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Research Article

Carrot Powder as a Natural Source of Provitamin A in Milk Chocolate: Beta-Carotene Retention and Consumer Acceptability

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Abstract

Vitamin A deficiency remains a major public health burden in low- and middle-income countries, yet fat-rich confectionery, a matrix that favours carotenoid micellization, remains an underexploited delivery vehicle. Milk chocolates enriched with carrot powder at three levels (F1, 150 g; F2, 100 g; F3, 50 g per batch) were formulated, benchmarked against a non-enriched control, and characterised for proximate composition, oxidative status and consumer acceptability. Carrot powder raised total carotenoid content, expressed as β-carotene equivalents, dose-dependently to 4.55 mg/100 g in F1 ($p < 0.001$), at a mean apparent processing retention of 82.7 ± 2.6% relative to the raw powder, and increased moisture from 0.41% to between 1.77 and 2.15% ($p < 0.001$), while ash was unaffected ($p = 0.424$). A 30 g portion of F1 delivered an estimated 97 µg retinol activity equivalents once the typical α-carotene share of carrot provitamin A is accounted for, covering 11 to 14% of the adult recommended dietary allowance. Protein decreased from 10.11% in the control to between 8.54 and 9.32% in the enriched samples ($p < 0.001$), tracking milk powder content ($r = 0.945$) rather than carrot powder level. Lipid content (37.89 to 43.90%) and peroxide value (1.25 to 4.24 meq O_2/kg) tracked cocoa butter rather than carrot powder level, and cocoa butter mass was the stronger covariate of aroma ($r = 0.92$), taste ($r = 0.90$) and overall liking ($r = 0.77$). All formulations scored above the hedonic indifference threshold; F2 achieved the highest overall liking (7.35 ± 0.24), statistically indistinguishable from the control and significantly above F1 (6.27 ± 0.29). Carrot powder is therefore a technologically viable provitamin A carrier in chocolate at inclusion levels up to 10% of total mass.

Keywords

Functional Chocolate, Carrot Powder, Carotenoid Retention, Provitamin A, Proximate Composition, Consumer Acceptability

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1. Introduction

The prevention of diet-related non-communicable disease has become an explicit driver of product innovation across the food industry, and is reflected in the sustained expansion of the functional food sector, whose global market value was estimated at approximately USD 332 billion in 2024 and is projected to approach USD 638 billion by 2034 [1]. Developing foods enriched with bioactive ingredients nonetheless remains technically demanding, since it requires simultaneous control of the delivery vehicle, the stability of the added compound, and ingredient interactions during processing and storage [2]. Acceptability of such products is, in turn, strongly conditioned by the food matrix selected to carry the target compound [3].

Micronutrient deficiency is a pressing global nutrition problem that food-based fortification is well placed to address. Vitamin A deficiency continues to affect a substantial share of children in low- and middle-income countries, with a recent systematic review and modelling analysis estimating its prevalence at close to 20% among children aged 0 to 5 years and above 29% in low sociodemographic-index regions [4]; international monitoring confirms that only three-quarters of children requiring high-dose supplementation currently receive it [5]. Because vitamin A deficiency is the leading cause of preventable childhood blindness and materially increases mortality from common infections, food-based delivery of provitamin A carotenoids is recognised as a low-cost, sustainable complement to supplementation and biofortification programmes [6, 7].

Chocolate is itself widely regarded as a functional food [8] and has repeatedly proven an effective vehicle for bioactive fortification, successfully carrying omega-3 polyunsaturated fatty acids and probiotic cultures without compromising consumer acceptance [9, 10]. This suitability is not incidental. Chocolate is a lipid-continuous matrix, typically 35 to 45% fat, and dietary lipids promote the intestinal micellization, and hence the bioaccessibility, of lipophilic carotenoids far more effectively than aqueous or low-fat matrices [11, 12]. A fat-rich confectionery product is therefore, in principle, a more favourable vehicle for β-carotene than the raw vegetable, in which the compound remains sequestered within chromoplasts and a rigid cell wall that limits its release during digestion [12].

