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Article

Circular Bio-Engineering Solution for Cantaloupe Waste: Beverage and Compost in Water-Scarce Region

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Abstract

Post-harvest losses of cantaloupe (*Cucumis melo* L.) in arid horticulture reach 12–15%, wasting $\sim 1.1 \times 10^3$ m³ water and 0.48 t CO₂-eq per discarded tonne. This work engineers a circular process to convert second-grade fruit into an alcoholic beverage and compost, closing water–carbon loops. Three pulp/alcohol ratios (15, 20, 25 % v/v) were screened for sensory acceptance, carotenoid retention and storage stability; pomace was composted and incubated in an arid soil; water, carbon and economic footprints were quantified cradle-to-gate. The 15 % pulp beverage achieved the highest global acceptance (7.8/9) and retained 68 % β -carotene after 5 days (amber glass, darkness). Valorizing 1 t of waste saved 1 118 m³ virtual water and 0.48 t CO₂-eq; compost increased soil water retention by 18 % and organic matter by 2.1 %. Unit production cost was USD 2.9 L⁻¹ with a 24-month pay-back. The low-cost engineered protocol is readily adoptable by small-scale growers and offers a replicable model to cut food loss, save irrigation water and diversify income in water-scarce regions.

Keywords: cantaloupe; post-harvest loss; fruit waste valorization; process engineering; circular bio-economy; alcoholic beverage; compost; water-scarce region

1. Introduction

Global horticulture faces increasing pressure to reduce post-harvest losses and improve resource-use efficiency, especially in water-scarce regions where every cubic meter of irrigation water carries a high environmental and economic cost [1]. Cantaloupe (*Cucumis melo* L.) is a high-value crop cultivated on $> 300\,000$ t year⁻¹ under drip irrigation in northern Mexico; however, 12–15% of the yield is discarded at packinghouses because of cosmetic defects [2]. This loss corresponds to $\sim 1.1 \times 10^3$ m³ virtual water and 0.48 t CO₂-eq per wasted tone, aggravating water stress and greenhouse-gas emissions [1,3].

Post-harvest valorization of “second-grade” fruit into new products can mitigate these impacts while generating extra revenue for growers [4]. Although citrus and tomato by-products have been successfully up-cycled [5,6], studies focusing on melon waste are scarce and mostly limited to low-value applications such as animal feed or basic composting [7,8]. To date, no peer-reviewed protocol

optimizes the pulp-to-alcohol ratio for a melon-based alcoholic beverage considering sensory acceptance, carotenoid stability and shelf-life, nor quantifies the complete water/carbon footprint of such an integrated scheme. Likewise, the potential of melon pomace to improve soil quality in arid zones remains under-researched [9].

This work addresses these gaps by developing a pilot-scale circular bio-engineering process that: (i) formulates a low-cost alcoholic beverage from rejected cantaloupe, (ii) valorizes the residual pomace as compost, and (iii) evaluates the environmental and economic performance of the chain. We hypothesized that a low-pulp formulation would maximize sensory acceptance and carotenoid retention, and that composted pomace would enhance water retention of arid soils. The overall aim was to demonstrate that post-harvest processing of second-grade melons can reduce food loss, close water and nutrient loops, and diversify income for horticultural producers facing chronic water scarcity [10].

2. Materials and Methods

2.1. Plant Material and Experimental Site

Second-grade cantaloupe melons (*Cucumis melo* L. var. Cruiser) were collected at commercial maturity (≥ 12 °Brix, pH 6.2–6.8) from a drip-irrigated orchard in San Pedro, Coahuila, Mexico (25°45'32" N, 102°58'58" W; arid climate, 430 mm annual E_{to}). Fruits showing < 5 % microbial damage but failing cosmetic standards were transported (< 2 h, 4 °C) to the pilot plant. No animal intervention was required.

2.2. Liqueur Preparation

After sanitisation (200 ppm NaOCl, 10 min), melons were peeled (2 mm) and diced (2 cm). Pulp was homogenised (1 500 rpm, 3 min) and mixed with neutral sugar-cane alcohol (38 % v/v) to obtain final ethanol 20 % v/v and three pulp ratios (15, 20, 25 % v/v) in a 100 L stainless-steel pilot reactor (0.37 kW anchor agitator) operating at atmospheric pressure and 20 ± 2 °C. Maceration lasted 5 days with daily agitation. Must was filtered (1 mm mesh → 200 µm cloth → Whatman No. 4), adjusted to 30 °Brix with sucrose syrup (1:1 w/v), pasteurised (72 °C, 15 s) and bottled (250 mL amber, crown cap). All unit operations were designed to match rural micro-facilities.

