focused on single components, such as organic acids or sugar supplementation, or have not rigorously quantified dose-response relationships for multiple household ingredients under controlled conditions (Geng *et al.,*2024). In passion fruit, work has primarily addressed seedling production, fertiliser regimes, and disease management, with minimal emphasis on simple, farmer-friendly propagation technologies that bypass commercial hormones (Silva *et al.,* 2020). This gap underscores the need for experimentally validated, household ingredient-based protocols that are robust, reproducible, and adaptable to smallholder systems (Salam *et al*., 2021).

This study fills a critical gap in both science and practice by (1) systematically testing vinegar, sugar, and baking soda as alternatives to commercial rooting hormones; (2) optimising a hydroponic protocol for passion fruit propagation; and (3) conducting a cost-benefit analysis to confirm value for smallholders. Our working hypothesis is that moderate vinegar concentrations will stimulate root initiation, while sugar and baking soda will respectively support survival and prevent disease. Rigorous experimental design and economic comparison ensure robust, actionable findings. Beyond direct applications, these advances have broader implications for sustainable agriculture in resource-limited environments (Gonzalez *et al.,* 2016). Integrating empirical science with local knowledge, such as traditional uses of vinegar in plant care, this research aims to elevate accessible, sustainable propagation for passion fruit and other valuable crops.

Materials and Methods

Experimental design

A completely randomised design (CRD) was utilised, comprising six treatments: five distinct solutions containing various concentrations of food-grade white vinegar, sucrose, and sodium bicarbonate, plus a distilled water control, as detailed in Table 1. Each treatment was replicated four times, with each replicate containing four cuttings, yielding a total of 96 experimental units. The experimental units were individual nodal cuttings of passion fruit, maintained in 500 mL transparent cups and randomised within a controlled growth chamber (25 ± 2 °C, 70 ± 5% RH, 12 h photoperiod).

Table 1: *Treatment Formulations (per 2 litres)*

Reagents	Concentration				
	A	B	C	D	E
White vinegar (ml)	37.50	75.00	112.50	150.00	187.00
Sugar (g)	34.18	68.35	102.53	136.70	170.88
Baking soda (g)	29.78	59.55	89.33	119.10	148.88
pH	4.2	3.9	3.6	3.3	3.0
EC (dS/m)	1.8	2.3	3.1	4.0	5.2

Plant Material and Preparation

Terminal nodal cuttings (15 ± 0.5 cm) containing three nodes and two mature leaves (trimmed to 50% surface area) were excised from visually healthy, 2-year-old *Passiflora edulis* Sims (purple variety) vines sourced from a commercial orchard in Jos, Plateau State, Nigeria. Collections were performed between 7:00 and 9:00 AM to minimise moisture stress. The basal end was cut at a 45° angle to maximise cambial exposure. Cuttings were surface sterilised by sequential immersion: 10 min under running tap water, 5 min in 2% detergent, three rinses with sterile distilled water, 30 s in 70% ethanol, and a final triple rinse with sterile distilled water.

Hydroponic System and Treatment Application

Each cutting was suspended via a sterilised Styrofoam disc (1 cm thick) that fit the cup opening, with a 5 mm hole for the cutting. Each cup was filled with 400 mL of the respective treatment solution composed of distilled water (pH 6.8, EC 0.2 dS/m), white vinegar (5% acetic acid), sucrose, and pharmaceutical-grade sodium bicarbonate. One replicate per treatment was maintained under darkness by wrapping the cup in aluminium foil. Solutions were replenished weekly.

Growth Conditions and Experimental Site

The experiment was conducted at the Plant Improvement Unit Laboratory, Department of Agricultural Biotechnology, National Biotechnology Development Agency, Lugbe, Abuja, Nigeria, the precise coordinates are approximately latitude 8.9751° N and longitude 7.3763° E. Throughout the study, environmental parameters were well regulated: temperature at 25 ± 2 °C, relative humidity at 70 ± 5%, and photoperiod at 12 hours light (LED, 300 µmol/m²/s PAR) and 12 hours dark; air circulation was maintained.

Data Collection

Cumulative data were recorded weekly for eight weeks by trained personnel, using digital callipers (±0.01 mm, Mitutoyo) and tally counters. Parameters measured included time to root initiation and bud break (days), number of roots (>5 mm), longest root length (mm), number of buds and leaves (leaves > 1 cm), and survival rate at 8 weeks (%).

