Research Article

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Optimizing carrageenan–citric acid synergy in mango gummies using response surface methodology

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Abstract: Seasonal mango surpluses in tropical regions result in substantial postharvest losses (30–40%), highlighting the need for sustainable utilization. This study optimized carrageenan and citric acid ratios in mango-flavored gummies to create clean-label confectionery using response surface methodology. The optimal formulation (1.3–1.55% carrageenan, 0.42–0.48% citric acid) stabilized moisture (20–22%), water activity (0.665), and sensory scores (≥6.5/9) at a production cost of Php65/kg (US$1.12/kg). Excess carrageenan (>2%) hardened the texture and dulled the natural pigmentation, while citric acid >0.48% heightened sourness. Validation trials confirmed consistency, with slight deviations in sensory acceptability (6.80 vs predicted 7.30). The method proved effective for mango and jackfruit but unsuitable for lipid-rich fruits like avocado. Economically viable for small-scale producers (break-even: 154.2 kg/month), this approach offers a scalable solution to valorize surplus fruits, though industrial adaptation and lipid-resistant formulations require further exploration.

Keywords: mango, gummy candy, clean-label confectionery, food product development, response surface methodology

1 Introduction

The confectionery industry is moving toward natural ingredients and plant-based, clean-label, and ethical sourcing products due to the growing consumer demand for sustainable and better nutrition [1,2]. The trend has spurred intensified efforts to identify replacements for animal-based additives such as gelatin. As such, this positions carrageenan, a seaweed-derived hydrocolloid, as a prominent alternative for gelatin (an animal-derived collagen), owing to its ability to form stable gels and compatibility with vegan product standards [3]. However, significant challenges remain in optimizing carrageenan for high-acid fruits like mango, particularly regarding pH sensitivity, where the gel strength decreases sharply at pH ≤ 4.0 and flavor volatility during processing [3].

Mango (*Mangifera indica* L.) is known for its vibrant color and natural sweetness, making it ideal for clean-label confectionery, and a rich profile of health-promoting compounds, including vitamin C, carotenoids (e.g., β-carotene), and polyphenols [4,5]. These secondary metabolites – volatile organic compounds, carotenoids, and flavonoids [6] – enhance flavor and color while providing antioxidant benefits that may support immune function. Despite these advantages, seasonal surpluses during peak harvest often strain processing capacity in tropical regions, with inadequate facilities contributing to substantial postharvest losses of 30–40% [7].

To address this waste challenge while meeting consumer demand, this work proposes converting surplus mango puree, a common but perishable intermediate, into gummy candies. This approach leverages the fruit's natural flavor and color, and nutritional properties to create a diversified, clean-label product that offers a healthier alternative to synthetic, additive-laden confectionery. The optimized gummies provide dual benefits: (1) valorization of food waste through surplus utilization, and (2) delivery of fruit-derived phytochemicals in a shelf-stable format, aligning with global dietary recommendations for whole-fruit consumption [2].

Despite these opportunities, current research on carrageenan-based gummies primarily focuses on temperate fruits, leaving applications for tropical fruits underexplored [8,9]. Additionally, many studies overlook the scalability of formulations for small-scale producers in developing regions [10]. To bridge these gaps, this work

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addresses three key issues: (1) optimizing the ratios of carrageenan to citric acid to achieve a balance between quality and stability, (2) utilizing mango puree as a natural pigment and flavor enhancer, and (3) assessing the economic feasibility of the formulation for small-scale producers to reduce postharvest losses. Ultimately, this study promotes clean-label vegan gummies tailored to tropical fruit systems while supporting sustainable agricultural processing in resource-limited regions.

2 Materials and methods

2.1 Materials

κ-Carrageenan (Shemberg Corp., Cebu City, Philippines), Philippine mango puree (pH 4.2 ± 0.1, 15°Brix), sucrose, glucose syrup (DE 4sorbitolitol, citric acid (OngKinKing Trading, Cebu City, Philippines), and sodium lactate (Cornell Foods, Metro Manila, Philippines) were sourced locally. All ingredients were of food-grade.

2.2 Gummy candy preparation

A 3 × 3 factorial design tested carrageenan (1–3% w/w) and citric acid (0.3–0.9% w/w) levels (Table 1). The process, summarized in Figure 1, involved homogenization of ingredients (500 rpm, 5–7 min), heating (90–100°C until 75°Brix), molding into 1 cm^3 cubes, drying (50–60°C, 16 h), sweating (room temperature for 2 h), and sugar-coating to prevent sticking.

2.3 Physicochemical analysis

2.3.1 Moisture content (MC)

MC was determined using the AOAC method 925.10 [11]. Samples (0.5–1.0 g) were dried at 105°C for 5 h in a forced-air oven (Biobase BOV-T105F, Shandong, China), cooled in a desiccator, and reweighed.

2.3.2 Water activity (a_w)

Water activity was measured using a water activity meter (WA 60-A, Guangzhou, China) at 25°C following ISO 21807:2004 [12]. Powdered samples (5 g) were equilibrated for 10 min before recording.

2.3.3 Caloric content

Caloric content was analyzed via bomb calorimetry (Parr Instrument Co., IL, USA) using benzoic acid (6.318 kcal/g) for calibration. Cubed samples weighing 0.5 and 1.0 g were combusted, and the energy released was quantified [13], with analyses conducted in triplicate.

2.4 Sensory evaluation

Ninety experienced panelists rated color, aroma, texture, taste, and overall acceptability on a 9-point hedonic scale. An incomplete block design [14] minimized fatigue, with responses analyzed via Response Surface Regression (SAS 9.0). This work employed a 9-point hedonic scale (1 = dislike extremely; 9 = like extremely) and descriptive scoring quantified responses, following the standards for sensory testing [15].

Informed consent: Informed consent was obtained from the panelists and the procedures followed the ethical guidelines of the Cebu Technological University Research Ethics Committee.

2.5 Product yield and total cost

Product yield (%) was calculated using (1):

$$\%\text{Yield} = \frac{\text{weight before drying} - \text{weight after drying}}{\text{total weight of the formulation}} \times 100. \quad (1)$$

The cost analysis focused on the proportions of raw materials used in various formulations based on the local market rates [10]. The raw material cost (RMC) was derived

Table 1: Treatment combinations and formulation parameters

Treatment	Variable (a) Carrageenan (% w/w)	Variable (b) Citric acid (%w/w)	Other ingredients (%)
1–3	1.0	0.3, 0.6, 0.9	Water (49.35–52.35%), glucose syrup (25%), refined sugar sorbitol (2.5%), sodium lactate (0.6%), mango puree (0.25%)
4–6	2.0	0.3, 0.6, 0.9	
7–9	3.0	0.3, 0.6, 0.9	