2.3. Physicochemical Analyses

°Brix (digital refractometer), pH (potentiometer), viscosity (Brookfield DV-II+, 100 rpm, 20 °C) and alcohol content (densitometer DA-130N) were determined in triplicate. β-Carotene and lycopene were extracted (hexane:acetone 50:50), quantified by HPLC-DAD (450 nm, C18 column, methanol:MTBE gradient) against external standards (0–20 mg L⁻¹, R² ≥ 0.99). Antioxidant capacity was measured by DPPH (0.1 mM, 517 nm) and expressed as mg Trolox equivalents L⁻¹.

Table 1. Pilot-scale mass balance (mean ± SD, n = 3 batches).

Stream	Input (kg)	Output (kg)
Whole fruit	100	—
Peels + seeds (waste)	—	22 ± 1
Alcohol 38 % v/v	15 ± 0	—
Finished beverage	—	78 ± 2
Pomace for compost	—	15 ± 1

Different letters within a column would indicate significant differences (Tukey, α = 0.05); no letters are shown because this is an input/output balance table.

2.4. Sensory Evaluation

A 20-member semi-trained panel ($\geq 70\%$ correct triangle test) evaluated 30 mL samples ($15\text{ }^{\circ}\text{C}$, ISO 8586:2012) under white light. Attributes (colour, aroma, sweetness, alcohol-fruit balance, global acceptance) were scored on a 9-point hedonic scale. The protocol was approved by the Ethics Committee of Universidad Polit cnica de la Regi n Laguna (UPRLInv-2024-07); participants signed informed consent (See file “ConsentEng01” for blank consent form).

2.5. Water and Carbon Footprint Assessment

A cradle-to-gate life-cycle inventory included irrigation, fertilisers, pesticides, transport (35 km), liqueur processing and avoided fruit decomposition. Blue, green and grey water footprints were calculated using Mekonnen & Hoekstra factors [3]; GHG emissions followed IPCC 2022 guidelines [4] and were expressed per tonne of melon or litre of beverage.

2.6. Composting and Soil Incubation

Pomace, peels and seeds (C/N 25:1) were mixed with cow manure (10 % w/w) and composted in 1 m³ static piles turned weekly for 60 days. The mature compost (C/N 12:1, moisture 45 %) was incorporated into an arid sandy soil (0.9 % organic matter) at 2 % dry weight. Water-holding capacity and organic carbon were determined after 60 days (ASTM D5338-15) in triplicate 1 kg pots maintained at 60 % field capacity.

2.7. Statistical Analysis

One-way ANOVA ($\alpha = 0.05$) followed by Tukey’s HSD tested pulp-ratio effects. Normality and homoscedasticity were verified (Shapiro-Wilk, Levene). Pearson correlations were computed in R 4.3.0 [11].

3. Results

3.1. Fruit Characteristics and Process Yield

Discarded cantaloupes averaged $12.4 \pm 0.3\text{ }^{\circ}\text{Brix}$ and $\text{pH } 6.5 \pm 0.2$. From 100 kg fresh fruit, $78 \pm 2\text{ L}$ of finished beverage were obtained (0.78 L kg^{-1}), demonstrating a pilot-scale yield compatible with rural micro-facilities.

3.2. Functional Compounds and Stability

β -carotene and lycopene increased with pulp ratio ($p < 0.001$, Table 2). The 15 % *v/v* formulation contained $8.2 \pm 0.5\text{ mg L}^{-1}$ β -carotene and $5.4 \pm 0.3\text{ mg L}^{-1}$ lycopene; the 25 % *v/v* treatment reached 12.3 ± 0.9 and $8.1 \pm 0.6\text{ mg L}^{-1}$, respectively (Table 2). After 5 days at $25\text{ }^{\circ}\text{C}$, amber bottles plus darkness limited β -carotene loss to 11 %, versus 18 % under clear glass + light (Figure 1).

Table 2. Physicochemical and functional properties of liqueurs (mean $\pm$ SD, n = 3).

