Development and Evaluation of Sugar-Free Bengal Currant (*Carissa carandas* L.) Instant Beverage Powders: Physicochemical Properties, Total Phenolic Content, Antioxidant Activity, and Nutritional Composition

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Abstract

This study details the formulation of a sugar-free instant beverage powder derived from Bengal currant (*Carissa carandas* L.), with a comprehensive evaluation of its physicochemical characteristics, total phenolic content, antioxidant activity, and nutritional composition. Fresh Bengal currant pulp was homogenized with 10% (w/w) maltodextrin, oven-dried at 60 °C for 8 h, milled, and sieved to produce powder (yield 13.3% w/w). Three sucralose-sweetened formulations containing 10-20% fruit powder were compared with a sucrose-sweetened control to investigate the effects of fruit concentration and sweetener type. Physicochemical analyses included color, water activity (a_w), pH, and water solubility index (WSI). Total phenolic content was quantified using the Folin-Ciocalteu assay, while antioxidant capacity was evaluated via the DPPH free-radical scavenging assay. Nutritional composition was calculated using INMUCAL-Nutrients. All formulations exhibited low water activity (0.40-0.48) and acidic pH (2.93-2.99), indicating favorable microbiological stability. The powders exhibited a reddish-yellow color. The WSI ranged from 60.08 to 66.01%, with higher values observed in formulations with lower fruit powder content. Total phenolic content ranged from 10.07 to 14.07 mg GAE/g, with the 15% fruit formulation (F2) showing the highest phenolic retention. Antioxidant activity, determined by the DPPH assay, ranged from 43.20 to 53.97% inhibition, with the 20% fruit formulation (F3) exhibiting the highest activity. Replacement of sucrose with sucralose markedly reduced energy and available carbohydrate compared with the control. Increasing the proportion of fruit powder enhanced the mineral and provitamin A content. Formulation F2 is recommended for further development due to its high phenolic retention and potential cost-effectiveness. These results suggest that Bengal currant powder can be effectively utilized to produce health-oriented, low-calorie functional beverages. The product shows potential as a convenient, low-sugar fruit-based alternative, while further studies on sensory acceptability and storage stability are recommended to support commercialization.

Keywords: Bengal currant (*Carissa carandas*), Sugar-free beverage, Instant beverage powder, Phenolic content, Functional food

Introduction

The global demand for convenient functional beverages has increased substantially due to growing awareness of diet-related chronic diseases and the health risks associated with excessive sugar intake (Fakhri et al., 2023). Instant beverage powders are widely consumed because of their long shelf life, ease of transportation, and simple preparation before consumption. However, many commercially available fruit-based instant beverages contain high levels of added sucrose, contributing significantly to daily sugar intake and increasing the risk of obesity, insulin resistance, and type 2 diabetes (Fakhri et al., 2023). Consequently, reformulation strategies aimed specifically at reducing added sugars in instant beverage systems have become a priority in contemporary food product innovation. In instant beverage powder systems, product quality depends not only on ingredient composition but also on key physicochemical parameters such as water activity, pH, solubility, and color stability, which directly influence shelf stability and reconstitution performance. Effective formulation must ensure rapid dissolution, microbiological safety, and retention of bioactive compounds during storage. Therefore, sweetener substitution strategies may affect not only nutritional value but also technological and functional characteristics of the final powdered product. Among sugar-reduction approaches, non-nutritive sweeteners (NNS) are widely applied to maintain sweetness while minimizing caloric contribution. Sucralose is particularly attractive due to its exceptionally high sweetness intensity—approximately 600 times sweeter than sucrose—while contributing negligible calories because it is not metabolized by the human body (Magnuson et al., 2017). It is also highly stable under acidic conditions, elevated temperatures, and storage environments, making it suitable for powdered beverages and instant drink systems (Magnuson et al., 2017). Clinical and reformulation studies demonstrate that replacing sucrose with sucralose can reduce energy and carbohydrate intake without compromising sweetness or polyphenol bioavailability (Ghanbari et al., 2021; Rostampour et al., 2024). These characteristics make sucralose an appropriate sweetener for developing sugar-free functional beverages consistent with current public health recommendations. In Thailand, the use of sucralose is regulated under the food additive notifications of the Thai Food and Drug Administration (Thai FDA). For beverages, including powdered drink products, sucralose is permitted at levels not exceeding 0.3 g/kg (300 mg/kg) of the final product, depending on product category specifications (Muangsri et al., 2021). These characteristics, together with its regulatory approval and safety evaluation, make sucralose an appropriate sweetener for developing sugar-free functional beverages consistent with current public health recommendations.

