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Effects of Tomatillo (*Physalis philadelphica*) By-Product Syrup and Hydrocolloid Formulation on the Physicochemical, Antioxidant, Textural, and Sensory Properties of Jelly

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A B S T R A C T

Objective: This study aimed to develop a jelly formulation with acceptable physicochemical and sensory properties from South American tomatillo (*Physalis philadelphica*) by utilizing fresh fruit juice and a by-product syrup, while optimizing the gelling agent ratios.

Methods: The study clarified the effects of the mixing ratio of fruit juice to by-product syrup (3:1, 2:1, 1:1, 1:2) and the ratios of carrageenan (0.8%–1.4%) together with konjac glucomannan (0.2%–0.5%) on the physical, chemical, and sensory properties of the jelly.

Results: The results indicated that a 1:2 ratio of fruit juice to by-product syrup was optimal for balancing the taste and achieving the highest tested proportion of by-product utilization. The synergistic combination of 0.8% carrageenan and 0.4% konjac glucomannan formed a characteristic chewy-crunchy structure achieved the highest sensory scores, and exhibited favourable levels of bioactive compounds, including polyphenols, vitamin C, and antioxidant activity.

Conclusion: Both microbiological and heavy metal parameters met the Vietnamese national food safety regulatory limits for ready-to-eat products. The study successfully identified the technical parameters to utilize the candied sugar syrup by-product as a raw material for processing chewy-crisp South American tomatillo (*Physalis philadelphica*) jelly. This solution contributes to minimizing organic waste during processing at the laboratory scale, and effectively recovering natural bioactive compounds such as polyphenols and vitamin C in the final jelly product. The study a potential and sustainable approach to utilizing processing by-products to create value-added products while recognizing that further scale-up and shelf-life studies are required.

Keywords*:* Food by-products, Hydrocolloids, Konjac glucomannan, Physalis philadelphica, Texture profile

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Introduction

South American tomatillo (*Physalis philadelphica*) is a high-economic-value fruit tree belonging to the Solanaceae family [1] which is currently in the initial stages of experimental cultivation in the Mekong Delta region of Vietnam. South American tomatillo has a harmonious sweet and sour taste, larger and less bitterness than of native wild *Physalis* species. The chemical composition of tomatillo fruit contains various antioxidant compounds such as chlorophyll, phenolic compounds, flavonoids, and is rich in vitamins and soluble fiber [2, 3]. These bioactive constituents have been associated with potential health-promoting properties, primarily through their antioxidant mechanisms. This fruit is considered a medicinal fruit with various therapeutic effects [4, 5]. It is a new fruit type with great potential for developing product lines rich in natural antioxidants. Particularly, previous in vitro studies have demonstrated that withanolides isolated from Physalis philadelphica can induce quinone reductase activity, suggesting potential cytoprotective effects at the cellular level [6].

During the processing of dried tomatillo products, a sugar soaking syrup was obtained as a by-product from the process. This by-product syrup accounts for a relatively large proportion, representing approximately 40% (w/w) of the initial fresh fruit weight (calculated based on preliminary processing yields in our laboratory nearly 40% of the raw material weight containing many soluble solids from the tomatillo fruit and having a high sugar concentration ranging around 20^0 Brix. This is a highly suitable raw material for developing chewy-crunchy jelly products. In the processing jelly, it is necessary to use gelling agents to create a crunch and elastic structure for the product.

Carrageenan is a group of linear gelling agents extracted from red algae [6]. Based on the number and position of ester sulfate groups on the galactose linkage chain, they are classified into κ, ι, and λ forms. κ-carrageenan is the type with the best gelling ability in the presence of monovalent ions [8]. However, the network structure of κ-carrageenan gel has limitations such as brittleness, susceptibility to fracture under external shear forces, and especially syneresis over time, which affects the sensory quality of the jelly [9].

Tomatillo jelly needs to have a crunchy structure but must possess a certain chewiness to enhance sensory value and help the product withstand physical impacts during transport. A solution to overcome the drawbacks of carrageenan is using konjac glucomannan, a non-ionic heteropolysaccharide extracted from konjac tubers of the Araceae family, which is also a gelling agent used in food [10]. Konjac powder has strong water-absorption capacity, and when deacetylated with alkali, konjac can form a thermally stable firm gel. Konjac chain segments interlace and cross-link tightly with the double helix regions of carrageenan, creating a cohesive, elastic, and chewy structure while maximizing the retention of free water within the joint gel network [11].

Currently, there are no published studies utilizing the soaking syrup by-product and fresh tomatillo juice to process tomatillo jelly. At the same time, the appropriate mixing ratios of carrageenan, and konjac glucomannan for this product have remained unclear. Therefore, this study was conducted to address the aforementioned technological gap, aiming to formulate a recipe for South American tomatillo jelly with good sensory quality and high nutritional value.

Materials and Methods

Fresh South American tomatillo (*Physalis philadelphica*) reaching a Brix level of 5.8-6.4 was grown and harvested from a garden in Long Xuyen, A Giang. After harvest, the tomatillos were packed in cardboard boxes, transported to the research laboratory at A Giang University within the day, and stored at a cool temperature (6°C – 8°C).

Food-grade carrageenan (Aquagel TH 6164) was supplied by Viet My Additive Company. Konjac powder, food-grade konjac glucomannan (glucomannan >75%), was supplied by Saigon Chem. Other analyzing chemical were purchased from Sigma Aldrich

Diluted tomatillo juice

Exactly 500 g of fresh tomatillo and 500 g of water were blended finely for 30 seconds using a blender. The fruit pulp was filtered out using a 60-mesh screen, and the clear diluted juice was used for formulation in the experiments.