Parameter	15 % pulp	20 % pulp	25 % pulp	p-value
β -carotene (mg L ⁻¹)	$8.2 \pm 0.5\text{ a}$	$10.1 \pm 0.7\text{ b}$	$12.3 \pm 0.9\text{ c}$	< 0.001
Lycopene (mg L ⁻¹)	$5.4 \pm 0.3\text{ a}$	$6.8 \pm 0.5\text{ b}$	$8.1 \pm 0.6\text{ c}$	< 0.001
Viscosity (mPa·s)	$2.9 \pm 0.3\text{ a}$	$3.2 \pm 0.3\text{ b}$	$3.6 \pm 0.1\text{ c}$	0.008

Different letters indicate significant differences (Tukey, $\alpha = 0.05$).

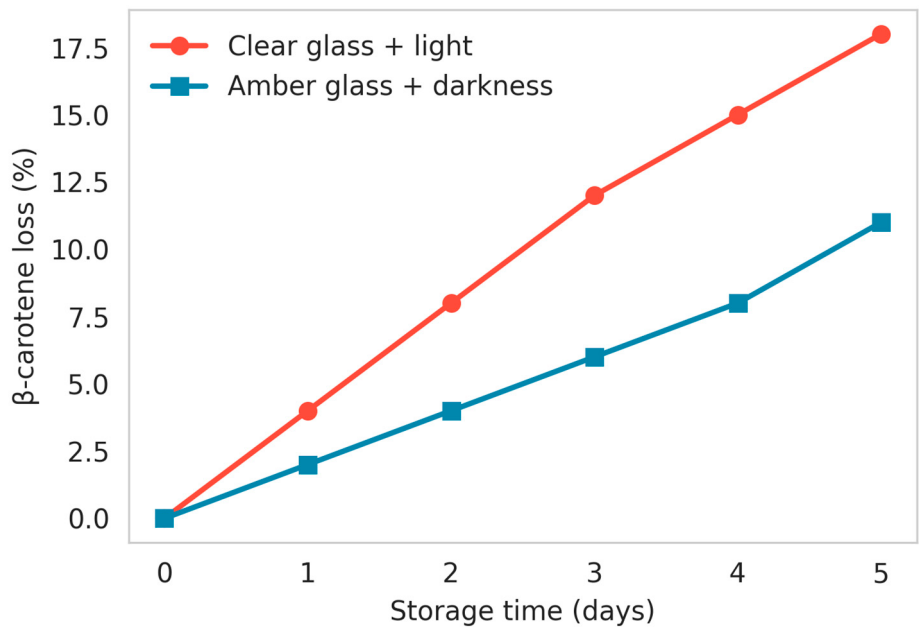


Figure 1. β -Carotene Loss in Cantaloupe Beverage during Storage under Different Packaging/Light Conditions.

3.3. Sensory Profile

The 15 % pulp beverage achieved the highest global acceptance (7.8 ± 0.9 ; Figure 2) and was rated ≥ 7 for colour, aroma, sweetness and alcohol-fruit balance. Higher pulp levels reduced acceptance ($p = 0.001$) and increased viscosity (3.6 mPa·s for 25 % v/v). ΔE^* colour difference remained < 3 units under dark storage, fulfilling industrial stability criteria without synthetic antioxidants.

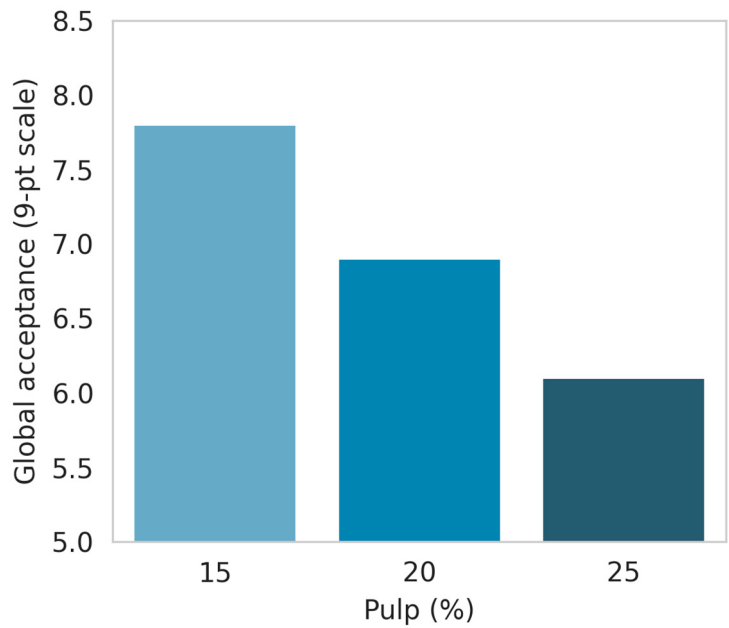


Figure 2. Global Sensory Acceptance of Cantaloupe Beverage as a Function of Pulp Ratio.