Bengal currant (*Carissa carandas* L.), long used in traditional South Asian medicine, is increasingly recognized as a promising nutraceutical source due to its rich phytochemical and nutrient profile. Studies report antioxidant, anti-inflammatory, antidiabetic, antimicrobial, and hepatoprotective activities associated with its phenolic acids, flavonoids, and anthocyanins (Dhatwalia et al., 2021; Neimkhum et al., 2021; Saeed et al., 2024; Singh et al., 2020; Wanna et al., 2024). As an underutilized fruit ingredient rich in vitamins, minerals, and bioactive phytochemicals, Bengal currant presents strong potential for incorporation into functional beverage formulations. Despite these promising attributes, most existing research has focused on crude extracts, fresh juice, or laboratory-scale phytochemical analyses. Limited studies have investigated Bengal currant within shelf-stable, sugar-free instant beverage powder systems. Furthermore, the combined effects of fruit powder concentration and sucrose replacement with non-nutritive sweeteners on physicochemical stability, phenolic retention, and nutritional composition remain insufficiently explored. This gap restricts the translation of Bengal currant's bioactive potential into standardized, commercially viable instant beverage products.

Therefore, the objective of this study was to develop and evaluate sugar-free instant beverage powders formulated with Bengal currant powder. Sucralose was used to replace sucrose to reduce caloric contribution while maintaining sweetness, consistent with its established functional beverage applications (Magnuson et al., 2017; Rostampour et al., 2024). By varying the proportion of Bengal currant powder (10–20%), this study systematically examined the effects on physicochemical properties (pH, color, water activity, water solubility index), total phenolic content, antioxidant activity, and nutritional composition. This integrated formulation strategy aims to optimize sugar reduction while preserving bioactive compounds and enhancing micronutrient value, thereby contributing to the development of health-oriented, low-sugar fruit-based beverage powders with potential functional and commercial applications.

Materials and Methods

Preparation of raw materials

Semi-ripe Bengal currant fruits (Fig. 1) were obtained from Lat Bua Luang District, Phra Nakhon Si Ayutthaya Province, Thailand. The fruits were thoroughly washed with clean tap water, and the pulp was separated from the seeds. The seeds were recombined with the pulp to retain the whole-fruit composition, including dietary fiber and associated phytochemicals, and to minimize raw material loss during processing. The fruit pulp was homogenized using a blender (MB600W-BL, Minimx, MiniMex, Thailand) and subsequently recombined with the separated seeds. Maltodextrin (10% w/w) was incorporated into the fruit mixture as a carrier agent. The mixture was then dried in a hot-air oven (ED 260, Binder, BINDER GmbH, Germany) at 60 °C for 8 h. The dried material was ground into fine powder using an ultrafine grinder (ZM 200, Retsch, Retsch GmbH, Germany) and sieved through a 100-mesh screen to obtain uniform powder particles. Sieving through a 100-mesh screen corresponds to an approximate particle size of ≤150 µm, producing a fine powder suitable for instant beverage applications.