Carrot is a well-established dietary source of β-carotene and antioxidant compounds supporting visual function and immune competence, with reported carotenoid contents spanning 3.2 to 170 mg/kg depending on cultivar and growing conditions [13], while cocoa contributes energy and flavanols associated with cardiovascular benefit [8]. Combining the two is a logical strategy for a confectionery product that retains the sensory appeal of chocolate while addressing a documented micronutrient gap. Precedents exist for enriching confectionery and bakery matrices with plant-derived powders, including dark chocolate fortified with Nypa fruticans sugar [14], wheat germ [15] or cactus stem powder [16], and biscuits enriched with prickly pear cladode powder [17]; this literature has recently been reviewed by Abedini et al. [18]. Carrot powder, however, has not been evaluated in this way. No published study reports a multi-level incorporation series in milk chocolate characterised simultaneously for proximate composition, oxidative status and consumer acceptability, and none has examined whether the responses attributed to such a powder are separable from those of the cocoa butter and milk solids it displaces.

The present study therefore formulated milk chocolates enriched with carrot powder at three incorporation levels, benchmarked them against a non-enriched control, and characterised their proximate composition, oxidative status and consumer acceptability. Correlation analysis was used to identify which formulation variable best accounted for the observed differences. We hypothesised that carrot powder would raise β-carotene and moisture content dose-dependently, whereas changes in oxidative status and sensory quality would track cocoa butter content rather than carrot powder level.

2. Materials and Methods

2.1. Raw Materials

Cocoa paste, cocoa butter, whole milk powder, sugar, soy lecithin and carrot powder were purchased on the local market. The control chocolate was formulated with 300 g cocoa paste, 150 g cocoa butter, 247 g milk powder, 300 g sugar and 3 g lecithin, and contained no carrot powder. The proximate composition of the carrot powder used as the functional ingredient is presented in Table 1; its high fibre, mineral and β-carotene contents underpin its selection for chocolate enrichment.

Table 1. *Proximate composition of the carrot powder used as the functional ingredient.*

Component	Content
Moisture (%)	6.50 ± 0.51
Protein (%)	10.00 ± 1.53
Lipids (%)	2.20 ± 0.52
Ash (%)	6.00 ± 1.08
Fibre (%)	13.00 ± 2.01
Carbohydrates (%)	62.30 ± 3.00
Total carotenoids (mg/100 g)*	36.33 ± 0.10

Values are means ± standard deviation (n = 3). Carbohydrate content determined by difference. *Total carotenoids determined by visible spectrophotometry and expressed as β-carotene equivalents (Section 2.4).

2.2. Production of Carrot Powder

Carrot powder was produced according to the flow diagram presented in Figure 1. Raw carrots were received, sorted, washed, drained, weighed and peeled, then grated and dried to reduce moisture content and limit microbial activity. The dried material was ground and sieved to a fine, homogeneous powder, weighed to determine yield, then packaged, labelled and stored under conditions appropriate for preserving nutritional quality.

2.3. Chocolate Formulation and Processing

Enriched chocolates were formulated at three carrot powder incorporation levels, corresponding to 15%, 10% and 5% of the total batch mass for F1, F2 and F3 respectively; each batch totalled 1000 g. Expressed relative to the cocoa phase alone, that is the combined carrot powder, cocoa paste and cocoa butter mass, the same additions correspond to 27.3%, 18.2% and 10.0%. The complete formulation matrix is given in Table 2. Carrot powder content covaried with cocoa butter and milk powder content across formulations, a design feature that is addressed explicitly in Section 3.

Table 2. *Formulation matrix of the experimental chocolates (g per production batch).*

Ingredient	Control	F1	F2	F3
Carrot powder	0	150	100	50
Cocoa paste	300	300	300	300
Cocoa butter	150	100	150	150
Milk powder	247	147	147	197
Sugar	300	300	300	300
Lecithin	3	3	3	3

Chocolate manufacture followed the flow diagrams presented in Figures 2, 3 and 4 for F1, F2 and F3 respectively. Raw materials were received and weighed, and the mixture was conched to homogenise the paste and develop its organoleptic qualities, then tempered to promote formation of stable cocoa butter crystals and confer a smooth, crisp texture. Moulding and refrigeration promoted setting, after which the chocolate was demoulded, packaged, labelled and stored.

2.4. Chemical Analyses

Moisture, fat, ash, carbohydrate and protein contents were determined following AOAC [19] procedures. Moisture content was determined by forced-air oven drying at 105 ℃ to constant weight (Memmert 854, Schwabach, Germany). Nitrogen content was measured by the rapid Kjeldahl method (Labconco model 652, Labconco Corp., Kansas City, MO, USA), applying a conversion factor of 6.25 to obtain protein content. Ash content was determined by incineration in a muffle furnace (OSK405) at 550 ℃ for 4 h. Total lipid content was determined by Soxhlet extraction with chloroform-methanol (2: 1, v/v) on a 4 g sample, using a 4 h reflux at 40 to 60 ℃ with ISO-grade petroleum ether (Bracco, Milan, Italy). Carbohydrate content was calculated by difference.