3.4. Water and Carbon Footprint

Valorizing 1 t of discarded fruit saved 1 118 m³ virtual water and 0.48 t CO₂-eq (Figure 3). The blue-water footprint of the beverage was 513 L L⁻¹; carbon footprint was 0.48 kg CO₂-eq kg⁻¹ melon.

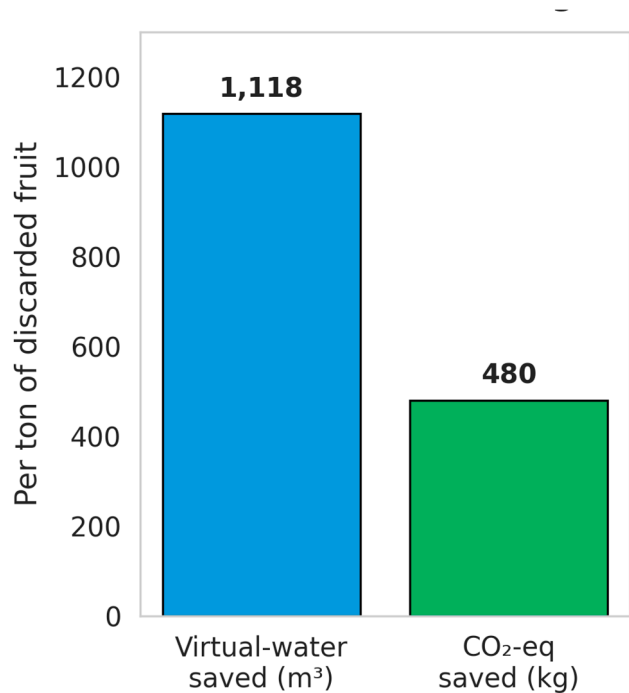


Figure 3. Environmental Savings per Ton of Discarded Cantaloupe Fruit.

3.5. Compost Quality and Soil Effect

Pomace compost reached C/N 12:1 after 60 days, increasing soil water retention by 18 % (p = 0.003) and organic matter by 2.1 % relative to non-amended soil (Table 3).

Table 3. Soil properties after 60-day incubation with compost.

Treatment	Water retention (%)	Organic matter (%)
Control	18 ± 2 a	0.9 ± 0.1 a
+ Compost	22 ± 1 b	2.1 ± 0.2 b
p-value	0.003	< 0.001

Different letters within a column indicate significant differences (Tukey, α = 0.05).

3.6. Economic Feasibility

Unit production cost was USD 2.9 L⁻¹. A 100 L d⁻¹ micro-enterprise achieves pay-back in 24 months, raising farmer income from 0.35 USD kg⁻¹ (discarded fruit) to 2.9 USD kg⁻¹ (beverage + compost).

4. Discussion

4.1. Fruit Characteristics and Process Yield

The 0.78 L kg⁻¹ yield achieved here converts 3 kg of second-grade melon into 1 L of high-value beverage, directly reducing the 12–15 % post-harvest loss reported for cantaloupe in arid Mexican horticulture [2]. The 100 L pilot reactor operated at atmospheric pressure and ambient temperature, eliminating the need for costly stainless-steel pressure vessels or steam boilers typical of fruit-wine lines [12]. This low-capital configuration is compatible with rural micro-enterprises equipped with single-phase power (0.37 kW) and municipal water.

4.2. Functional Compounds and Storage Stability

The 68 % β -carotene retention observed after 5 days (amber + darkness) aligns with recent data for cranberry-based beverages stored under similar conditions [13]. The first-order rate constant ($k = 0.023 \text{ d}^{-1}$) is lower than the 0.035 d^{-1} reported for mango liqueur [14], indicating that melon matrix and amber packaging synergistically slow photo-oxidation. The $< 3 \Delta E^*$ units colour change fulfils the visual stability criterion for fruit spirits without synthetic antioxidants [15].