Figure 1 Maturity stage of Bengal currant fruits selected for use in this study

The percent of Bengal currant powder (%yield) was calculated using the formula below (Jaroennon, Nuanchankong, & Manakla, 2023).

$$\%yield = \frac{Bengal\ currant\ fruits\ powder}{initial\ weight\ of\ bengal\ currant\ fruits} \times 100$$

Physical properties evaluation of raw material

The physicochemical properties of Bengal currant fruit powder were evaluated in terms of water activity and color using appropriate analytical instruments. Water activity (a_w) was determined using a water activity meter (LabSwift-aw; Novasina, Switzerland) in auto-start mode, with approximately 1 g of sample placed in the sample dish; measurements were performed at room temperature. Color measurements were carried out using a Chroma Meter CR-400 (Konica Minolta, Tokyo, Japan), which was calibrated with a standard white plate (CR-A43; Y = 85.70, x = 0.3177, y = 0.3340) and operated in DP mode. Powder samples were presented in a sample cup (filled to a consistent depth and not compacted) and measured at three different positions per sample. The color parameters measured included L* (lightness; 0 = black, 100 = white), a* (redness/greenness; negative values indicate greenness and positive values indicate redness), and b* (yellowness/blueness; negative values indicate blueness and positive values indicate yellowness). All analyses were conducted in triplicate, and the results were reported as water activity (a_w), and L*, a*, b* values, respectively.

Preparation of Bengal currant instant beverage powder

Preliminary palatability assessment was conducted to determine appropriate ingredient ratios for the development of Bengal currant instant beverage powder, with particular emphasis on achieving a balance between sourness and sweetness. In the initial stage, a control formulation was established using 15 g of Bengal currant powder. This level was selected based on previous studies on instant fruit-based beverage powders, which reported that incorporating fruit powder at approximately 15% (w/w) in combination with a high proportion of sugar provides optimal sensory acceptability (Akther et al., 2020). Other ingredients were kept constant across all formulations to control experimental variables, including citric acid (1 g; Chemipan, Thailand), salt (0.5 g; Prung Thip, Thailand), xanthan gum (0.3 g; Chemipan, Thailand), and lemon powder (2.5 g; Moon Farms, Thailand). Sugar was incorporated at 80.7 g in the control formulation to provide sweetness and to balance the overall flavor profile, particularly the sourness of the product.

Based on this formulation framework (Table 1), Bengal currant powder levels were varied (10, 15, and 20 g) in the developed formulations. In these formulations, sucrose was replaced with sucralose (0.135 g; Chemipan, Thailand), a high-intensity sweetener approximately 600 times sweeter than sucrose, to develop reduced-sugar formulations. All ingredients were thoroughly mixed to obtain a homogeneous instant beverage powder.

Table 1 Formulations of Bengal currant instant beverage powder

Ingredients	Formulations			
	Control	F1	F2	F3
Bengal currant powder (g)	15	10	15	20
Citric acid (g)	1	1	1	1
Salt (g)	0.5	0.5	0.5	0.5
Xanthan gum (g)	0.3	0.3	0.3	0.3
lemon powder (g)	2.5	2.5	2.5	2.5
Sucralose (g)	-	0.135	0.135	0.135
Sugar (g)	80.7	-	-	-

Physicochemical properties of Bengal currant instant beverage powder

Color analysis

The color of the instant beverage formulations was measured using a Chroma Meter CR-400 colorimeter (Konica Minolta, Tokyo, Japan). The instrument was calibrated with a standard white plate (CR-A43) and operated in DP mode. Powder samples were placed in a sample cup (filled to a consistent depth) and measured at three different positions per sample. Measurements were performed in triplicate for each formulation, and the color parameters L*, a*, and b* were recorded.

pH analysis

The pH of the samples was determined by homogenizing (Vortex Mixer Genie 2, Scientific Industries, USA) 1.0 g of sample in 50 mL of distilled water at 70 °C. After homogenization, the suspension was cooled to room temperature (≈25 °C) and allowed to equilibrate for 10 min before measurement. The pH was measured using a digital pH meter (SI Analytics, Mainz, Germany) equipped with a glass combination electrode. The meter was calibrated with standard buffer solutions (pH 4, 7, and 10) before use. All measurements were performed in triplicate.

Water activity analysis

The water activity (a_w) of the sample powders was determined using a LabSwift-aw water activity meter (Novasina, Switzerland) operated in auto-start mode. Approximately 1.0 g of powder was placed into the instrument sample dish, which was then loaded into the measurement chamber. Samples were allowed to equilibrate until a stable reading was indicated by the instrument. Measurements were conducted at room temperature. Measurements were performed in triplicate.