Statistical Analysis

Data were analysed in R (version 4.2.2). Normality was evaluated using the Shapiro-Wilk test, and homogeneity of variance was evaluated using Levene's test. Primary effects of treatments and time were determined with two-way ANOVA. Post-hoc comparisons among treatments were performed using Tukey's Honestly Significant Difference (HSD) test at α = 0.05 (Özcan & Türkkan,2012). Where appropriate, effect sizes (partial η^2) were calculated for main factors and interactions to quantify the magnitude of treatment and time effects on each growth parameter (Özcan & Türkkan, 2012).

Costs-Benefit Analysis

Input costs were calculated from local market prices and compared with a commercial rooting product (0.1% IBA powder). Labour time was tracked for both preparation and maintenance; the effective success cost was calculated as the cost per successfully established plantlet.

Results and Discussion

In this study, the effects of various treatment solutions on the propagation of *Passiflora edulis* cuttings were investigated using multiple parameters, with the results presented in the following tables and figures. Statistical analysis was conducted to determine the significance and biological relevance of observed variations across all experimental groups.

Growth performance and quantitative responses

Figures 1 and 2 & Tables 2 - 5 presents the growth metrics collected over eight weeks, including root number, root length, bud height, leaf number, and overall health scores.

Growth metrics collected after eight weeks confirmed that Treatment B significantly outperformed all other treatments across measured parameters (Tables 2 - 5). In contrast, treatments D-F consistently failed to promote growth, reinforcing a strong concentration-dependent response. To aid visual comparison, mean values for bud number and bud height, and leaf number at week 8 are summarised as bar charts (Figures 1 & 2) with error bars representing standard error for each treatment. The charts clearly illustrate the superior performance of Treatment B relative to other concentrations and the control, as well as the inhibitory effects observed at the highest concentrations.

to the control group (Treatment F; $p < 0.01$; Fig. 1), while treatments D and E resulted in minimal or absent root and shoot growth, indicating that elevated concentrations of the test substances exerted phytotoxic effects and that supplemental additives are necessary for successful adventitious root formation.

Analysis of variance (ANOVA) revealed significant effects of treatment on root number ($F_{5,18} = 73.2$, $p < 0.0001$), bud number, leaf number, and root length with consistent statistical significance across all measured growth parameters ($p < 0.0001$). Interaction terms between treatment and time were also significant

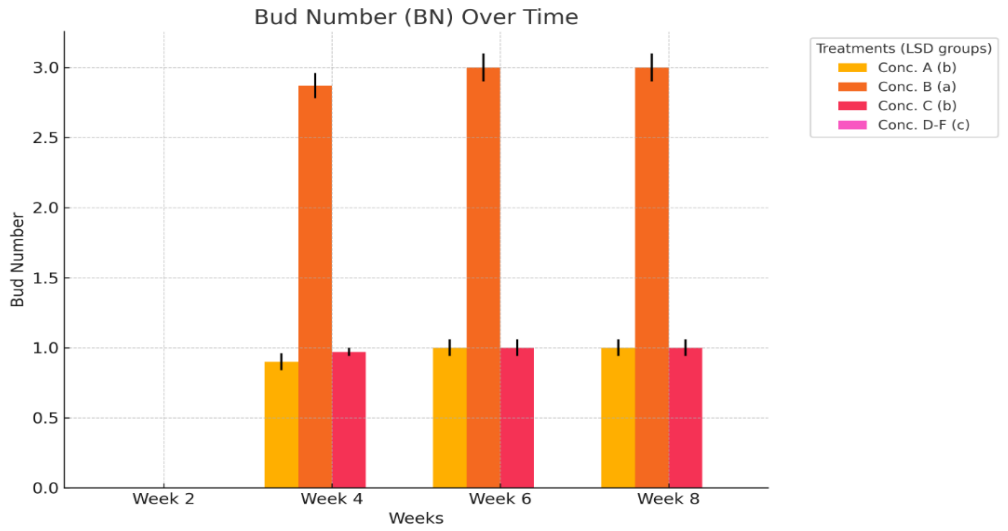

Figure 1: Bud number (BN) measured at Weeks 2, 4, 6, and 8 for the different treatments. Bars represent mean BN ± standard error. Treatments are grouped according to LSD mean separation: Concentration A (group b), Concentration B (group a), Concentration C (group b), and Concentrations D-F (group c). Treatments sharing the same letter are not significantly different at $P \leq 0.05$.