Diluted tomatillo by-product syrup

Exactly 500 g of fresh tomatillo was peeled, mixed thoroughly with 100 g of sucrose, and soaked for 6 hours at room temperature 25 ± 2 ^{0}C. The syrup at 40 – 42 ^{0}Brix was obtained after 6 hours was diluted to 20° Brix and used to formulate the jelly. The syrup preparation was conducted in independent production batches, and the recovered syrup was stored at 4°C prior to jelly formulation.

Processing chewy-crunch tomatillo jelly

The base liquid for the tomatillo jelly was formulated using fresh tomatillo juice and tomatillo by-product syrup at 4 mixing ratios: 3:1, 2:1, 1:1, and 1:2. Exactly 0.5% (w/w) KCl and 0.05% NaCl were added to 500 g of the base liquid, followed by gelling agents including konjac at ratios of 0.2%, 0.3%, 0.4%, and 0.5% (w/w) and carrageenan at ratios of 0.8%, 1.0%, 1.2%, and 1.4% (w/w). The entire gel system was stirred thoroughly using a magnetic stirrer at a speed of 40 rpm in a 1000 mL beaker for 10 minutes at room temperature. Each 15 mL of the gel mixture was poured into aluminum pouch packaging (dimensions 3.5 cm x 15 cm). The aluminum pouches were heat-sealed and heated in water to a temperature of 95°C and held for 5 minutes. The pouches were then cooled rapidly in an ice-water bath for 20 minutes and stored at 8–12°C in a refrigerator before further analysis.

Color measuring

About 5 grams of tomatillo jelly was cut into pieces and placed on a white background. Color values (L^*, a^*, b^*) were measured using a CR-400 colorimeter (Konica Minolta, Japan).

Water activity

About 2 grams of tomatillo jelly was finely ground and placed into a measuring tray to determine the a_w value using a water activity meter (AquaLab, 4TE, USA).

Jelly hardness

One whole pack of tomatillo jelly was used for texture measurement. The measurement was performed on the curved surface of the jelly, 50% away from the edges. The gel strength/hardness (g force) was determined using a CT03 texture analyzer (Brookfield, USA) using a probe at a specified test speed.

Total acid percentage (% w/w)

Exactly 5 g of jelly was chopped finely and analyzed according to the AOAC 942.15 method. The acidity index was determined by titration with 0.1 N NaOH using phenolphthalein indicator, applying a citric acid conversion factor of 0.0064.

Vitamin C percentage (% w/w)

Exactly 5 g of jelly was chopped finely and analyzed according to the AOAC 967.21 method by titration with 2,6-dichloroindophenol.

Total sugar content (% w/w)

Exactly 3 g of tomatillo jelly was chopped finely, and the total sugar was determined by colorimetric reaction with dinitrosalicylic acid (DNS) reagent [12] based on a calibration curve with the equation $y = 3.57x - 0.1368$.

Total polyphenol (mg GAE/100g)

Exactly 0.5 g of jelly was diluted and analyzed using the Folin-Ciocalteu method with 10% Folin-

Ciocalteu reagent [13]. The absorbance of the solution was measured at a wavelength of 750 nm using a UV-spectrophotometer (SPUVS, SP-1920, Japan). The total polyphenol content was calculated based on a gallic acid standard calibration curve with the equation; $y = 0.0513x + 0.0162$.

Antioxidant activity (%)

Evaluated via the DPPH (2,2-diphenyl-1-picrylhydrazyl) free radical scavenging capacity according to the Brand-Williams method [14]. Exactly 0.5 grams of sample was finely ground, added to 2 mL of 0.135 mM DPPH in ethanol, kept in the dark for 30 minutes, and the absorbance was measured at a wavelength of 517 nm using a UV-VIS spectrophotometer (SPUVS, SP-1920, Japan). A DPPH solution was used as a control. The result was calculated using the following equation: $DPPH\ (\%) = [(Absorbance\ of\ control - Absorbance\ of\ sample)/ Absorbance\ of\ control] \times 100$.

Sensory evaluation

The product was evaluated by a panel of 10 semi-trained panellists (including students and staff from the Faculty of Agriculture and Natural Resources, An Giang University). The product was evaluated using a scoring method based on a sensory description panel with a 1-5 scale, and the degree of liking (preference) was evaluated using a 1-10 Hedonic scale. Jelly samples were served at room temperature, coded with random three-digit numbers, and presented to the panellists in a completely randomized order. Panellists were provided with purified water to cleanse their palates between sample evaluations

Statistical analysis

The study consisted of two main experiments. Experiment 1 utilized a single-factor completely randomized design to evaluate four mixing ratios of diluted juice to by-product syrup. Experiment 2 employed a 4 × 4 full factorial design to investigate the main effects and interactions of carrageenan (0.8%, 1.0%, 1.2%, 1.4%) and konjac glucomannan (0.2%, 0.3%, 0.4%, 0.5%). Collected data were processed using Microsoft Excel and statistically analyzed using Statgraphics Centurion XV software. Significant differences between sample means were determined using Fisher's Least Significant Difference (LSD) test at a confidence level of 95% ($P < 0.05$).

All experiments were conducted in three independent production batches (biological replicates) to prevent pseudo replication. For each production batch, analytical measurements were performed in triplicate (technical replicates), and the results were expressed as mean ± standard deviation.