Water solubility index

Water solubility index (WSI) was determined using a modified shake-flask method (Suwannakham et al., 2023). Briefly, 1 g of the instant beverage powder was dispersed in 50 mL of distilled water and incubated at 60 °C for 1 h with intermittent shaking to ensure complete hydration. The suspension was then centrifuged at 5000 rpm for 30 min. The supernatant was carefully decanted, and the insoluble residue was collected and dried at 60 °C until a constant weight was achieved. The WSI (%) was calculated using the following equation.

$$WSI(\%) = \frac{Insoluble\ residue\ weight(g)}{Original\ sample\ weight(g)} \times 100$$

Determination of phenolic content and antioxidant activity of Bengal currant instant beverage powder

Sample preparation

Ten grams of each instant beverage powder formulation were accurately weighed and dispersed in 50 mL of water at 80 °C (200 mg/mL). This temperature corresponds to typical hot beverage preparation conditions. Each suspension was centrifuged at 4,500 rpm for 10 min. The resulting clear supernatants were diluted with water to a final concentration of 0.02 g/mL for subsequent analyses. This final concentration was selected to simulate typical consumption conditions of instant beverage products, equivalent to dissolving 3 g of powder in 150 mL of water.

Folin-Ciocalteu method

The total phenolic content of the instant beverage powder was determined using the Folin–Ciocalteu method as described by Jaroennon et al. (2021). A gallic acid calibration standard (150–1,000 µg/mL) was prepared for quantification. Briefly, 0.3 mL of either the gallic acid standard solution (Sisco Research Laboratories Pvt. Ltd., India) or the sample solution was mixed with 1.5 mL of 0.2 N Folin–Ciocalteu reagent (Sisco Research Laboratories Pvt. Ltd., India). After mixing, the reaction mixture was allowed to stand for 6 min, followed by the addition of 1.2 mL of sodium carbonate solution (75 g/L; Ajax Finechem Pty Ltd, Australia). The mixture was then incubated in the dark at room temperature for 30 min. Absorbance was measured at 765 nm using a spectrophotometer (Libra S22 UV, Biochrom, UK). All analyses were performed in triplicate. The total phenolic content was quantified from the gallic acid calibration curve ($y = 0.0008x + 0.0058$, $R^2 = 0.9955$) and expressed as milligrams of gallic acid equivalents (mg GAE/g).

2,2-Diphenyl-1-Picrylhydrazyl (DPPH) free radical scavenging assay

The antioxidant activity method was adapted from Jaroennon, & Manakla, 2021. Different concentrations of standard (ascorbic acid, 1-10µg/ml) were prepared. One-hundred microliter of either standard (Sigma-Aldrich, St Louis, MO, U.S.A.) or sample solutions were mixed with 100 µL of 208 µM DPPH (Sigma-Aldrich, St Louis, MO, U.S.A.) in methanol (Merck, Darmstadt, Germany). After incubating in darkness for

30 minutes, the absorbance was measured at 517 nm using a microplate reader. All reactions were carried out in triplicate.

$$\%inhibition = \frac{A_{control} - A_{sample}}{A_{control}} \times 100$$

Where: $A_{control}$ is the absorbance of the DPPH solution

A_{sample} is the absorbance of sample or standard with DPPH solution

Nutritional Calculation of Bengal currant instant beverage powder

The nutritional composition of the Bengal currant instant beverage powder was estimated using the INMUCAL-Nutrients software (version 4.0; Institute of Nutrition, Mahidol University). The analyzed parameters included energy, protein, fat, carbohydrate, calcium, phosphorus, magnesium, sodium, potassium, iron, copper, zinc, betacarotene, and vitamin A (RAE). The results were expressed per 100 g of Bengal currant instant beverage powder.

Data analysis

Statistical analysis was performed using LSD one-way analysis of variance (ANOVA) to determine significant differences in the phenolic content, antioxidant activity, and physical characteristics of the instant beverage powder. The results were expressed as mean ± standard deviation. Statistical analysis was performed using SPSS software. When significant differences were detected, the Least Significant Difference (LSD) test was employed as a post-hoc comparison. Differences were considered statistically significant at $p < 0.05$.