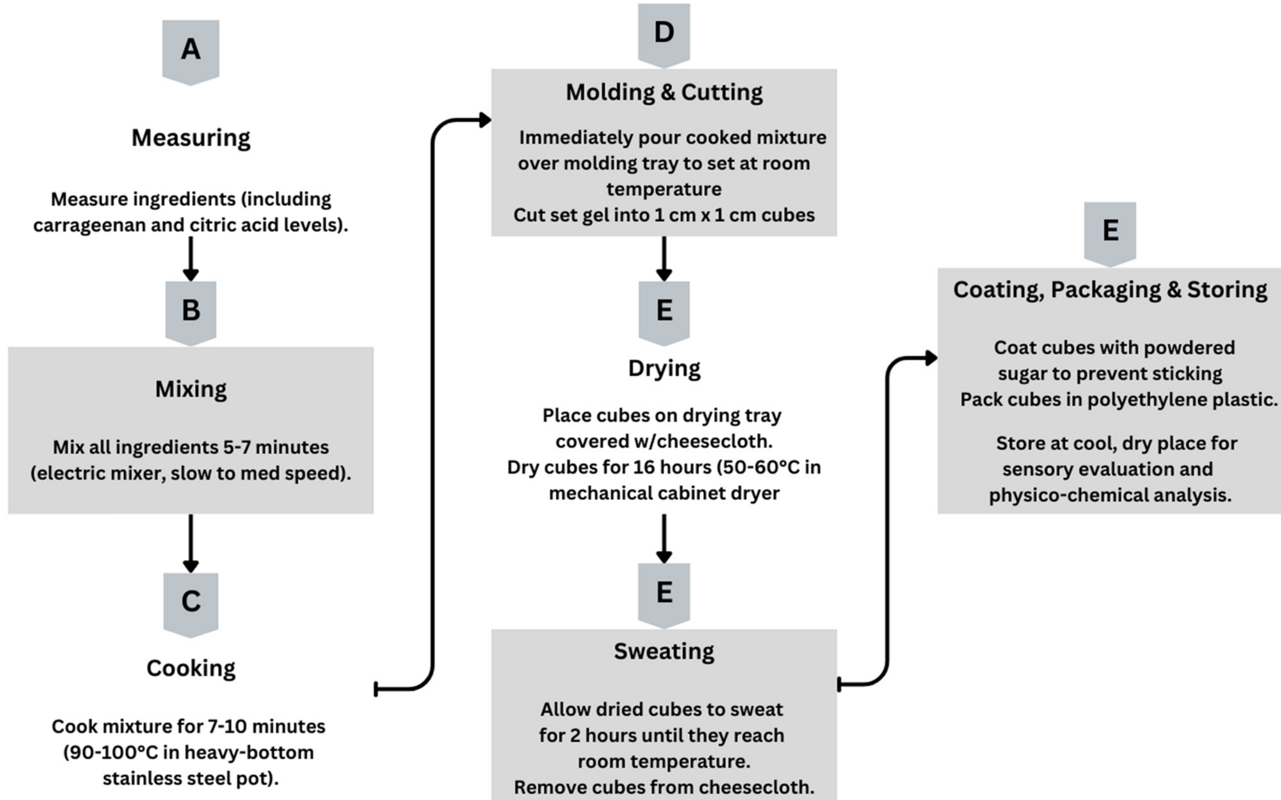

Figure 1: Flowchart of mango gummy preparation.

from these prices [16], while the labor cost (LC) was calculated using a regional minimum wage of Php50 (US$0.87) per hour and time-motion studies. Energy cost (EC) was based on electricity consumption at Php10 (US$0.17) per kWh for mixing and drying. Overhead cost (OC) included packaging and equipment depreciation. Total production cost was computed as follows (2):

$$\text{Total cost} = \text{RMC} + \text{LC} + \text{EC} + \text{OC}. \quad (2)$$

The break-even (BEP) analysis for small-scale production used a retail price of PH/kg from local clean-label confectionery benchmarks, with the BEP calculated as follows (3):

$$\text{BEP(kg)} = \frac{\text{Fixed cost(Php)}}{\left(\text{Selling price}\left(\frac{\text{Php}}{\text{kg}}\right) - \text{Variable cost}\left(\frac{\text{Php}}{\text{kg}}\right)\right.}. \quad (3)$$

2.6 Optimization and experimental validation

Response surface methodology (RSM) using STATISTICA 6.0 was utilized to optimize the ratios of carrageenan to citric acid, exploring carrageenan concentrations from 1 to 3% (w/w) and citric acid from 0.3 to 0.9% (w/w). Quadratic models were validated via ANOVA at a significance level of $p < 0.01$. The optimal acceptable region (OAR) was defined with criteria including sensory scores of 6.5 or higher on a 9-point scale, MC ≤ 22%, and $a_w \leq 0.70$. Verification involved comparing predicted and actual scores using paired *t*-tests ($\alpha = 0.05$).

For the experimental validation, triplicate batches of the optimized formulation and a suboptimal control were produced, with 32 experienced panelists assessing sensory attributes on a 9-point scale. The optimized formulation was tested on local fruit purees (jackfruit, guyabano, avocado, melon, and macapuno), and sensory differences were analyzed using Friedman's test and one-way ANOVA.

3 Results and discussion

3.1 Physicochemical analysis

3.1.1 MC

MC ranged from 19.47 to 23.99% (Table 2), with higher carrageenan levels (3% w/w) surpassing typical gummy ranges (15–22%) due to its hygroscopic properties [17]. Co-solutes

Table 2: Percent moisture, dry matter, and water activity of mango gummies

Carrageenan level (% w/w)	Citric acid level (%w/w)	MC (%)	Dry matter (%)	Water activity (A_w)
1	0.3	20.38	79.62	0.650
1	0.6	21.20	78.80	0.658
1	0.9	21.78	78.22	0.649
2	0.3	19.47	80.53	0.671
2	0.6	20.91	79.09	0.678
2	0.9	21.66	78.34	0.667
3	0.3	23.36	76.64	0.701
3	0.6	22.96	77.04	0.704
3	0.9	23.99	76.01	0.702

like sucrose and glucose syrup in mango puree weakened gel networks by competing for water [18], which reduced hydration efficiency and destabilized the gel structure [19].

The quadratic model indicated a U-shaped relationship between carrageenan and moisture (R^2 = 0.949, p < 0.01) (Table 3). The negative linear term (−4.85, p < 0.01) showed that initial increases in carrageenan lowered moisture due to gel formation. In contrast, the positive quadratic term (1.60, p < 0.01) indicated that beyond 2% carrageenan, excess water was trapped in helical aggregates. The positive effect of citric acid (2.58, p < 0.01) revealed its role in disrupting carrageenan helices at pH < 4.0, releasing bound water. The optimal moisture stabilization occurred with 1.3–1.55% carrageenan and 0.42–0.48% citric acid, maintaining moisture at 20–22% (Figure 2a) and conforming to commercial standards while preventing syneresis.

3.1.2 Water activity (a_w)

The a_w levels ranged from 0.65 to 0.71 and remained stable across treatments (Figure 2b), with values at or below 0.70 inhibiting microbial growth [20]. Mango puree functioned as a natural humectant due to its soluble solids (28–51°Brix) [21] and pectin (15–20%) [22], maintaining a_w without synthetic additives. This contrasts with the findings of Goztok et al. [23], who reported lower a_w values (0.46–0.52) in fruit juice-based gummies due to higher sugar concentrations (DE 60 vs DE 42).