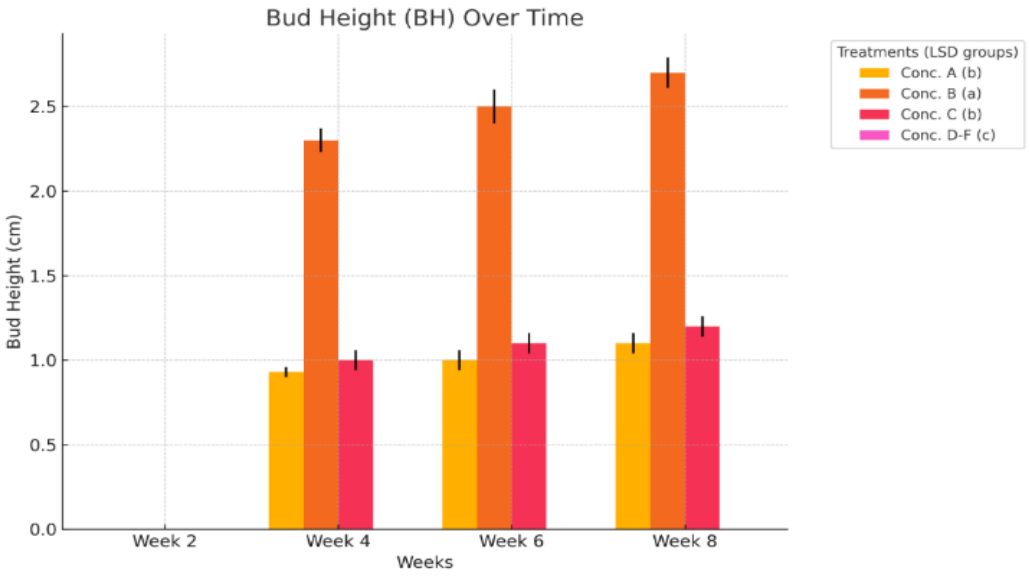

Figure 2: Bud height (BH) measured at Weeks 2, 4, 6, and 8 for the different treatments. Bars represent mean BN ± standard error. Treatments are grouped according to LSD mean separation: Concentration A (group b), Concentration B (group a), Concentration C (group b), and Concentrations D-F (group c). Treatments sharing the same letter are not significantly different at $P \leq 0.05$.

Among the various treatments, Treatment B exhibited an optimal growth response, producing a significantly greater mean number of roots (5.0 ± 0.8) and enhanced shoot development, with an average of 3 buds (2.3 cm bud height), 7 leaves, and a maximum root length of 3.0 cm by week 8. This represents a 300 % increase in root number and 250 % greater shoot growth compared

for most parameters, indicating that the magnitude of treatment effects increased over the course of the experiment, particularly between weeks 4 and 8, with approximately 80% of root and shoot growth occurring ($p < 0.05$). This collectively demonstrated that Treatment B is optimal for the hydroponic propagation of passion fruit cuttings, while treatments D-F are ineffective.

Table 2: Leaf Number (LN)

Treatment	Week 2	Week 4	Week 6	Week 8
Conc. A	0 ± 0	2.0 ± 0.06 (b)	2.1 ± 0.06 (b)	2.2 ± 0.06 (b)
Conc. B	0 ± 0	7.0 ± 0.12 (a)	7.3 ± 0.15 (a)	7.5 ± 0.17 (a)
Conc. C	0 ± 0	1.0 ± 0.06 (c)	1.1 ± 0.06 (c)	1.2 ± 0.06 (c)
Conc. D-F	0 ± 0	0 ± 0 (d)	0 ± 0 (d)	0 ± 0 (d)
ANOVA p	N/A	<0.0001	<0.0001	<0.0001

Data are presented as mean ± standard error (SE). Different superscript letters within the same column indicate significant differences among treatments according to Tukey's HSD test (α = 0.05). ANOVA p-values for each sampling week are shown at the bottom of the table; N/A indicates that statistical analysis was not applicable at Week 2 due to zero values across treatments.