Results and Discussion

Physical properties of raw material

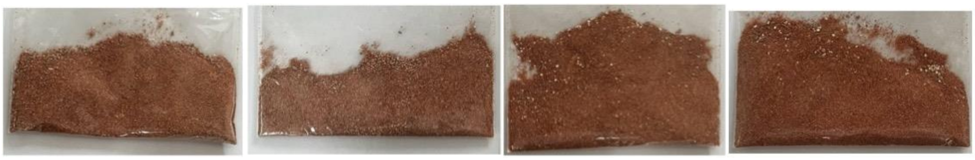
In this study, oven drying was selected due to its operational simplicity, cost-effectiveness, and suitability for small- to medium-scale food processing. The physical properties of the raw material are shown in Table 2. The powder yield of Bengal currant was approximately 13.3% (w/w). Color measurements in the CIE Lab* color space for the Bengal currant powder were L* = 48.77 ± 0.61, a* = 19.36 ± 0.08, and b* = 14.08 ± 0.08. These values indicate a medium lightness and a reddish-yellow hue, consistent with an orange-red coloration of the powder (Fig. 1). The water activity of the powder was 0.33 ± 0.00. Water activity values below approximately 0.6 generally limit the growth of most spoilage microorganisms and help retard enzymatic and oxidative degradation, thereby supporting the storage stability of powdered food ingredients (Liu et al., 2022; Xie et al., 2021).

Table 2 Color, yield, and water activity properties of Bengal currant power

Raw material	yield (%)	Color			water activity (a_w)
		L*	a*	b*	
Bengal currant	13.30	48.77±0.61	19.36±0.08	14.08±0.08	0.33±0.00

Physicochemical properties of Bengal currant instant beverage powder

The Bengal currant instant beverage powder is shown in Fig. 2. Color parameters of the Bengal currant instant beverage powder differed significantly among formulations ($p < 0.05$). The control exhibited an L* of 57.40 ± 0.39, whereas supplemented formulations showed L* values ranging from 59.83 ± 0.46 to 54.15 ± 0.07 (Table 3). The observed decrease in lightness with increasing fruit powder concentration is likely attributable to the intrinsic dark-red pigmentation of Bengal currant, which is rich in anthocyanins and carotenoid-derived pigments that deepen sample coloration (Khuanekkaphan et al., 2021; Li et al., 2022). Values on the red-green axis (a*) increased from 13.79 ± 0.52 (F1) to 16.59 ± 0.22 (F3), indicating a statistically significant enhancement of red chroma with higher powder inclusion. This trend is consistent with the anthocyanin profile of Bengal currant (Saxena et al., 2021). The b* values (yellow-blue axis) likewise increased from 9.85 ± 0.36 (F1) to 12.02 ± 0.12 (F3), suggesting an intensification of yellow components that may reflect carotenoid-polyphenol interactions in fruit-derived powders (Hasnul Hadi et al., 2021). Together, these changes demonstrate that the incorporation of Bengal currant powder produces measurable and formulation-dependent shifts in chromatic attributes of the instant beverage.



Control F1 F2 F3

Figure 2 Instant beverage powder of Bengal currant

Measured water activity values for all formulations ranged between 0.40 ± 0.003 and 0.48 ± 0.003, placing the products within the low-moisture domain typically associated with good shelf stability. Formulations with greater fruit powder content (F2-F3) tended to exhibit slightly lower a_w. This decrease may be explained by the higher solid fraction and the hygroscopic nature of fruit polysaccharides and polyphenolic constituents, which bind available water (Liu et al., 2022). All measured a_w values were well below 0.60, a commonly cited threshold for inhibition of growth of most spoilage microorganisms, yeasts, and molds (Xie et al., 2021), indicating favorable microbiological stability for powdered beverage matrices.