Citric acid did not significantly impact a_w values (p > 0.05), demonstrating the effectiveness of carrageenan in water-binding across different pH levels (p = 0.86 for carrageenan, and p = 0.12 for citric acid). This stability highlights mango puree as both a flavoring agent and humectant, differing from gelatin-based systems that require additional humectants like glycerol [24].

3.2 Sensory properties

Sensory evaluation demonstrated that carrageenan and citric acid levels significantly influenced consumer perceptions of mango gummies (Tables 3–6; Figure 3a–e). Color acceptability scores peaked at lower carrageenan concentrations (1–1.5% w/w), where the bright yellow hue from mango carotenoids (β-carotene) was preserved (scores: 6.02–7.19). With a significant linear effect on color (p < 0.01), carrageenan concentrations above 2% result in denser gel networks with obscured pigmentation, supported by the work of Kurniadi et al. [25], which indicated that kappa-carrageenan interacts with natural pigments, such as carotenoids in mango, to alter color intensity in fruit-based products. In contrast, citric acid had minimal impact on color (p > 0.05), differing from pectin systems where acidity is crucial for gelling [26]. This highlights carrageenan's role in color dynamics, independent of pH. The optimized formulation (1.4% carrageenan, 0.48% citric acid) scored the highest (7.16), reflecting consumer preference for the bright-yellow hue typical of mango carotenoids.

Aroma acceptability remained stable (mean = 6.34) due to the uniform amount of mango puree, which steadily releases volatile compounds. A contour plot (Figure 3b) indicated a peak aroma score of 6.5–6.75 at a carrageenan concentration of 1.2% and citric acid at 0.29%. This

Table 3: Parameter estimates of physicochemical and processing parameters of mango gummies

	MC	A_w	% Yield	Cost
Intercept	22.85778	0.624444	199.300	56.35556
Carrageenan	−4.85000*	0.002667^{ns}	-70.840^{ns}	3.86000*
Carrageenan^2	1.59833*	0.005333^{ns}	9.930^{ns}	0.02667^{ns}
Citric acid	2.51667^{ns}	0.083333^{ns}	-211.633^{ns}	1.90000^{ns}
Citric acid^2	0.92593^{ns}	-0.074074^{ns}	97.333^{ns}	-0.70370^{ns}
Carrageenan*citric acid	-0.64167^{ns}	0.001667^{ns}	36.517^{ns}	0.00000^{ns}
R^2	0.948964	0.994193	0.849836	0.999802

*significant at p < 0.05 and ns = not significant.

Table 4: Quality description of the sensory attributes of mango gummies

Treatment	Carrageenan (% w/w)	Citric acid (% w/w)	Color	Aroma	Texture	Taste
1	1	0.3	Light yellow to yellow	Perceptible mango	Soft and less gummy	Sweet and sour
2	1	0.6	Light yellow to yellow	Perceptible mango	Soft and less gummy	Sweet and sour
3	1	0.9	Yellow	Perceptible mango	Gummy and elastic	Sweet and sour
4	2	0.3	Yellow	Perceptible mango	Gummy and elastic	Sweet and sour
5	2	0.6	Yellow	Perceptible mango	Strong gummy	Sweet and sour
6	2	0.9	Yellow	Perceptible mango	Strong gummy	Sweet and very sour
7	3	0.3	Yellow	Perceptible mango	Firm	Sweet and very sour
8	3	0.6	Dark yellow	Perceptible mango	Firm	Sweet and very sour
9	3	0.9	Dark yellow	Perceptible mango	Firm	Sweet and very sour

enhancement shows that carrageenan and citric acid concentrations influenced aroma perception but did not produce significant variations overall. The stable aroma acceptability can be attributed to carrageenan's ability to slow the diffusion of aroma compounds. Bylaite et al. [27] and Chana et al. [28] confirmed that carrageenan interacts with flavor molecules, delaying their release. Increased carrageenan levels form firmer gels, further restricting the escape of volatiles, as seen in studies on hydrocolloid gummy systems like strawberry gummies [29].

The texture acceptability of mango gummies decreased linearly with increasing carrageenan concentration ($p < 0.01$, Table 6), with scores ranging from 5.00 to 6.98 (mean = 6.11). Lower carrageenan levels (1–1.5% w/w) produced softer, more elastic textures preferred by consumers, while concentrations above 2% w/w resulted in excessive firmness and reduced acceptability. These findings align with Minguito [30], who noted that levels over 3% led to excessively rigid textures that were disliked. On the other hand, citric acid further complicates texture dynamics; it can weaken gelatin networks by disrupting hydrogen bonding [8]. However, small amounts of citric acid (≤1.5%) may enhance gel strength in high-sugar gels due to improved molecular mobility during formation. Conversely, excessive hydrolysis from heating acidified mixtures above 100°C can lead to softer, less cohesive textures [31]. This highlights the intricate balance between formulation (carrageenan and citric acid concentrations) and processing conditions (e.g., heating).

Taste acceptability (mean = 6.45) was inversely linked to carrageenan ($p < 0.01$), as higher concentrations (>2%) trapped flavored compounds, reducing perceived sweetness [32]. Citric acid's quadratic term ($p < 0.05$) highlighted 0.48% as ideal for harmonizing sourness with mango's natural sugars, contrasting with commercial gummies that rely on >2% acid to intensify tartness [33].

The quadratic model for overall acceptability (coefficients from Table 6), derived from experimental sensory data collected via a 9-point hedonic scale (Section 2.4), expressed as in (4)):

$$\text{Overall Acceptability} = 8.0885 - 1.7266x + 2.1441y + 0.3047x^2 - 1.3021y^2 - 0.2083xy. \quad (4)$$

where x = carrageenan (% w/w) and y = citric acid (% w/w). The negative linear carrageenan term (−1.73, $p < 0.01$) and quadratic citric acid term (−1.30, $p < 0.01$) underscored the risks of overuse. The optimum region (1.3–1.55% carrageenan, 0.42–0.48% citric acid) maximized scores (Figure 3e), aligning with Song et al. [3] on carrageenan's textural trade-offs but diverging from Göztok et al. [23], where higher acidity improved synthetic systems.

Table 5: Mean acceptability scores of the sensory attributes of mango gummies

Treatment	Factor level		Sensory attributes				
	Carrageenan (% w/w)	Citric acid (% w/w)	Color	Aroma	Texture	Taste	Overall acceptability
1	1	0.3	7.19[a]	6.58[ab]	6.97[a]	7.19[a]	7.22[a]
2	1	0.6	7.02[a]	6.79[ab]	6.84[a]	7.14[a]	7.30[a]
3	1	0.9	7.11[a]	6.79[ab]	6.98[a]	7.32[a]	7.33[a]
4	2	0.3	6.71[ab]	5.83[ab]	6.05[b]	6.03[bc]	6.04[c]
5	2	0.6	6.89[a]	6.47[ab]	6.46a[b]	6.30[b]	6.61[b]
6	2	0.9	6.60[ab]	6.26[ab]	6.36[ab]	6.28[bc]	6.38[bc]
7	3	0.3	6.36[bc]	6.36[a]	5.16[c]	5.93[bc]	6.10[bc]
8	3	0.6	6.20[bc]	6.30[ab]	5.17[c]	5.79[c]	5.97[c]
9	3	0.9	6.02[c]	5.69[b]	5.00[c]	6.11[bc]	5.97[c]
	Overall response mean		6.69	6.34	6.11	6.45	6.55

Note: Means with the same letters are not significantly different. 9 – like extremely, 8 – like very much, 7 – like moderately, 6 – like slightly, 5 – neither like nor dislike, 4 – dislike slightly, 3 – dislike moderately, 2 – dislike very much, 1 – dislike extremely.