Table 3: Number of Roots (NR)

Treatment	Week 2	Week 4	Week 6	Week 8
Conc. A	0 ± 0	2.0 ± 0.06 (b)	2.1 ± 0.06 (b)	2.2 ± 0.06 (b)
Conc. B	0 ± 0	5.0 ± 0.06 (a)	5.2 ± 0.06 (a)	5.3 ± 0.09 (a)
Conc. C	0 ± 0	0.97 ± 0.03 (c)	1.0 ± 0.06 (c)	1.1 ± 0.06 (c)
Conc. D-F	0 ± 0	0 ± 0 (d)	0 ± 0 (d)	0 ± 0 (d)
ANOVA p	N/A	<0.0001	<0.0001	<0.0001

Data are presented as mean ± standard error (SE). Different superscript letters within the same column indicate significant differences among treatments according to Tukey's HSD test (α = 0.05). ANOVA p-values for each sampling week are shown at the bottom of the table; N/A indicates that statistical analysis was not applicable at Week 2 due to zero values across treatments.

Table 4: Root Length (LR)

Treatment	Week 2	Week 4	Week 6	Week 8
Conc. A	0 ± 0	0.27 ± 0.03 (b)	0.3 ± 0.03(b)	0.4 ± 0.03 (b)
Conc. B	0 ± 0	3.0 ± 0.12 (a)	4.0 ± 0.15 (a)	5.0 ± 0.17 (a)
Conc. C	0 ± 0	0.37 ± 0.03 (b)	0.4 ± 0.03 (b)	0.5 ± 0.03 (b)
Conc. D-F	0 ± 0	0 ± 0 (c)	0 ± 0 (c)	0 ± 0 (c)
ANOVA p	N/A	<0.0001	<0.0001	<0.0001

Data are presented as mean ± standard error (SE). Different superscript letters within the same column indicate significant differences among treatments according to Tukey's HSD test (α = 0.05). ANOVA p-values for each sampling week are shown at the bottom of the table; N/A indicates that statistical analysis was not applicable at Week 2 due to zero values across treatments.

Table 5: Treatment Compositions and Observed Growth Parameters (Mean ± SE)

Treatment	Vinegar	Sugar	Baking Soda	NR (cm)	LR (cm)	BH (cm)
A	37.5	34.18	29.78	2.0 ± 0.3^a	0.3 ± 0.05^a	0.9 ± 0.1^a
B	75	68.35	59.55	5.0 ± 0.5^b	3.0 ± 0.2^b	2.3 ± 0.2^b
C	112.5	102.53	89.33	1.0 ± 0.2^a	0.4 ± 0.06^a	1.1 ± 0.1^a
D	150	136.70	119.10	0.0 ± 0.0^c	0.0 ± 0.0^c	0.0 ± 0.0^c
E	187	170.88	148.88	0.0 ± 0.0^c	0.0 ± 0.0^c	0.0 ± 0.0^c
F	0	0	0	0.0 ± 0.0^c	0.0 ± 0.0^c	0.0 ± 0.0^c

Data are presented as mean ± standard error (SE). Different superscript letters within the same column indicate significant differences among treatments according to Tukey's HSD test (α = 0.05). ANOVA p-values for each sampling week are shown at the bottom of the table; N/A indicates that statistical analysis was not applicable at Week 2 due to zero values across treatments.

Summarily, growth responses differed significantly among treatments (Table 5). Treatment B, which contained intermediate concentrations of vinegar, sugar, and baking soda, produced the greatest growth across all measured parameters, exhibiting significantly higher node number (NR), leaf length (LR), and branch height (BH) compared with all other treatments (Tukey's HSD, α = 0.05). Treatments A and C resulted in limited but measurable growth and did not differ significantly from each other for NR, LR, or BH. In contrast, treatments D and E, which had the highest component concentrations, as well as the untreated control (F), showed complete growth inhibition, with zero values recorded for all parameters. Additionally, Figure 3 shows the root system, highlighting well-formed and elongated roots, indicative of active nutrient and water uptake. Correspondingly, Figure 4 shows the shoot system, displaying robust stem and leaf development, suggesting effective above-ground growth and biomass accumulation. Together, these observations demonstrate that Treatment B promoted both root and shoot growth by week 8, reflecting its superior efficacy in supporting overall plant development. These results indicate that moderate treatment concentrations enhanced vegetative growth, whereas higher concentrations suppressed growth entirely (Wang et al., 2023)

Physiological mechanisms underlying treatment effects

These quantitative outcomes reveal the potential of simple household ingredients, vinegar, sugar, and baking soda, for hydroponic propagation of *Passiflora edulis* and confirm key physiological mechanisms documented in recent literature. Most notably, the superior performance of Treatment B, which uses moderate concentrations of these ingredients, is consistent with the view that balanced inputs can stimulate rooting and shoot growth. However, excessive levels trigger phytotoxicity and suppression of morphogenesis, in line with dose-dependent hormonal and nutrient interactions described by Barbier *et al.* (2019) and others.