The pH of the formulations was acidic and narrowly distributed (2.93 ± 0.00 to 2.99 ± 0.02). This acidity is consistent with the intrinsic organic acid content (e.g., citric and malic acids) of Bengal currant and is expected to contribute to product flavor and preservation (Khuanekkaphan et al., 2021). Minor differences in pH among formulations likely reflect variations in fruit solids concentration; the combination of low pH and low a_w provides synergistic hurdles against microbial growth and chemical degradation, thereby enhancing overall product stability (Liu et al., 2022).

The water solubility index (WSI) of Bengal currant instant beverage powder formulations is presented in Table 3. The WSI values ranged from 60.08 ± 0.93 to 66.01 ± 0.81%, with significant differences among formulations ($p < 0.05$). Among all samples, F1 exhibited the highest WSI (66.01 ± 0.81%), followed by the control (62.70 ± 0.48%) and F2 (62.79 ± 0.58%), whereas F3 showed the lowest WSI (60.08 ± 0.93%). These results indicate that formulation composition significantly influenced the solubility characteristics of the powders. Differences in WSI were mainly attributed to variations in Bengal currant powder content and sweetening agents (Table 1). The control formulation, containing a high level of sugar (80.7 g), exhibited relatively high WSI due to the strong water solubility of sugars, which increases total soluble solids. Similarly, F1 showed the highest WSI despite being sugar-free, likely due to its lowest fruit powder content (10 g), which reduced insoluble components such as dietary fiber and pectin, thereby enhancing solubility. This is consistent with previous findings that soluble sugars and low-molecular-weight compounds contribute to higher WSI in fruit powders (Rafiquzzaman et al., 2025). In contrast, F3, with the highest fruit powder content (20 g), showed the lowest WSI, indicating that increased insoluble solids can limit water penetration and reduce dissolution efficiency. Insoluble polysaccharides and fibers in fruit powders are known to decrease solubility and promote sedimentation (Jagelaviciute et al., 2025). Although F2 contained the same fruit powder content as the control, its slightly lower WSI may be due to the replacement of sugar with sucralose, which contributes minimally to soluble solids. This supports the concept that WSI depends on the concentration of soluble components and their interaction with water (Pismag et al., 2024). Overall, the WSI values (60–66%) were relatively high and within the acceptable range for instant fruit powders, where values above 50% indicate good reconstitution properties (Rafiquzzaman et al., 2025).

Table 3 Color, water activity, pH and water solubility index properties of Bengal currant instant beverage powder

Formulations	color			Water activity (a_w)	pH	Water solubility index (%)
	L	a	b			
control	57.40 ± 0.39^a	14.88 ± 0.26^a	10.75 ± 0.15^a	0.44 ± 0.001^a	2.97 ± 0.02^a	62.70 ± 0.48^a
F1	59.83 ± 0.46^b	13.79 ± 0.52^b	9.85 ± 0.36^b	0.48 ± 0.003^b	2.93 ± 0.00^b	66.01 ± 0.81^b
F2	56.45 ± 0.30^c	15.49 ± 0.18^c	11.36 ± 0.08^c	0.42 ± 0.002^c	2.99 ± 0.01^c	62.79 ± 0.58^{ac}
F3	54.15 ± 0.07^d	16.59 ± 0.22^d	12.02 ± 0.12^d	0.40 ± 0.003^d	2.99 ± 0.02^d	60.08 ± 0.93^d

Note: Mean ± SD within a column with different superscript letters are significantly different at $p < 0.05$ from each other

Total phenolic content and antioxidant activity of Bengal currant instant beverage powder

The total phenolic content (TPC) of Bengal currant instant beverage powders ranged from 10.07 ± 0.51 to 14.07 ± 0.59 mg GAE/g, with a clear increase observed up to 15% fruit powder (F2). The F2 exhibited the highest TPC, significantly higher than F1 ($p < 0.05$), while no further increase was observed at 20% (F3), suggesting that moderate fruit inclusion optimizes phenolic retention (Table 4). These values were higher than those reported for several tropical fruit powders, highlighting the strong phenolic potential of Bengal currant (Rafiquzzaman et al., 2025).