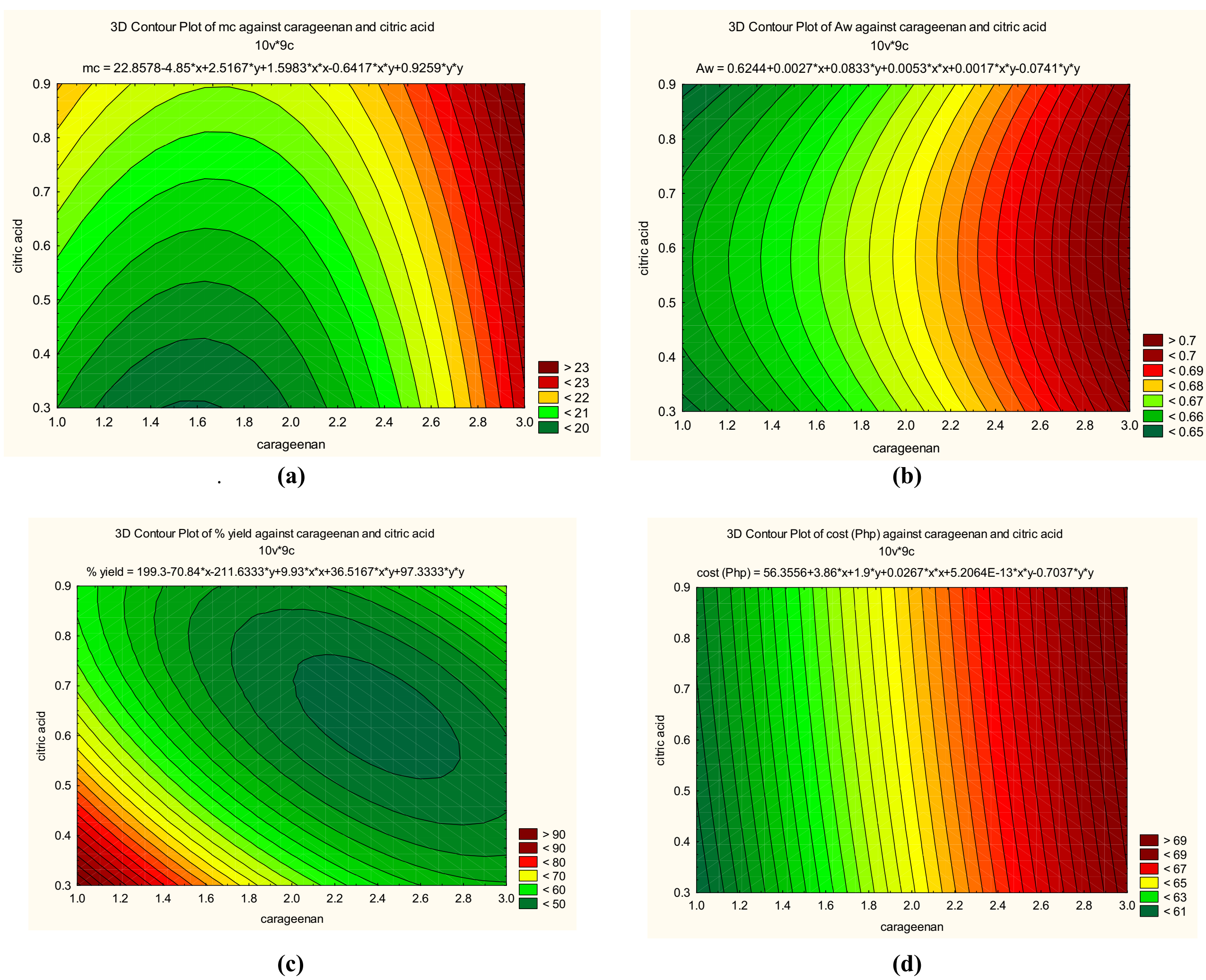

Figure 2: RSM contour plot for MC, water activity, yield, and production cost of mango gummies: (a) MC, (b) water activity, (c) production yield of gummy candy, and (d) production cost of gummy candy at 800 g.