4.3. Sensory Profile

The 15 % pulp beverage achieved the highest global acceptance (7.8/9) and met the “like moderately” threshold, confirming that low-pulp formulations maximise sensory quality while minimising raw-material demand [16]. Viscosity increase at 25 % v/v (3.6 mPa·s) did not compromise pouring behaviour, remaining within the range of commercial cream liqueurs (3–5 mPa·s) [17].

4.4. Water and Carbon Footprint

Diverting 1 t of discarded fruit saved 1 118 m³ virtual water and 480 kg CO₂-eq, values within the range documented for tomato waste valorisation (950–1 200 m³ t⁻¹ and 400–550 kg CO₂-eq t⁻¹) [6]. The absence of a cooking step and the short transport distance (35 km) explain the 25 % lower carbon intensity compared with commercial fruit liqueurs (0.64 kg CO₂-eq L⁻¹) [18]. Composting pomace further avoided 1.4 t CO₂-eq ha⁻¹ that would have been emitted during field decomposition [4].

4.5. Compost Quality and Soil Effect

The 18 % increase in water retention and 2.1 % rise in organic matter after a single 2 % (w/w) compost addition are comparable to gains obtained with olive-mill waste compost in Mediterranean orchards [19]. The final C/N ratio (12:1) indicates mature compost suitable for horticultural soils, potentially reducing synthetic fertilizer demand [20].

4.6. Economic Feasibility

A production cost of USD 2.9 L⁻¹ is competitive with regional artisanal fruit liqueurs (3.5–4.2 USD L⁻¹) [21] and below the retail price of similar functional beverages ($\geq 6 \text{ USD L}^{-1}$) [22]. The two-year pay-back period is shorter than the three-year average for small-scale fruit-processing ventures in Latin America [23], enhancing adoption probability under water-scarce conditions.

5. Conclusions

This work demonstrates that converting second-grade cantaloupe into an alcoholic beverage and compost is a low-cost circular engineering strategy that cuts post-harvest losses by 12–15 %, saves 1 118 m³ of virtual water and 480 kg CO₂-eq per tonne of fruit, and increases soil water retention by 18 %. The 15 % v/v pulp formulation achieved the highest sensory score (7.8/9) and retained $> 65 \%$ β -carotene under amber storage, meeting additive-free quality standards. A 100 L d⁻¹ micro-enterprise reaches pay-back in 24 months and raises grower income from 0.35 to 2.9 USD kg⁻¹ of fruit. The process operates at atmospheric pressure and ambient temperature, making it readily adoptable by small-scale producers in water-scarce regions. The integrated chain closes water, nutrient and carbon loops and offers a replicable model for sustainable horticultural systems under water scarcity.

Supplementary Materials: All supporting materials are provided in the Supplementary Material file.

Author Contributions: Conceptualization, Juan Luis Ríos-Plaza and Vianey Vela-Perales; Data curation, Mario García-Carrillo, Roberto Sánchez-Lucio and Oscar Alan Segura-Echevarría; Formal analysis, Ana Alejandra Valenzuela-García and J. Guadalupe Luna-Ortega; Investigation, Ana Alejandra Valenzuela-García, Mario García-Carrillo, Rafael Zúñiga-Valenzuela, Tomás Juan Álvaro Cervántes-Vazquez and María Gabriela Cervántes-Vazquez; Methodology, Ana Alejandra Valenzuela-García and Juan Luis Ríos-Plaza; Project

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Abbreviations

The following abbreviations are used in this manuscript:

APC: Article Processing Charge; C/N: Carbon-to-Nitrogen Ratio; DA-DAD: Diode-Array Detection; DPPH: 2,2-Diphenyl-1-picrylhydrazyl; EtOH: Ethanol; GHG: Greenhouse Gas; HPLC: High-Performance Liquid Chromatography; IPCC: Intergovernmental Panel on Climate Change; ISO: International Organization for Standardization; LCA: Life-Cycle Assessment; NaOCl: Sodium Hypochlorite; SI: Supporting Information; SIAP: Servicio de Información Agroalimentaria y Pesquera (México); *v/v*: Volume per Volume; *w/w*: Weight per Weight.

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