The antioxidant activity, determined by the DPPH assay (Table 4), ranged from 43.20 ± 0.28 to 53.97 ± 0.32% inhibition, with F3 showing the highest activity. In general, antioxidant activity increased with fruit powder content, reflecting the contribution of phenolics and other bioactive compounds such as flavonoids and organic acids (Santos et al., 2024). However, despite F2 having the highest TPC, F3 exhibited the greatest antioxidant activity. This suggests that antioxidant capacity is influenced not only by total phenolic content but also by compound composition, reactivity, and the presence of other antioxidants such as ascorbic acid. The lower activity in F1 was associated with its reduced fruit content, resulting in lower concentrations of antioxidant compounds (Kumar et al., 2024). Although the control and F2 contained equal fruit powder levels, the slightly higher activity in the control may be attributed to the presence of sugar, which may facilitate the extraction and stabilization of phenolic compounds in aqueous systems. The DPPH assay is based on hydrogen atom transfer

(HAT) and single electron transfer (SET) mechanisms. The relatively high inhibition values (>40%) confirm that Bengal currant powder is a potent source of natural antioxidants, comparable to other fruit-based powders (Seke et al., 2023). Overall, a positive, though not strictly linear, relationship between TPC and antioxidant activity was observed.

Table 4 Total phenolic content and antioxidant activity of Bengal currant instant beverage powder

Formulations	Total phenolic content (mg GAE/g)	Antioxidant activity (% inhibition)
control	13.57±1.32^{a}	52.37± 0.25^{a}
F1	10.07±0.51^{b}	43.20 ± 0.28^{b}
F2	14.07± 0.59^{ac}	49.44 ± 0.33^{c}
F3	13.57 ± 0.26^{ad}	53.97 ± 0.32^{d}

Note: Mean ± SD within a column with different superscript letters are significantly different at $p < 0.05$ from each other

Nutritional composition

The estimated nutritional composition of the Bengal currant instant beverage powders, calculated based on ingredient formulation data using INMUCAL-Nutrients (version 4.0), is presented in Table 5. The control formulation exhibited the highest energy content (419.4 kcal/100 g), followed by F3 (92.5 kcal/100 g), F2 (71.4 kcal/100 g), and F1 (50.3 kcal/100 g). This pattern reflects the substantially greater added sugar in the control (87% sucrose), whereas F1–F3 were formulated without added sugar and were sweetened with the non-caloric sweetener sucralose. Consistent with the energy data, the control also showed the highest carbohydrate content (97.8 g/100 g); the sugar-free formulations displayed markedly lower carbohydrate levels (7.9–13.8 g/100 g), which increased in proportion to the amount of fruit powder (F1 < F2 < F3). The large reductions in energy and available carbohydrate in F1–F3 are therefore attributable to sucrose replacement with sucralose, an approach that has been widely used to lower product caloric and sugar content while preserving sweetness (Sylvetsky & Rother, 2016; Russell et al., 2021). Replacing nutritive sugars with non-nutritive/low-calorie sweeteners typically yields substantial decreases in measured energy and available carbohydrate in reformulated foods and beverages, and randomized trials and meta-analyses indicate that non-nutritive sweetener use can reduce short-term energy and carbohydrate intake compared with sugar (Rostampour et al., 2024). This strategy is consistent with industry and public-health driven reformulation trends that favor low- or no-calorie sweeteners to meet sugar-reduction targets (Gallagher et al., 2021; Russell et al., 2021). Key minerals (calcium, phosphorus, magnesium, and potassium) showed a clear increasing trend corresponding to the amount of Bengal currant powder incorporated into the formulations. Among the developed samples, F3 contained the highest levels of calcium, phosphorus, magnesium, and potassium (55.8, 27.2, 25.7, and 618.7 mg/100 g, respectively), whereas F1 exhibited the lowest concentrations. This pattern is consistent with the differing fruit contents across formulations (F1 < F2 < F3). Because Bengal currant is naturally rich in various minerals, increasing the proportion of fruit powder proportionally raises the mineral concentration in the final product. These findings align with previous studies on fruit powders and instant beverage mixes, which similarly report that increasing the amount of concentrated or dried fruit in formulations leads to significant enhancements in mineral content and other bioactive constituents (Bochnak-Niedzwiecka & Swieca, 2020; Fernandez-Ramirez et al., 2022). The levels of beta-carotene and total vitamin A (RAE) increased in proportion to the amount of fruit powder incorporated into the formulations. F3 exhibited the highest values (beta-carotene: 107.1