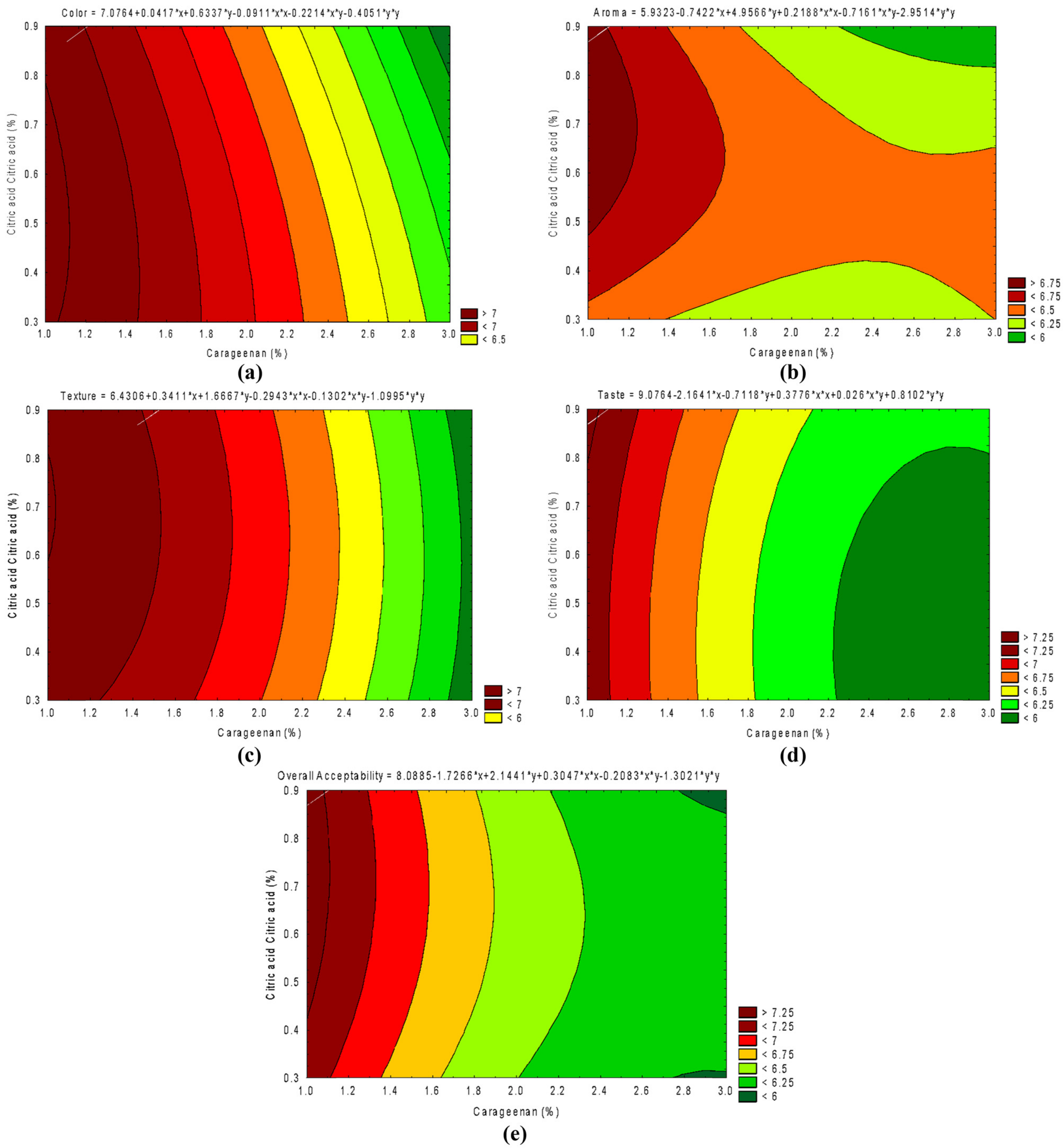

Figure 3: RSM contour plots for color, aroma, texture, taste, and overall acceptability of mango gummy candy: (a) color acceptability, (b) aroma acceptability, (c) texture acceptability, (d) taste acceptability, and (e) overall acceptability.

3.3 Production parameters and cost analysis

The combination of carrageenan and citric acid significantly affected production efficiency and economic viability (Tables 7 and 3; Figure 2a–d). Product yields ranged from 53.04 to 61.02%, with higher yields observed at lower carrageenan levels (1% w/w) and moderate citric acid (0.6–0.9% w/w). Excessive carrageenan (>2%) created dense networks, lowering water retention [34]. The yield's quadratic model ($R^2 = 0.85$) showed a negative effect from citric acid (−211.63, $p < 0.01$), likely due to partial hydrolysis during heating [31].

Production costs increased with increased carrageenan concentration, from Php60.70/kg (US$1.05/kg; 1%

Table 6: Parameter estimates of sensory attributes of mango gummies

	Color	Aroma	Texture	Taste	Overall acc
Intercept	7.076389	5.93229	6.43056	9.07639	8.08854
Carrageenan	0.04166**	−0.74219^{ns}	0.34115**	−2.16406*	−1.72656**
Carrageenan^2	−0.091146**	0.21875^{ns}	−0.29427**	0.37760^{ns}	0.30469**
Citric acid	0.63368*	4.95660^{ns}	1.66667^{ns}	−0.71181^{ns}	2.14410^{ns}
Citric acid^2	−0.40509*	−2.95139^{ns}	−1.09954^{ns}	0.81019^{ns}	−1.30208^{ns}
Carrageenan* citric acid	−0.221354*	−0.71615^{ns}	−0.13021^{ns}	0.02604^{ns}	−0.20833**
R^2	0.179748	0.132250	0.408352	0.282285	0.269357

Note: **significant at $p < 0.01$, *significant at $p < 0.05$, and ns = not significant.

w/w) to Php69.34/kg (US$1.19/kg; 3% w/w), primarily due to raw material and drying costs (Table 7). However, industrial automation can reduce costs by 40% [35]. The quadratic cost model (R^2 = 0.999) confirmed carrageenan's strong cost influence (3.86, $p < 0.05$).

The optimal carrageenan range (1.3–1.55%) balanced the cost (Php64.72–65.02/kg, US$1.12/kg), yield (56–60%), and sensory scores (≥6.5/9), presenting a practical framework for small producers. Cooperative sourcing and modular drying could help meet the break-even point (154.2 kg/month), addressing postharvest losses [7]. Additionally, mango puree's natural humectant decreases the need for preservatives [24], while manual processing (3.5 h/kg) and energy inefficiencies (1.2 kWh/kg) reveal scalability challenges [36].

4 Optimization and experimental validation

The RSM identified an optimal formulation region for mango gummy candy production, consisting of 1.3–1.55% carrageenan and 0.42–0.48% citric acid. This region met several constraints: sensory acceptability (over 6.5/9), MC (≤22%), water activity (≤0.70), and production cost (≤Php65/kg, US$1.12/kg) (Figure 4). The central formulation of 1.4% carrageenan and 0.48% citric acid achieved an MC of 20.25%, a water activity of 0.665, a 60% yield, and a Php65/kg (US$1.12/kg) production cost.

Excessive carrageenan (over 2%) negatively impacted structural integrity, flavor, and cost, aligning with Song et al. [3]. Figure 5 presents the experimental validation results, showing that the actual acceptability of the optimized formulation (A) was 6.80, which is close to the predicted value of 7.30 (p = 0.020). Conversely, a suboptimal formulation (B) with 3% carrageenan and 0.6% citric acid received a low rating of 4.91 compared to a predicted 5.70 (p = 0.022), underscoring the risks of exceeding carrageenan levels. These findings support those of Ramadhanty et al. [32] but contrast with those of Matulyte et al. [33], which suggested that higher acid levels can enhance sourness.

Table 7: Production yield and cost of mango gummies

Carrageenan level (% w/w)	Citric acid level (%w/w)	MC (%)	Yield (%)	*Production cost (Php)
1	0.3	20.38	60.70	60.70
1	0.6	21.20	59.58	61.22
1	0.9	21.78	61.02	61.34
2	0.3	19.47	56.62	64.72
2	0.6	20.91	53.04	65.02
2	0.9	21.66	55.52	65.34
3	0.3	23.36	54.80	68.70
3	0.6	22.96	57.90	69.02
3	0.9	23.99	57.64	69.34

*Calculation computed at 800 g formulation; Php: Philippine Peso currency.

4.1 Application to tropical fruit flavors

The RSM-optimized formulation, which included 1.4% carrageenan and 0.48% citric acid, was tested in gummies flavored with six tropical fruit purees: mango, jackfruit, guyabano, avocado, melon, and macapuno. Table 8 presents the ranking of the gummies with fruit flavors. Friedman's rank test showed significant differences in flavor and color attractiveness ($p < 0.01$), but there were no significant differences in texture, as the carrageenan levels remained consistent. Mango and jackfruit were the top performers, with flavor scores ranging from 6.24 to 6.32 and a color score of 6.52 (Table 9). In contrast, avocado and macapuno received the lowest scores due to lipid interference. The texture remained uniform ($p > 0.05$) across all fruit flavors, confirming the structural consistency of carrageenan [37].