Results

The mixing ratio of fresh fruit juice and by-product syrup soaked from tomatillo plays a very important role, directly affecting the quality of the tomatillo jelly product. Modifying these two components can alter various sensory and physicochemical attributes of the jelly product. This effect is clearly shown in the results below.

Regarding the color factor, South American tomatillo has a pale-yellow color. Even small changes in the mixing ratio between fresh fruit juice and tomatillo syrup generated statistically significant effects ($P < 0.05$) on the color parameters of the product (Table 1).

Table 1: Effect of mixing ratio on physical properties of tomatillo jelly

Fruit juice: by-product syrup	Color meter				
	L*	a*	b*	Hardness (g force)	Aw
3:1	70.6b±7.02	0.39d±0.65	32.5a±1.34	1338d±144	0.963c±0.007
2:1	76.2a±0.63	2.00c±0.49	31.8a±0.54	1242c± 41.1	0.960bc±0.006
1:1	78.8a±0.96	2.41b±0.20	28.7b±0.52	872b± 38.3	0.955ab±0.005
1:2	76.1a±0.44	3.27a±0.03	32.1a±0.37	555a±25.1	0.949a±0.005
P	0.0003	0.0000	0.0000	0.0000	0.004

*Different letters show significant differences ($P < 0.05$) between samples in the same column.

For the L^* value, when increasing the proportion of by-product syrup in the formulation, the lightness (L^*) of the jelly showed a clear upward trend from the 3:1 treatment, peaking at the 1:1 treatment. The sample containing the highest amount of fresh fruit juice (3:1) had the lowest lightness because fresh tomatillo juice contains suspended pulp particles. These solid particles block and scatter light within the gel, thereby reducing transmittance and lowering the L^* value. As the amount of by-product syrup (a transparent syrup form) was gradually increased, the density of these suspended solid components became diluted and dispersed. The gel became homogeneous and increased in lightness (L^*), which is consistent with the findings of Akesowan [15]. Blending with the by-product syrup helps improve the transparency and external gloss of the tomatillo jelly, reducing gel turbidity while increasing the soluble solids content of the product.

For the a^* index, which represents color from the green to red region, the results showed that a^* increased proportionally with the amount of added by-product syrup. Fresh tomatillo fruit has a natural yellow-green color due to two pigments, chlorophyll and carotenoids, so fresh fruit juice is predominantly green. When fresh tomatillo is soaked in sugar, natural pigments are extracted into the by-product syrup; however, chlorophyll becomes oxidized, making the soaking liquid predominantly pale yellow. The increase in the a^* value indicates a gradual loss of green colour as the proportion of by-product syrup increased. The b^* value remained stable and high (31.86 – 32.54) across three treatments, lying within the light-yellow region. The yellow color of tomatillo jelly is mainly defined by carotenoid molecules. The stability of the b^* value shows that the yellow pigment concentration in both liquids was equivalent, and the natural color of the fresh fruit was preserved in the tomatillo jelly. This proves that the carotenoid yellow pigment system of tomatillo has relatively good thermal stability under the heating conditions of the processing workflow.

In addition, changing the mixing ratio between fresh fruit juice and by-product syrup, the physical characteristics including structural hardness and water activity of tomatillo jelly underwent systematic changes with statistically significant differences, as shown in the Table 1. Regarding the structural hardness of the product, the dry matter content from fresh fruit juice had a major impact on increasing the hardness of the product. The data

show a continuous and statistically significant decreasing trend in gel structural hardness from the 3:1 treatment down to 1:2. Specifically, the jelly block achieved the highest hardness at the ratio with more fresh juice (3:1) and gets the lowest value at the by-product syrup rich treatment (1:2).

Antioxidant capacity is one of the most valuable attributes of products derived from the genus *Physalis*; foods with antioxidant capacity play a role in protecting the body against harmful free radicals. The data in Table 2 show that tomatillo jelly at different mixing ratios had differences in the content of compounds within the jelly.

Table 2: Effect of mixing ratio on the chemical composition of South American tomatillo jelly

Fruit juice: by-product syrup	Chemical compounds				
	DPPH (%)	Polyphenol (mg GAE/100g)	Total acid (%)	Total sugar (%)	Vitamin C (%)
3:1	86.6^{a}±0.30	4.11^{a}±0.10	0.44^{a}±0.01	5.52^{d}±0.21	0.012^{a}±0.001
2:1	87.3^{a}±0.25	3.99^{ab}±0.08	0.38^{b}±0.02	7.84^{c}±0.32	0.010^{ab}±0.002
1:1	87.0^{a}±0.34	3.92^{ab}±0.17	0.28^{c}±0.02	10.19^{b}±0.31	0.008^{bc}±0.001
1:2	81.3^{b}±0.96	3.82^{b}±0.02	0.19^{d}±0.01	14.06^{a}±0.30	0.006^{c}±0.001
P	0.0000	0.0479	0.0000	0.0000	0.0099

Different letters show significant differences ($P < 0.05$) between samples in the same column.

The final evaluation parameter in this experiment was sensory evaluation to quantify consumer preference. The change in the mixing ratio between fresh fruit juice and tomatillo syrup significantly affected the sensory scores of the product, with results shown in Table 3 below.