μg; vitamin A: 7.5 μg RAE), whereas the control and F2 showed comparable levels (approximately 80–81 μg beta-carotene). F1 had the lowest beta-carotene content among the fruit-based formulations (53.6 μg). The highest beta-carotene concentration was observed in F3, and the lowest in F1, directly reflecting the differing proportions of fruit powder in the formulations. Because beta-carotene is naturally present in Bengal currant in amounts that correspond to the proportion of fruit tissue, increasing the quantity of fruit powder enhances the functional nutrient profile of the product. Similar trends have been reported in previous studies, indicating that the incorporation of fruit powder into instant beverage formulations significantly increases carotenoid and vitamin A contents (Srisuk & Jirasatid, 2023; Melendez-Martinez et al., 2022). Overall, the findings indicate that increasing the proportion of Bengal currant powder has a positive impact on the product's nutritional quality and represents an effective formulation strategy for enhancing its nutrient profile and health-related attributes.

Table 5 Nutritional composition per 100 g of Bengal currant instant beverage powder

Nutritional composition	control	F1	F2	F3
Energy (kcal)	419.4	50.3	71.4	92.5
Protein (g)	1.2	0.8	1.2	1.7
Fat (g)	2.7	1.8	2.7	3.5
Carbohydrate (g)	97.8	7.9	10.8	13.8
Calcium (mg)	41.9	27.9	41.9	55.8
Phosphorus (mg)	20.4	13.6	20.4	27.2
Magnesium (mg)	19.2	12.8	19.2	25.7
Sodium (mg)	2.3	1.5	2.3	3.0
Potassium (mg)	464.0	309.4	464.0	618.7
Iron (mg)	0.4	0.3	0.4	0.5
Copper (mg)	0.1	0.1	0.1	0.2
Zinc (mg)	0.5	0.3	0.5	0.6
Beta-carotene (μg)	80.4	53.6	80.4	107.1
Total vitamin A (RAE) (μg)	5.7	3.8	5.7	7.5

This study has several limitations. The nutritional composition was estimated using software calculations based on ingredient databases rather than determined by direct laboratory analysis. Furthermore, sensory evaluation and consumer acceptability testing were not conducted. Future research should address these aspects to provide a more comprehensive assessment of product quality and practical applicability.

Conclusion and Suggestions

The present study developed sugar-free Bengal currant instant beverage powders by formulating three sucralose-sweetened products (F1, F2, and F3) with varying fruit powder levels and comparing them to a sucrose-based control. All formulations exhibited low water activity and acidic pH. These parameters, combined with pigment retention consistent with the raw fruit, suggest high physicochemical stability and inherent resistance to microbial proliferation in the dry state. The use of sucralose substantially reduced the estimated energy content of the products, and increasing the proportion of fruit powder enhanced the levels of key minerals and beta-carotene. Formulation F2 is recommended for further development, as it maintains phenolic levels comparable to higher fruit inclusion while potentially offering improved cost efficiency. Overall, these findings suggest that sugar-free fruit-based instant beverage powders may serve as reduced-calorie alternatives to conventional sugar-sweetened products. While this study establishes a proof-of-concept for Bengal currant powder, it is constrained by a lack of direct laboratory-based nutritional assays and consumer sensory testing. To transition from a laboratory prototype to a viable commercial product, subsequent research must prioritize accelerated shelf-life testing and hedonic sensory evaluation.

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Author Contributions

Author 1: Sakunta Manakla prepared sample material and formulated Bengal currant instant beverage powder.

Author 2: Jutawan Nuanchankong designed the study and performed experiments on physicochemical properties and total phenolic content.

Author 3: Pattamaporn Jaroennon performed nutritional studies and analyzed data. All authors wrote and edited the manuscript for submission for publication.

Conflict of Interests

All authors declare that they have no conflicts of interest.

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