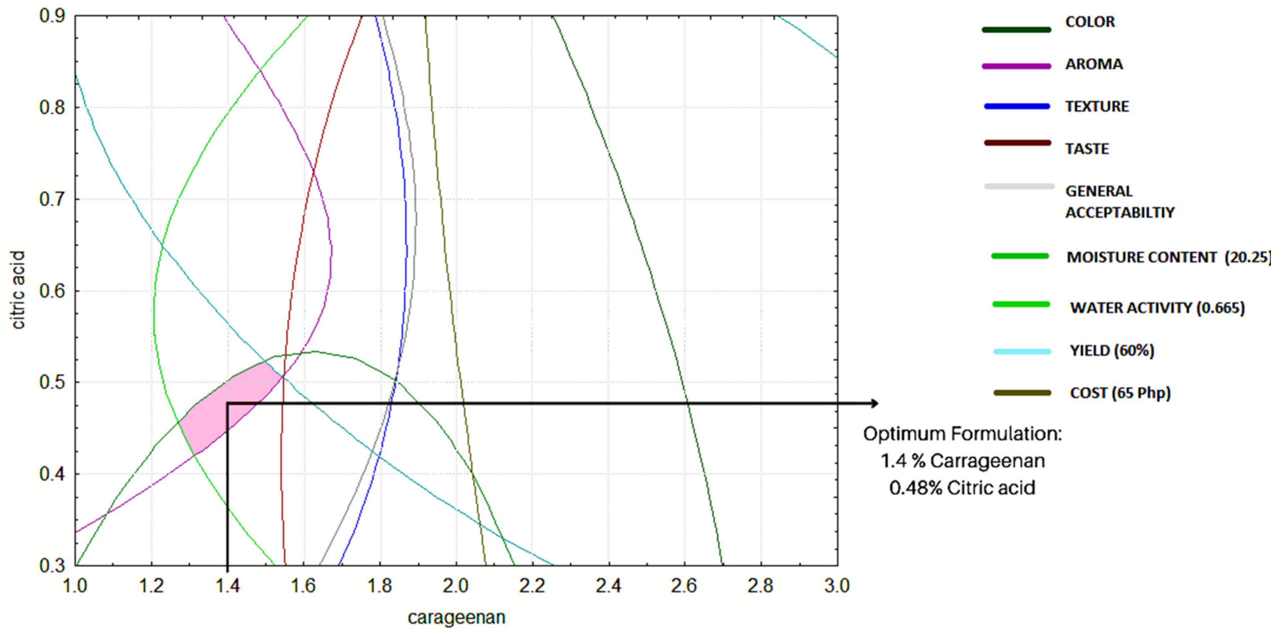

Figure 4: Optimum region (pink shaded) for carrageenan and citric acid levels of mango gummies.

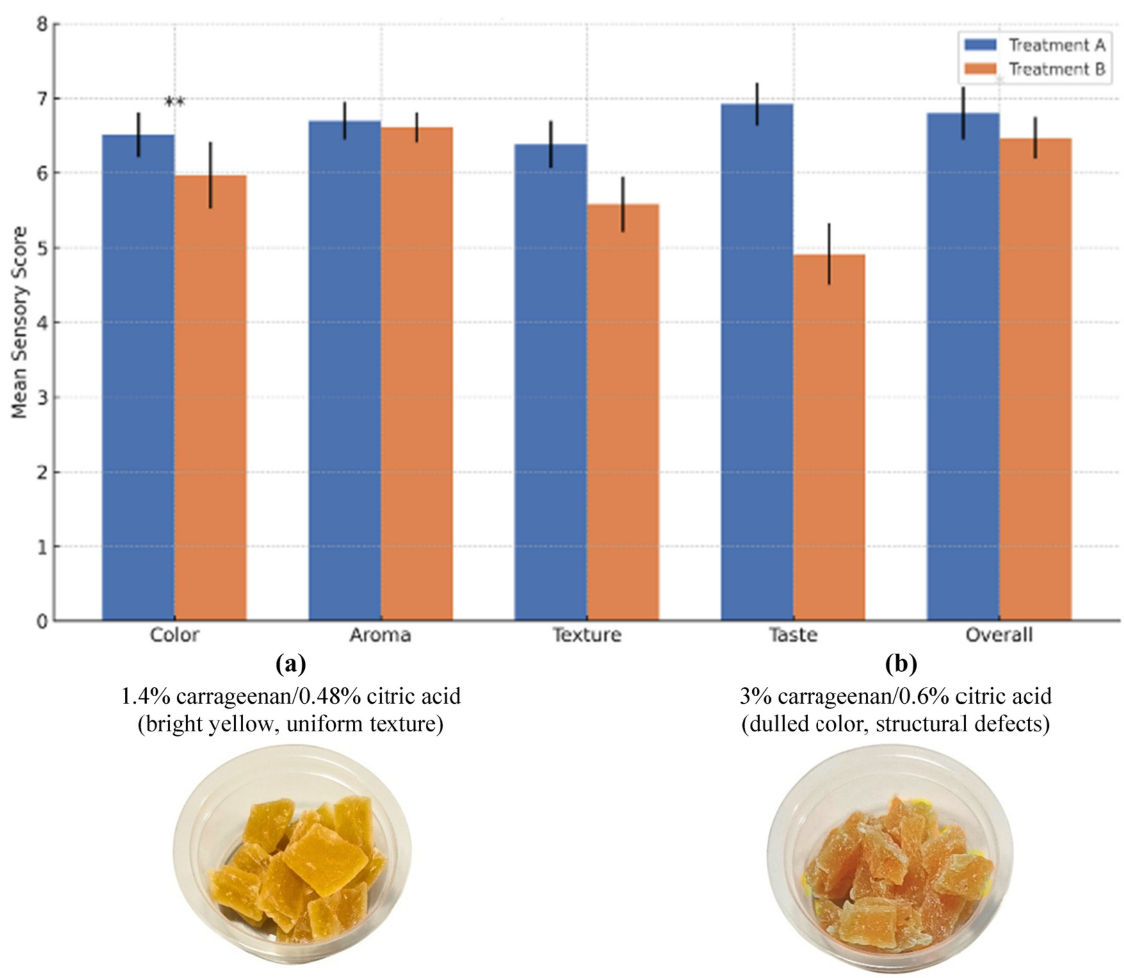

Figure 5: Visual comparison of optimized (a) vs suboptimal (b) mango gummies. Sensory evaluation of optimized (Treatment A) and suboptimal (Treatment B) formulations. Values represent mean ± SD (n = 32). Significant differences are denoted by $*p < 0.05$ and $**p < 0.01$. Treatment A outperformed Treatment B in color (p = 0.003) and overall acceptability (p = 0.020), aligning with RSM predictions. Source: Created by the authors.