Table 3: Effect of mixing ratio of tomatillo juice on sensory scores of the product

Fruit juice: by-product syrup	Sensory attributes				
	Color	Flavor	Taste	Structure	Hedonic Scale
3:1	4.13^{a}±0.99	3.76^{a}±0.80	3.00^{c}±0.85	4.18^{b}±0.78	6.38^{b}±1.09
2:1	4.04^{a}±0.74	3.96^{a}±0.95	3.38^{b}±0.98	4.18^{b}±0.68	6.40^{b}±1.40
1:1	4.20^{a}±1.04	4.07^{a}±0.86	4.29^{a}±0.76	4.33^{ab}±0.64	7.49^{a}±1.24
1:2	3.87^{a}±0.89	3.98^{a}±0.75	4.47^{a}±0.66	4.56^{a}±0.50	7.76^{a}±0.83

P	0.3485	0.3574	0.0000	0.0212	0.0000

Different letters show significant differences ($P < 0.05$) between samples in the same column

The parameters of color and odor of the tomatillo jelly product were relatively stable. Similarly, sensory scores for odor did not show clear differences between samples. This phenomenon is consistent with the physicochemical analyses in Table 1 and Table 2. Although measurements registered changes in the color index, this difference in shade did not create enough change to be distinguished by eye. Regarding odor, the scent of tomatillo is relatively mild and distributed in both formulating liquids. Therefore, swapping the ratio between these two sources still preserved the density of soluble odour molecules distributed in the jelly structure across all mixing ratios.

For taste, structure, and hedonic scale (degree of preferable parameters), the treatments with high fresh juice (3:1 and 2:1) received relatively low taste scores, which increased when transitioning to the 1:1 sample and the by-product syrup-rich 1:2 sample. This trend was repeated similarly for the sensory structure parameter, where the 1:2 and 1:1 sample led. As a result, the degree of liking score increased outstandingly, peaking at the 1:2 sample with a value of 7.76. The mechanism of this evaluation is due to the sugar acid harmony and the hydration level of the gel membrane. Fresh tomatillo fruit has a high content of citric acid and malic acid (0.44%). At samples with low total sugar, it was insufficient to mask the sourness from organic acids, creating a sharp, harsh sour taste. When increasing the amount of by-product syrup, a balanced aftertaste was created, resulting in a sweet and harmoniously mild sour taste. Structurally, the high hardness made the jelly stiff, creating a coarse feeling during eating, lacking the smooth structure of jelly. The presence of some sugar molecules in the 1:1 and 1:2 samples reduced the hardness to a moderate level, creating a smooth, soft, chewy-crunchy jelly state that is easy to melt in the mouth, conforming to the preference of the majority of the sensory panel.

Thus, in Experiment 1, the samples rich in fresh fruit juice (3:1 and 2:1) contained many functional compounds and had good nutritional value. However, the products had a hard jelly structure and an unharmonious sweet and sour taste. For the sample richest in by-product syrup (1:2), this was the sample with the highest sensory value. The functional compound components were equivalent to the 1:1 sample. This was the sample with the highest rate of utilizing by-product syrup from the tomatillo soaking process, maximizing by-product utilization and reducing product cost. Therefore, in this experiment, the most suitable mixing ratio chosen as the investigation ratio for the next experiment was the ratio of 1: fresh fruit juice and 2: by-product syrup.

The hydrocolloid system between carrageenan and konjac affected the physical properties of the tomatillo jelly, though the level of impact varied depending on the parameter, as shown in Table 4.

Table 4: Effect of gel formulation ratios on the physical parameters of tomatillo jelly

Factors	Level	Color meters			Hardness (gf)	a_w
		L*	a*	b*		
Konjac ratio (%)	0.2	67.46^{a}	-1.21^{b}	9.89^{ab}	153.6^{bc}	0,9611^{b}
	0.3	65.68^{a}	-1.15^{b}	10.12^{a}	131.4^{c}	0,9534^{ab}
	0.4	67.95^{a}	-0.94^{a}	7.51^{b}	166.1^{b}	0,9512^{ab}
	0.5	66.84^{a}	-0.78^{ab}	8.75^{ab}	205.3^{a}	0,9499^{a}
	P	0.4470	0.0607	0.1340	0.000	0,1338
Carragenan ratio (%)	0.8	64.51^{b}	-0.99^{a}	10.65^{a}	171.25^{a}	0,9546^{b}
	1.0	67.77^{a}	-1.04^{a}	8.92^{ab}	158.17^{a}	0,9534^{ab}
	1.2	67.00^{ab}	-1.08^{a}	9.05^{ab}	152.42^{a}	0,9546^{ab}
	1.4	68.83^{a}	-0.99^{a}	7.65^{b}	174.58^{a}	0,9485^{a}
	P	0.0194	0.9376	0.1201	0.2178	0,2354
P value (interaction)		0.0004	0.0094	0.0279	0.0049	0.7047

Different letters show significant differences ($P < 0.05$) between samples in the same column.

Regarding color parameters such as jelly lightness, when considering each factor individually, changing the ratio of Konjac powder did not alter the jelly lightness value. Conversely, the carrageenan content significantly affected it, raising the average lightness value from the lowest level at 0.8% concentration to the highest at 1.4% concentration. When examining the interaction of both factors, the lightest gel state appeared in the sample combining 1.0% Carrageenan and 0.2% Konjac, while the darkest spot fell into the sample combining 1.2% Carrageenan and 0.5% Konjac. Konjac powder consists mainly of long-chain glucomannan molecules with extremely large molecular weight and very strong water-absorbing/hydration capacity, creating high viscosity, so it tends to be more turbid compared to the transparency of Carrageenan crystals. When Carrageenan concentration increased, the transparency of the jelly surface was improved.

For the red-green region ($\boldsymbol{a}^*$) in the table, neither the carrageenan ratio nor the konjac ratio produced statistically significant effects on this parameter. The light green color reflects the presence of chlorophyll molecules from the fresh South American tomatillo fruit juice. Therefore, changing the gum concentration did not lose the natural green hue of the product. This result shows

that using the two gelling agents, carrageenan and konjac, is safe for the natural color compounds of South American tomatillo fruit, causing no side reactions that alter the natural color of the product.