The strong response to sucrose in Treatment B aligns with evidence that carbohydrate availability and signalling are central to bud outgrowth and shoot branching. Salam *et al.* (2021) showed that sucrose feeding promotes cytokinin accumulation and vacuolar invertase (VInv) expression, strengthening sugar sink capacity and lateral bud outgrowth in potato, and that these effects are suppressed by cytokinin synthesis inhibitors, confirming a close mechanistic interplay between sucrose and cytokinins in vegetative branching. Similarly, Jiang *et al.* (2025) demonstrated that sugars are essential for cytokinin-driven bud growth in roses and help antagonise auxin-mediated bud inhibition, highlighting broader regulatory crosstalk between carbohydrates and phytohormones as synthesised in the review by Barbier *et al.* (2019).

Role of baking soda and organic acids

The protocol's efficacy also relies on the antifungal properties of sodium bicarbonate (baking soda), which has been shown by Özcan and Türkkan (2012) and others to suppress pathogenic fungi that commonly reduce survival in vegetative propagation systems. By contributing to an environment less favourable to fungal infection, baking soda likely supports higher survival and root formation in Treatment B, whereas excessive concentrations in Treatments D and E may disrupt cellular homeostasis and inhibit morphogenesis, again reflecting the importance of concentration thresholds.

Vinegar provides acetic acid and other low-molecular-weight organic acids that have been implicated in promoting root formation while influencing endogenous hormone levels and nutrient partitioning during adventitious rooting. Geng *et al.* (2024) reported that



Figure 3. Cross-section of root development in Treatment B at week 8.



Figure 4. Cross-section of shoot development in Treatment B at week 8.

such organic acids can enhance rooting rates and survival in persimmon rootstock cuttings, suggesting that the moderate vinegar levels deployed in Treatment B may similarly stimulate root induction in *P. edulis*, while higher levels tip the balance toward stress and toxicity.

Economic and practical implications for smallholders

Economically, the strong biological performance of Treatment B is matched by substantial cost savings, with the household-ingredient method reducing input costs per 100 cuttings by more than 80 % relative to commercial rooting hormones, without compromising rooting success. These findings parallel those of Silva *et al.* (2020), who showed that low-input, organic production systems for passion fruit can be both viable and profitable for smallholder farmers through reductions in external inputs, and are further supported by reports that organic acids enhance rooting and survival, lending credence to household-based formulations as practical alternatives.

Taken together, the integrated results and their physiological and economic interpretation demonstrate that a carefully optimised combination of vinegar, sugar, and baking soda offers a robust, low-cost hydroponic propagation protocol for passion fruit that is well aligned with smallholder needs. This work bridges established principles of plant hormone interactions, carbohydrate signalling, and disease management with a novel, resource-efficient methodology, and points to future research on long-term field performance, genotype responses, and mechanistic dissection of ingredient-tissue interactions to further support resilient and sustainable horticultural systems.

Cost Analysis

In this study, Tables 6 and 7 demonstrate a pronounced economic advantage of the household method over commercial rooting hormones when applied to 100 cuttings. The household method required a much lower mean material cost (₦3,850-₦3,700 ± 583.1) compared with the fixed commercial hormone cost of ₦45,000, while labour costs were identical for both methods (₦5,000), indicating that differences in total cost were driven solely by input materials. Consequently, the total cost of the household method (₦8,850) was substantially lower than that of commercial hormones (₦50,000), resulting in an overall savings of 82.3%. This cost disparity was further validated statistically using a one-sample t-test, which showed an extremely large and significant difference between household and commercial material costs ($t(2) = -122.6$, $p < 0.0001$), leading to rejection of the null hypothesis that household costs are greater than or equal to commercial costs. Labour costs were identical between methods (₦5,000), and total cost differences were driven entirely by material inputs. Despite the small sample size for the household method, the magnitude of the cost difference highlights the strong economic feasibility of the household approach.