Table 8: Ranking of fruit flavors (1 = best, 6 = worst)

Treatment	Sensory qualities	
	Flavor**	Color**
Guyabano (*Annona muricata*)	4.30[bc]	3.16[b]
Avocado (*Persea americana)*	3.44[bc]	4.16[c]
Mango (*Mangifera indica*)	2.06[a]	2.26[a]
Macapuno (*Cocos nucifera var. makapuno*)	4.36[c]	4.78[c]
Jackfruit (*Artocarpus heterophyllus*)	2.14[a]	3.16[b]
Melon (*Cucumis melo* L.)	3.70[bc]	3.48[b]

**significant at $p < 0.01$ and ns = not significant. Means having the same letter are not significantly different.

5 Practical applications and future work

The optimized formulation (1.4% carrageenan and 0.48% citric acid) offers immediate practical value for small-scale producers in tropical regions, particularly the Philippines, where mango postharvest losses exceed 30–40% [7]. Producers can utilize surplus mango puree in vegan gummies to enhance economic resilience while meeting clean-label demands by using natural color pigments [5].

Shelf-life projections, based on physicochemical properties ($a_w \leq 0.665$, pH 3.8–4.2) and literature [20,24,37], indicate ≥90-day ambient stability (25°C, 65% RH) without the use of preservatives. This is enabled by (a) water activity below the microbial growth threshold ($a_w < 0.70$) inhibits the growth of molds and yeasts [20], and (b) carrageenan's hydrolysis resistance at pH > 3.5 [37].

For potential scalable adoption, a phased implementation pathway is proposed for small producers:

1. Phase 1 (Manual Production)

   Artisanal batches (≤50 kg/day) using existing village kitchen infrastructure, achieving break-even at 154.2 kg/month.
2. Phase 2 (semi-automated scaling)

   Integration of multi-purpose benchtop depositors (US $6,000–$16,000) and modular hybrid solar drying systems (≈US$2,000–$7,000/unit), increasing output 5-fold and reducing labor by 40% and energy costs by 30% [35].
3. Phase 3 (cooperative model)

   Centralized puree processing to lower ingredient costs by 15% via collective sourcing with local mango associations [7].

Future work should prioritize validation of shelf-life testing under tropical conditions (30°C/75% RH), pilot-scale trials using cooperative models in high-loss postharvest regions, and lipid-resistant variants for avocado/macapuno using lecithin [26].

The model's success with jackfruit (*Artocarpus heterophyllus*) broadens its applicability to other underutilized fruits, diversifying product portfolios for niche vegan markets. This balances artisanal feasibility with industry scalability, converting postharvest losses into market-ready value-added products.

6 Conclusions

This study successfully optimized a clean-label, vegan gummy formulation using Philippine mango puree, carrageenan, and citric acid using RSM. The optimal region (1.3–1.55% carrageenan, 0.42–0.48% citric acid) balanced sensory acceptability (>6.5/9), physicochemical stability (moisture ≤22%, $a_w \leq 0.70$), and economic feasibility (Php65/kg, US$1.12/kg, addressing the mango industry's postharvest losses and processing challenges). This formulation directly addresses the mango industry's postharvest losses (30–40%) by valorizing surplus puree into shelf-stable products.

Key advantages include that the natural carotenoids in mango puree can potentially replace artificial colorants,

Table 9: Mean acceptability scores (9-point Hedonic scale)

Treatment	Sensory properties				
	Color**	Aroma**	Flavor**	Texture[ns]	Overall**
Mango	6.52[a]	6.2[a]	6.24[a]	6.48	6.28[a]
Guyabano	5.40[b]	5.40[dbc]	5.32[b]	5.24	5.72[ab]
Avocado	6.36[a]	4.76[c]	4.40[c]	5.72	4.16[c]
Macapuno	5.80[ab]	4.92[c]	4.92[bc]	5.56	4.16[b]
Jackfruit	6.52[a]	6.04[ab]	6.32[a]	6.00	6.28[a]
Melon	6.08[ab]	5.16[bc]	5.24[bc]	5.16	5.68[ab]

**significant at $p < 0.01$ and ns = not significant. Means having the same letter are not significantly different.

maintaining consistent color ratings (6.69/9) while providing antioxidant benefits. Though not a substitute for fresh fruit, these gummies offer a palatable vehicle for fruit phytochemicals in contexts where fresh produce access is limited. The approach proved viable for jackfruit but requires adjustments for lipid-rich fruits (e.g., avocado), highlighting the need for composition-specific customization. Validation trials confirmed the RSM model's reliability, with minor sensory deviations (<7%) attributed to natural pigment variability. For small-scale producers, this offers a low break-even (154.2 kg/month) solution to convert seasonal surpluses into value-added products, promoting economic resilience in resource-limited regions.

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References

[1] Kazibudzki P, Trojanowski T. Examination of marketing mix performance in relation to sustainable development of the poland's confectionery industry. PLoS One. 2020;15(10):e0240893. doi: 10.1371/journal.pone.0240893.
[2] Trojanowski TW, Kazibudzki PT. Prospects and constraints of sustainable marketing mix development for Poland's high-energy consumer goods. Energies. 2021;14(24):8437. doi: 10.3390/en14248437.
[3] Song X, Chiou BS, Xia Y, Chen M, Liu F, Zhong F. The improvement of texture properties and storage stability for kappa carrageenan in developing vegan gummy candies. J Sci Food Agric. 2021;102(9):3693–702. doi: 10.1002/jsfa.11716.
[4] Cases CMP, Rapliza AA, Munsayac FET, Bugtai NT, Billiones RKD, Baldovino RG. Quality assessment and prediction of Philippine mangoes: A convolutional neural network approach. Int J Adv Sci Eng Inf Technol. 2019;9(6):2128. doi: 10.18517/ijaseit.9.6.9951.
[5] Cedeño-Pinos C, Martínez-Tomé M, Murcia MA, Jordán MJ, Bañón S. Assessment of rosemary (Rosmarinus officinalis L.) extract as antioxidant in jelly candies made with fructan fibres and stevia. Antioxidants. 2020;9(12):1289. doi: 10.3390/antiox9121289.
[6] Peng L, Gao W, Song M, Li M, He D, Wang Z. Integrated metabolome and transcriptome analysis of fruit flavor and carotenoids biosynthesis differences between mature-green and tree-ripe of cv."Golden Phoenix" mangoes (Mangifera indica L.). Front plant Sci. 2022 Feb 24;13:816492. doi: 10.3389/fpls.2022.816492.
[7] Gan D, Xu M, Chen L, Cui S, Deng C, Qiao Q, et al. Intake of sugar substitute gummy candies benefits the glycemic response in healthy adults: A prospective crossover clinical trial. Gels. 2022;8(10):642. doi: 10.3390/gels8100642.
[8] Ge H, Wu Y, Woshnak LL, Mitmesser SH. Effects of hydrocolloids, acids and nutrients on gelatin network in gummies. Food Hydrocoll. 2021;113:106549. doi: 10.1016/j.foodhyd.2020.106549.
[9] Wang R, Hartel RW. Citric acid and heating on gelatin hydrolysis and gelation in confectionery gels. Food Hydrocoll. 2022;129:107642. doi: 10.1016/j.foodhyd.2022.107642.
[10] Al-Jaloudi R, Al-Refaie DA, Shahein M, Hamad HJ, Al-Dabbas MM, Shehadeh N, et al. Development of functional jelly gums using blueberry concentrate and honey: Physicochemical and sensory analysis. Processes. 2025;13(2):508. doi: 10.3390/pr13020508.
[11] AOAC International. Official methods of analysis of AOAC international. 21st edn. Rockville, Maryland, USA: Association of Official Analytical Chemists; 2019.
[12] ISO. Microbiology of food and animal feeding stuffs: Determination of water activity. Geneva: ISO; 2004.
[13] Fauziah RR, Suwasono S, Oktafiana A. Physicochemical profile of gummy candy made from semboro orange (citrus nobilis lour var. microcarpa Hassk) and rosella (Hibiscus sabdariffa l.) extract with various agar concentration. Proceedings of the 8th International Conference of Food, Agriculture and Natural Resources; 2024. p. 7–19. doi: 10.2991/978-94-6463-451-8_2.
[14] Cochran WG, Cox GM. Experimental designs. New York: Wiley; 1957.
[15] Meilgaard MC, Carr BT, Civille GV. Sensory evaluation techniques. Florida, USA: CRC Press; 1999. doi: 10.1201/9781003040729.
[16] Philippine Statistics Authority (PSA). 2023. https://psa.gov.ph/major-fruit-crops. Major Fruit Crops Quarterly Bulletin, April to June 2023.
[17] Tavassoli-Kafrani E, Shekarchizadeh H, Masoudpour-Behabadi M. Development of edible films and coatings from alginates and carrageenans. Carbohydr Polym. 2016;137:360–74. doi: 10.1016/j.carbpol.2015.10.074.
[18] Wang X, Zhou D, Guo Q, Liu C. Textural and structural properties of a κ-carrageenan–konjac gum mixed gel: effects of κ-carrageenan concentration, mixing ratio, sucrose and Ca2 + concentrations and its application in milk pudding. J Sci Food Agric. 2021;101(7):3021–9. doi: 10.1002/jsfa.10936.