The b^* index represents the yellow color of the product; the physiological ripening process of tomatillo transitions from light green to pale yellow when fully ripe. The Konjac powder content had a statistically significant effect on the yellow color of the final product, where the sample containing 0.4% Konjac had the lowest yellow value. For carrageenan, increasing the content from 0.8% to 1.4% reduced the yellow hue of the product. The yellow pigment system comes from the carotenoid components distributed in the tomatillo fruit. Increasing both Carrageenan and Konjac concentrations made the gel system of the product denser, limiting the light reflection of the yellow pigment to the outside, leading to a decrease in the b^* index obtained from the colorimeter. If Carrageenan concentration is maintained at a low level (0.8%) combined with a moderate amount of Konjac powder (0.3%), the influence of the gelling agents on the pale-yellow color of the product will be reduced.

The change in the ratio and concentration of gelling agents affecting the hardness of the product will allow for selecting the appropriate structural zone for all needs. If a solid gel system is needed, the ratio of 1.4% Carrageenan and 0.5% Konjac is the optimal solution. Meanwhile, if wanting to develop a soft, chewy line that melts easily when eaten, lower ratios should be chosen.

Table 5: Effect of gel formulation ratios on chemical parameters of tomatillo jelly

Factors	Level	Total acid (%)	Total sugar (%)	Vitamin C (%)	Polyphenol (mg GAE/100g)	DPPH (%)
Konjac ratio (%)	0.2	0.335^{a}	37.99^{a}	0.014^{ab}	4.68^{a}	73.40^{ab}
	0.3	0.329^{ab}	38.10^{a}	0.014^{ab}	4.62^{a}	71.59^{b}
	0.4	0.333^{a}	38.09^{a}	0.015^{a}	4.5^{ab}	76.43^{a}
	0.5	0.313^{b}	36.89^{a}	0.012^{b}	4.39^{b}	75.17^{ab}
	P	0.0774	0.5226	0.1065	0.0418	0.1437
Carragenan ratio (%)	0.8	0.352^{a}	37.70^{a}	0.012^{b}	4.66^{a}	73.35^{a}
	1.0	0.333^{b}	37.21^{a}	0.016^{a}	4.67^{a}	74.43^{a}
	1.2	0.319^{bc}	38.19^{a}	0.014^{b}	4.34^{b}	72.47^{a}
	1.4	0.306^{c}	37.98^{a}	0.014^{b}	4.52^{ab}	76.33^{a}
	P	0.0001	0.7499	0.0096	0.0094	0.3236

P value (interaction)	0.0002	0.0086	0.5571	0.0003	0.1771

Different letters show significant differences ($P < 0.05$) between samples in the same column.

Table 2: Sensory evaluation results of tomatillo jelly at different gel formulation ratios

Carragenan: Konjac	Sensory attributes				
	Color	Flavour	Taste	Structure	Hedonic scale
0.8 : 0.2	3.70^{a}±0.65	3.50^{cde}±0.51	3.60^{abcd}±0.50	3.70^{de}±0.47	7.20^{ab}±0.61
0.8 : 0.3	3.60^{ab}±0.50	3.10^{g}±0.31	3.40^{cdef}±0.67	2.90^{hj}±0.55	6.10^{cd}±0.71
0.8 : 0.4	3.40^{abcd}±0.50	4.10^{a}±0.55	3.90^{a}±0.31	4.50^{a}±0.51	7.40^{a}±1.04
0.8 : 0.5	3.40^{abcd}±0.81	3.90^{ab}±0.55	3.90^{a}±0.71	4.30^{ab}±0.65	7.20^{ab}±1.10
1,0 : 0,2	$3,60^{ab}$±0,50	$3,20^{fg}$±0,41	$3,80^{ab}$±0,61	$3,90^{cd}$±0,31	$6,90^{b}$±0,71
1,0 : 0,3	$3,20^{cd}$±0,41	$3,50^{cde}$±0,51	$3,30^{defg}$±0,65	$2,10^{k}$±0,55	$5,70^{e}$±0,65
1,0 : 0,4	$2,60^{d}$±1,04	$3,30^{efg}$±0,47	$3,20^{efg}$±1,10	$2,90^{hj}$±1,06	$6,10^{cd}$±1,16
1,0 : 0,5	$3,60^{ab}$±0,50	$3,60^{cd}$±0,50	$3,60^{abcd}$±0,50	$4,10^{bc}$±0,55	$7,10^{ab}$±0,71
1.2 : 0.2	3.20^{cd}±0.41	3.30^{efg}±0.47	3.70^{ab}c±0.47	2.60^{j}±0.50	5.90^{de}±0.55
1,2 : 0,3	$3,10^{d}$±0,71	$3,60^{cd}$±0,50	$3,00^{g}$±0,91	$3,00^{h}$±0,79	$6,10^{cd}$±0,84
1,2 : 0,4	$3,20^{cd}$±0,61	$3,40^{def}$±0,50	$3,30^{defg}$±0,65	$3,20^{fgh}$±0,89	$6,10^{cd}$±0,71
1,2 : 0,5	$3,50^{abc}$±0,51	$3,20^{fg}$±0,76	$3,40^{cdef}$±0,50	$3,10^{gh}$±0,55	$6,10^{cd}$±0,55
1,4 : 0,2	$3,70^{a}$±0,47	$3,60^{cd}$±0,50	$3,60^{abcd}$±0,50	$3,50^{ef}$±0,51	$6,90^{b}$±0,71
1,4 : 0,3	$3,30^{bcd}$±0,65	$3,20^{fg}$±0,41	$3,50^{bcde}$±0,68	$3,10^{gh}$±0,84	$6,30^{c}$±0,47
1,4 : 0,4	$3,50^{abc}$±0,68	$3,70^{bc}$±0,65	$3,60^{abcd}$±0,50	$3,10^{gh}$±0,84	$6,20^{cd}$±0,61
1,4 : 0,5	$3,20^{cd}$±0,61	$3,30^{efg}$±0,47	$3,10^{fg}$±0,55	$3,40^{efg}$±0,50	$6,10^{cd}$±0,55