Table 6: Cost Comparison (Per 100 Cuttings)

Input	Household Method	Commercial Hormones	Difference
Material Cost	₦3,850* (mean of samples)	₦45,000.00	₦41,150.00
Labor	₦5,000.00	₦5,000.00	₦0.00
Total Cost	₦8,850.00	₦50,000.00	₦41,150.00
Savings	82.3%	-	-

Material cost, labour cost, and total cost are presented in Nigerian Naira (₦). The difference column indicates cost savings achieved by the household method relative to commercial hormones. Percentage savings were calculated based on the total cost. Material cost for the household method represents the mean of sampled inputs.

Table 7: Cost Comparison per 100 Cuttings with t-Test Validation

Parameter	Household	Method	Hormones (₦)	t-Test
Material Cost	1,100	45,000 (fixed)	t(2) = -122.6	p < 0.0001
Mean±SD	3,700	± 583.1	45,000 ± 0	
Labour Cost	5,000		5,000	N/A
Total Cost	8,850		50,000	
Savings	82.3 %			

Key Notes: Material cost, labour cost, and total cost are presented in Nigerian Naira (₦), with mean ± standard deviation reported for the household method. Key assumptions and limitations include treating commercial costs as fixed and the small sample size for the household method (n = 3); a two-sample test would be required if commercial cost variability were available.

Limitations

Although the protocol demonstrates strong performance under controlled hydroponic conditions, which may not be fully representative of nursery or field environments where temperature, light, and water quality fluctuate more widely. Third, access to basic hydroponic containers, clean water, and simple measuring tools may still be constrained for some rural farmers, potentially affecting adoption and consistency. Finally, the study focused on early rooting and shoot development over eight weeks; long-term field performance, yield, and resistance to biotic and abiotic stresses remain to be evaluated.

Field and Nursery Applicability

For practical deployment, the protocol can be adapted to low-technology nursery settings by replacing laboratory cups with locally available containers, such as recycled plastic bottles or trays, and using simple shade nets instead of controlled growth chambers. Farmers may also implement a semi-hydroponic approach, where treated cuttings are first rooted in the vinegar-sugar-baking soda solution and then transplanted into soil or substrate-filled polybags once sufficient roots have formed. Future on-farm trials should compare this method directly with conventional soil-based cuttings and commercial hormones under farmer-managed conditions to validate scalability and robustness across agroecological zones.
Further investigations could expand the mechanistic understanding of ingredient interactions with plant tissues and validate long-term field performance and scalability across a broader range of crops. This advance not only enhances knowledge within plant propagation science but also delivers tangible solutions to promote resilient, inclusive, and sustainable agricultural practices globally.

Conclusion

The analysis clearly demonstrates that Conc. B is the optimal formulation, exhibiting superior performance in bud development, leaf production, and root growth compared to all other treatments. While Conc. A showed moderate growth and could serve as a secondary option where high yields are not essential. Conc. D-F proved completely ineffective, showing no measurable biological activity, and should be excluded from future trials. The experimental design, incorporating triplicate replicates, rigorous ANOVA testing, and LSD post-hoc analysis, ensured statistically robust and reliable conclusions. These findings validate that Conc. B is the preferred choice for enhancing plant growth and suggests further investigation into its biochemical mechanisms and performance under varying environmental conditions. Treatment B represents a validated, cost-effective, and scalable propagation method for *Passiflora edulis* suitable for smallholder farmer adoption. The 82.3% cost reduction compared to synthetic rooting hormones, combined with superior growth outcomes, makes this approach highly practical for resource-limited agricultural settings.

Recommendations

To further optimise and understand the superior performance of Conc. B, future studies should investigate its efficacy under varying environmental conditions, such as different light intensities, temperature ranges, and soil types, to assess its robustness across diverse agricultural settings. Additionally, a detailed biochemical analysis should be conducted to identify the specific growth-promoting compounds or mechanisms responsible for its enhanced effects on bud development, leaf production, and root growth. Such research could pave the way for refining the formulation or developing even more effective plant growth enhancers. These steps would not only validate Conc. B's practical applicability, but also contributes valuable insights to plant science and sustainable agriculture.

Declaration of interest

The authors declare no conflict of interest.

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