[19] Liu Y, Zhao K, Ma Q. Insight into the glucose cosolvent induced gelation of κ-carrageenan by broadband dielectric spectroscopy. J Mol Liq. 2020;318:114268. doi: 10.1016/j.molliq.2020.114268.

[20] Sautour M, Mansur CS, Diviès C, Bensoussan M, Dantigny P. Comparison of the effects of temperature and water activity on growth rate of food spoilage moulds. J Ind Microbiol Biotechnol. 2002;28(6):311–5. doi: 10.1038/sj/jim/7000248.

[21] Guerrero SN, Alzamora SM. Effects of pH, temperature and glucose addition on flow behaviour of fruit purees: II. Peach, papaya and mango purees. J Food Eng. 1998 Jun;37(1):77–101. doi: 10.1016/S0260-8774(98)00065-X.

[22] Koubala BB, Kansci G, Garnier C, Mbome IL, Durand S, Thibault JF, et al. Rheological and high gelling properties of mango (*Mangifera indica*) and ambarella (Spondias cytherea) peel pectins. Int J Food Sci Technol. 2009 Sep;44(9):1809–17. doi: 10.1111/j.1365-2621.2009.02003.x.

[23] Goztok SP, Khiabani AH, Toker OS, Palabiyik I, Konar N. Development of healthier gummy candy by substituting glucose syrup with various fruit juice concentrates. Food Sci Nutr. 2024;12(10):7864–76. doi: 10.1002/fsn3.4389.

[24] Hani NM, Romli SR, Ahmad M. Influences of red pitaya fruit puree and gelling agents on the physico-mechanical properties and quality changes of gummy confections. Int J Food Sci Technol. 2015;50(2):331–9. doi: 10.1111/ijfs.12638.

[25] Kurniadi M, Parnanto NH, Saputri MW, Sari AM, Indrianingsih AW, Herawati ER, et al. The effect of kappa-carrageenan and gum Arabic on the production of guava-banana fruit leather. J Food Sci Technol. 2022 Nov;59(11):4415–26. doi: 10.1007/s13197-022-05521-1.

[26] Tarahi M, Tahmouzi S, Kianiani MR, Ezzati S, Hedayati S, Niakousari M. Current innovations in the development of functional gummy candies. Foods. 2023;13(1):76. doi: 10.3390/foods13010076.

[27] Bylaite E, Ilgunaite Z, Meyer AS, Adler-Nissen J. Influence of lambda-carrageenan on the release of systematic series of volatile flavor compounds from viscous food model systems. J Agric Food Chem. 2004;52(11):3542–9. doi: 10.1021/jf0354996.

[28] Chana A, Tromelin A, Andriot I, Guichard E. Flavor release from i-carrageenan matrix: A quantitative structure-property relationships approach. J Agric Food Chem. 2006;54(10):3679–85. doi: 10.1021/jf053192w.

[29] Zhang Y, Barringer S. Effect of hydrocolloids, sugar, and citric acid on strawberry volatiles in a gummy candy. J Food Process Preservation. 2018 Jan;42(1):e13327. doi: 10.1111/jfpp.13327.

[30] Minguito JT. Physicochemical properties, total plate count, and sensory acceptability of gummy guyabano (Annona muricata) candy enriched with kappa-carrageenan. Int J Adv Appl Sci. 2023;10(5):33–42. doi: 10.21833/ijaas.2023.05.005.

[31] Wang R, Hartel RW. Citric acid and heating on gelatin hydrolysis and gelation in confectionery gels. Food Hydrocoll. 2022 Aug;129:107642. doi: 10.1016/j.foodhyd.2022.107642.

[32] Ramadhanty A, Rosida DF, Yulistiani R. Chemical and organoleptic properties of dragon fruit gummy candy and apple snail collagen extract with carrageenan addition. AJARCDE (Asian J Appl Res Community Dev Empowerment). 2023;7(3):40–5. doi: 10.29165/ajarcde.v7i3.328.

[33] Matulyte I, Mataraite A, Velziene S, Bernatoniene J. The effect of Myristica fragrans on texture properties and shelf-life of innovative chewable gel tablets. Pharmaceutics. 2021;13(2):238. doi: 10.3390/pharmaceutics13020238.

[34] Horinaka JI, Takagaki H, Tanaka T, Takigawa T. Effects of gelation concentration on cyclic deformation behavior of κ-carrageenan hydrogels. Int J Biol Macromol. 2022 Oct;218:634–8. doi: 10.1016/j.ijbiomac.2022.07.128.

[35] Rodriguez-Fortun JM, Alvarez J, Monzon L, Salillas R, Noriega S, Escuin D, et al. Digitalization of an industrial process for bearing production. Sensors. 2024;24(23):7783. doi: 10.3390/s24237783.

[36] Binderbauer PJ, Woegerbauer M, Nagovnak P, Kienberger T. The effect of "energy of scale" on the energy consumption in different industrial sectors. Sustain Prod Consum. 2023;41:75–87. doi: 10.1016/j.spc.2023.07.031.

[37] Teixeira-Lemos E, Almeida AR, Vouga B, Morais C, Correia I, Pereira P, et al. Development and characterization of healthy gummy jellies containing natural fruits. Open Agric. 2021;6(1):466–78. doi: 10.1515/opag-2021-0029.