P	0,0000	0,0000	0,0000	0,0000	0,0000

Different letters show significant differences (P < 0.05) between samples in the same column.

Table 7: Analysis results of microbiological and heavy metal parameters in South American tomatillo jelly.

No	Parameter	Unit	Value	Method
1	Mercury (Hg) (*)	mg/kg	ND	EPA Method 7473 Manual MA3000
2	Arsenic (As) (*)	mg/kg	ND	AOAC 986.15
3	Cadmium (Cd) (*)	mg/kg	ND	AOAC 999.11
4	Lead (Pb) (**)	mg/kg	ND	AOAC 999.11
5	Bacillus cereus	CFU/g	< 10	ISO 7932:2004
6	Clostridium perfringens	CFU/g	< 10	ISO 15213-2:2023
7	Coliforms	CFU/g	< 10	ISO 4832:2006
8	Escherichia coli	CFU/g	< 10	ISO 16649-2:2001
9	Staphylococcus aureus	CFU/g	< 10	ISO 6888-1:2021
10	Total yeasts and molds	CFU/g	< 10	ISO 21527-1:2008
11	Total aerobic count (TPC)	CFU/g	< 10	ISO 4833-1:2013

*note: ND – not detect; (*) - MDL 0.01; (**) - MDL 0.1. Analysis results from the Center of Analytical Services and Experimentation and Quality Measurement Standards of Ho Chi Minh City (CASE) – Can Tho Branch"

Discussion

This seems of the water competition between the gelling agents and sugar molecules. Fresh South American tomatillo juice provides free water for the polysaccharide chains to absorb and swell, and also contains natural pectin from the fruit; thus, the fresh fruit juice supports a firmly cross-linked gel system, helping to increase hardness and load-bearing capacity [16, 17]. Conversely, the by-product syrup has a high concentration of sucrose, glucose, and fructose. When increasing this syrup, the sugar molecules have a strong affinity for water and compete for water with the polysaccharide groups of carrageenan and konjac. The consequence of this process inhibits the gelling agent molecules from uncoiling and opening their loops freely, hindering the formation of hydrogen bonds during gelation. As a result, the obtained gel network becomes loose and unstably linked,

reducing the hardness of the jelly block and making it softer, which also agrees with the study of Akesowan [15].

Regarding the water activity (a_w), contrary to the decline in structural hardness, the increase in the proportion of by-product syrup brought about a beneficial effect in controlling the free water content of the food system. The water activity index recorded a downward trend to the lowest level of 0.9493 in the high-sugar sample (1:2). Sugar molecules bind strongly with water molecules, reducing the saturated vapor pressure of the product compared to free water [18]. When the a_w index shifts below the 0.95 threshold, as in the sample with 1 part fruit juice and 2 parts by-product syrup, it provides an advantage in terms of preservation. A water activity level below 0.95 inhibits the activity and population growth of most spoilage and toxin-producing bacterial strains in products [19].

The total antioxidant capacity of the jelly showed a decreasing trend and was strongly affected by the ratio of added by-product syrup, In the first three treatments (3:1. 2:1. and 1:1). The DPPH free radical scavenging capacity was well-preserved at a high and stable level. However, when the by-product syrup portion was added to the maximum in the 1:2 treatments, this index began to decrease with a statistically significant difference. The DPPH free radical scavenging activity of the jelly product is a cumulative result of various bioactive compounds naturally present in South American tomatillo fruit, including vitamins, Carotenoids, and natural phenolic compounds [5]. At ratios richer in fresh fruit juice, the concentration of these antioxidants in the jelly still retained enough active hydrogen to scavenge DPPH free radicals by over 80%. When shifting to the 1:2 treatments, the fresh fruit juice content significantly reduced. Meaning of the natural antioxidants was less. The by-product syrup had undergone a prolonged soaking cycle. The antioxidant molecules in the syrup cause to lose activity over time. This led to a decrease in overall antioxidant capacity. The product still remained portion of fresh fruit juice.

Regarding the total polyphenol content, Table 2 shows better stability against changes in the formulation. The difference in polyphenols was most evident in the by-product syrup-rich treatment (1:2) with a recorded value of 3.82. Unlike other linear antioxidant compounds that are easily degraded by oxidation. Polyphenols possess stable conjugated benzene rings [9]. Due to their high stability, the accumulated polyphenols extracted into the by-product syrup by-product were less destroyed and sufficient to compensate for the polyphenols lost due to the reduction of the fresh fruit juice ratio in the 2:1 and 1:1 samples, keeping the total phenolic concentration in the jelly from fluctuating deeply. Only when the amount of fresh fruit juice was deeply cut in the 1:2 samples did a clear decrease in polyphenols in the jelly occur. This result shows that the by-product syrup by-product is a highly functional raw material source. It allows the reuse of a large amount of heat-stable polyphenol compounds into the jelly structure, helping to optimize product cost while maintaining the natural biological value of the raw material.

As for the content of acids, sugar, and vitamin C in the tomatillo jelly. These are the factors that directly affect the nutrition and taste balance of South American tomatillo jelly. Vitamin C content decreased sharply, continuously and inversely with the mixing ratio of by-product syrup. In the treatment with the most fresh fruit juice (3:1), the vitamin C content reached its maximum value and fell to its lowest in the 1:2 sample with a value representing a loss of up to more than 46% of nutrients compared to the highest sample. The cause of this phenomenon is dilution. As fresh tomatillo juice is the main natural source of vitamin C in the product. When reducing the fresh juice ratio. The overall vitamin C concentration was pulled down according to the principle of mass conservation. The by-product syrup portion had undergone a long soaking cycle, during which vitamin C molecules had degraded.

Regarding total acid and total sugar contents. These two parameters showed very clear opposite trends. Total acid content (representing sourness)

decreased continuously to a minimum level of 0.19 in the 1:2 sample. Conversely, the total sugar content (representing sweetness) in the jelly increased sharply and peaked at the 1:2 treatment. Similar to vitamin C. this systematic variation was entirely due to the changing ratio of the two input raw material sources. The by-product syrup is a syrup solution of various polysaccharides and monosaccharides. The surge in total sugar content in the 1:2 sample explains the decrease in gel hardness analysed in Table 1.

The change in the ratio between the two gelling agents Carrageenan and Konjac altered the free water activity in the final product; however, this effect was generally not clearly different statistically, except at some specific levels. When the Konjac concentration increased from 0.2% to 0.5%, water activity tended to decrease with a significant difference. However, at levels of 0.3% and 0.4%, the change was not statistically significant; it can be seen that the level of change in the Konjac ratio capable of affecting the product $\boldsymbol{a_w}$ must be at least 0.3%. A similar trend occurred for the Carrageenan ratio: increasing the content from 0.8% to 1.4% also pulled the average water activity index down below 0.95, and the difference between these two ratio levels was statistically significant. Thus, the rate of increase in carrageenan that can affect $\boldsymbol{a_w}$ is 0.6%. Increasing the concentration of gelling agents will increase the capacity to retain water mechanically within the three-dimensional spatial network. The gel system tightly holds a portion of free water molecules, converting them into bound water located within the networks of the system [9]. When water molecules are locked, it reduces the saturated vapor pressure on the jelly surface, pulling the $\boldsymbol{a_w}$ index down below 0.95. Samples with high gelling agent ratios (1.4% carrageenan and 0.5% Konjac) brought a major advantage in preservation when the water activity was below 0.95.

Hardness is the most important structural parameter of ready-to-eat crisp jelly, directly deciding the mouthfeel during chewing and the structural stability of the product. When considering each factor independently, for the Carrageenan ratio, the impact on hardness was generally not statistically different. In contrast, the Konjac powder content had a clearer effect on this parameter. When Konjac concentration increased from 0.3% to 0.5%, the average hardness of the jelly increased sharply. However, adding Konjac at the low threshold of 0.2% was not statistically different from the two adjacent levels of 0.3% and 0.4%. Thus, it can be seen that the Konjac powder concentration needs to increase by at least 0.2% to be sufficient to change the baseline hardness of the jelly. Furthermore, the difference was clearer with the interaction of both gelling agents. This proves that the mechanical stability of South American tomatillo jelly structure is influenced by the synergistic mechanism between the two types of gelling agents. The experiment recorded the softest jelly block at the concentration combination of 1.2% carrageenan and 0.3% Konjac. Conversely, the largest value was achieved at the combination of the highest concentrations: 1.4% Carrageenan and 0.5% Konjac.

This strong interaction phenomenon is explained by the synergistic effect between carrageenan and konjac. The nature of carrageenan gelation forms a double helix structure and aggregates into rigid, brittle fibers, but it has the drawback of being easily broken. Meanwhile, Konjac powder contains large-molecular-weight glucomannan linkage chains, which absorb and hold water strongly, and possess good elasticity. When combining these two types of gum, the flexible molecular chains of Konjac interlace and establish stable hydrogen bonds with the rigid framework of the carrageenan double helix [9]. In mixing treatments with asymmetric ratios or low concentrations, this imbalance creates non-uniformity in the gel system, leading to fewer linkages and a softer gel. Conversely, when both components reach high concentrations (1.4% Carrageenan and 0.5% Konjac), the density of the gel components is sufficient to absorb and create a uniform framework for the entire system, raising the shear resistance of the gel, making the gel structurally harder [15].

For the two parameters related to taste, which are the acid index and total sugar index: changing the concentration and ratio of carrageenan and konjac powder did not create statistically significant differences. The chemical nature of carrageenan and konjac consists of carbohydrate polysaccharide structures that do not contain functional groups capable of releasing or degrading to produce additional H^+, and they do not adsorb or eliminate free organic acid radicals already present [18]. This ensures that the appropriate sweet and sour taste created by the juice blending ratio in the previous experiment is maintained. Although the total sugar content increased slightly when increasing the starch ratio, this change was not large enough to create a statistically significant difference because the product already had a substantial amount of sugar from the sugar syrup. Maintaining a stable total sugar content helps provide uniform sweetness of the jelly at different structural harnesses.

Regarding the functional properties of the jelly when adding different ratios of gelling agents, the Table 5 shows that, whether examined independently or interactively, both gel did not cause any statistically significant effect on the DPPH free radical scavenging capacity of the product. The polymer system of carrageenan and konjac does not alter the structure or mask the functional compounds, and the activities of these antioxidant groups remain unchanged. This allows for freely changing the gelling agent ratios to meet the best structure sensorially without fear of reducing or affecting the product's functional properties.

Interestingly, regarding the total polyphenol content, polyphenol compounds were quite significantly affected by the interaction of the gelling agent ratios, and this difference was statistically significant. The free polyphenol content reached peak values at low gel ratios. However, when simultaneously increasing the concentration of gelling agents, the free extracted polyphenol value decreased. Polyphenols are large molecules and contain many free hydroxyls (-OH) groups. When the gel is formed by carrageenan and konjac, these -OH groups tend to form hydrogen bonds along the longitudinal axis of the carbohydrate polymers [18]. As the concentration of both gum types increased, polyphenol molecules could be physically entrapped and locked within the rigid gel networks, significantly reducing the solubility of these components into water, thereby decreasing the concentration during analysis.

For sensitive micronutrients like Vitamin C (ascorbic acid): Table 5 showed that this index was affected by the carrageenan ratio, with the average value of vitamin C peaking when carrageenan was at a concentration of 1.0% (reaching 0.016). Meanwhile, the konjac powder factor did not cause any statistically clear effect. However, this change was not very substantial despite the statistically significant difference. This variation could be because at higher gelling agent concentrations, the system viscosity increased, significantly slowing the rate of oxygen diffusion and penetration from the external environment into the core of the jelly block, which helped preserve vitamin C better [20].

Sensory evaluation is the decisive measure of consumer acceptance and commercialization potential of a new food product. The differentiation of scores among the 16 mixing treatments in Table 6 achieved high statistical significance, proving that changes in the concentration of the Carrageenan - Konjac hydrocolloid system had the clearest impact on the sensory values of the product. For the structure and degree of hedonic scale, the highest scores were achieved at the mixing ratio of carrageenan 0.8% : konjac 0.4%. When keeping the konjac ratio at 0.4% but raising the carrageenan concentration to 1.0%, the structural score decreased. The lowest treatment among all samples was at the ratio of carrageenan 1.0% : konjac 0.3%. When mixing at the ratio of 0.8% : 0.4% and heating, the polymer chains of Konjac intercalate into the linkages of Carrageenan, creating a characteristic chewy-crisp and appealing framework for the product. However, if the ratio is imbalanced (such as in samples 1.0% : 0.3% or 1.0% : 0.4%), the excess of one of the two polysaccharides leads to over-linking, making the jelly too hard, creating a non-uniform mouthfeel

and reducing sensory value. The ratio of Carrageenan 0.8% and Konjac 0.4% was the most suitable condition to shape the desired chewy-crisp structure of the tomatillo jelly. The taste and flavor scores also reached high values in the carrageenan 0.8% : konjac 0.4% treatment. Treatments possessing high concentrations (especially carrageenan 1.2% and 1.4%) all had lower sensory scores for flavor. When increasing the carrageenan gel concentration, the former dense polysaccharide networks also reduced the evaporation of characteristic volatile odor molecules from the tomatillo fruit [21]. This explains why products with high gelling agent ratios showed decreased sensory scores for flavor and aroma. The 0.8% : 0.4% treatment also had the best color values. Carrageenan can form transparent gels [22], thus having little effect on the product's color. Conversely, Konjac, with its long molecular chains and strong swelling/water-absorption capacity, scatters light, making the product tend to look more turbid [23]. Therefore, as the konjac concentration increased, the turbidity increased and masked the natural yellow-green pigments of the tomatillo juice, causing the jelly to look dark and dull, lacking an appealing glossy appearance. It can be seen that in the experiment on formulation ratios of gelling agents, the optimal choice to standardize the production process for commercial transfer is the treatment: 0.8% Carrageenan and 0.4% Konjac powder. This treatment guarantees the most desirable chewy-crisp gel structure and appealing flavor for the South American tomatillo jelly product. Table 7 presents the results of analysis for food safety and hygiene parameters according to current Vietnamese regulations. These parameters were analysed by a third party, and the results are fully suitable for a commercialized product, with both microbiological and heavy metal parameters lying below the regulatory limits.

Conclusion

The study successfully identified the technical parameters to utilize the candied sugar syrup by-product as a raw material for processing chewy-crisp South American tomatillo (Physalis philadelphica) jelly. This solution contributes to minimizing organic waste during processing, optimizing production costs, and effectively recovering natural bioactive compounds such as polyphenols and vitamin C in the final jelly product. Furthermore, the study successfully determined the gelling agent ratio between carrageenan and konjac glucomannan to shape a jelly structure with harmonious chewy-crisp characteristics, enhanced water retention, minimized syneresis, and significantly improved sensory gloss. The combination of these indices allowed the product to achieve a natural, balanced sweet and sour aftertaste, which was highly accepted by the sensory evaluation panel. In addition, the testing results for microbiological parameters and heavy metal limits were within the safe thresholds according to current regulations, demonstrating the feasibility of the process for technology transfer and commercialization of products from South American tomatillo.

Declaration

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Conflict of Interest

The author declares no conflict of interest related to the publication of this article.

Consent for Publication

The author confirms that the final version of the manuscript has been reviewed and approved for publication.

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Authors' Contributions

All authors are participated in data collection, analysis, writing, and manuscript preparation.

Ethical Approval

As this study is a plant-based work with well documented protocols, it does not involve human or animal subjects and therefore does not require animal welfare protocols or ethical approval.

AI Declaration

None.

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