The peroxide value was determined according to AFNOR [20]. Two grams of sample were weighed into a 100 mL flask with 10 mL chloroform, 15 mL glacial acetic acid and 1 mL saturated potassium iodide solution; the flask was sealed and held in the dark for 5 min before addition of 75 mL distilled water and starch indicator, and the liberated iodine was titrated with 0.01 N sodium thiosulfate against a parallel blank.

Total carotenoid content of the carrot powder and of the finished chocolates was determined by visible spectrophotometry and expressed as β-carotene equivalents following Rodriguez-Amaya and Kimura [21], with adaptations for the fat- and pigment-rich milk chocolate matrix. A weighed sample (approximately 5 g) was gently melted at or below 45 ℃ and saponified overnight under nitrogen in 10% (w/v) methanolic KOH containing 0.01% butylated hydroxytoluene, to remove cocoa butter and milk fat and release esterified carotenoids. Carotenoids were partitioned into petroleum ether (boiling point 40 to 60 ℃), washed to neutrality, dried over anhydrous sodium sulfate and purified on a short neutral-alumina column retaining polar cocoa interferents while eluting the carotene fraction. Absorbance of the purified eluate was read at 450 nm against a petroleum ether blank, with dilution as needed to keep absorbance at or below 0.8. Total carotenoid content was calculated as $C = (A \times V \times 10^4) / (A^{1\%}{}_{1cm} \times P)$, where V is extract volume (mL), P is sample mass (g), and $A^{1\%}{}_{1cm}$ is 2592, the specific absorptivity of β-carotene in petroleum ether [22]. Determinations were performed under subdued light in amber glassware, and method performance was verified by standard addition of authentic β-carotene prior to extraction. Following the reference procedure for carotenoid analysis in foods [21], the assay quantifies the total carotenoid fraction and expresses it in β-carotene equivalents. Values are therefore designated total carotenoids (as β-carotene equivalents) throughout, and the provitamin A calculation in Section 3.1 weights this fraction according to the α-carotene share established for orange carrot rather than treating it as pure β-carotene.

2.5. Sensory Evaluation

Sensory acceptability was assessed using a nine-point hedonic scale [23]. Thirty untrained consumer assessors aged 19 to 45 years were recruited among students and staff of Gamal Abdel Nasser University of Conakry, equally distributed between men and women. Assessors were briefed on the procedure and scoring system before evaluation, which took place at room temperature under white lighting, with panellists

seated to avoid mutual influence. Coded samples were presented in randomised order within a single session to control for order and position effects. Assessors rated colour, aroma, taste, texture, crispness and overall liking from 1 (disliked extremely) to 9 (liked extremely), with 5 representing the point of indifference. Water and bread were provided between samples to eliminate residual taste. All participants provided informed consent, and the protocol was approved by the Ethics Committee of the Department of Food Technology and Quality Control (TCPA), ISSMV Dalaba.

2.6. Statistical Analysis

Chemical analyses were performed in triplicate (n = 3) and sensory data were obtained from thirty assessors (n = 30). Data were analysed in IBM SPSS Statistics version 26 according to a completely randomised design. Treatment means for moisture, fat, protein, ash, carbohydrate, peroxide value, β-carotene and sensory scores were compared by one-way analysis of variance (ANOVA) followed by Tukey's honestly significant difference (HSD) post-hoc test at $\alpha = 0.05$. Significance is reported as a compact-letter display, with means sharing at least one common letter not differing at the 5% level. Pearson correlation coefficients were additionally computed between formulation-level variables (carrot powder and cocoa butter mass), physicochemical parameters and sensory scores, using formulation means as observations; given four observations, these coefficients are interpreted as descriptive pattern indicators rather than as formal hypothesis tests.

3. Results and Discussion

3.1. Proximate Composition and Oxidative Status

Moisture content increased significantly with carrot powder incorporation ($F = 24.87$, $p < 0.001$), rising from 0.41% in the control to between 1.77 and 2.15% in the enriched formulations, which did not differ significantly from one another (Table 3). This pattern is consistent with the hygroscopic behaviour of the hydroxyl-rich polysaccharide network, principally pectin and hemicellulose, that constitutes the carrot fibre fraction (13.0% in the raw powder; Table 1). These polymers present abundant hydrogen-bonding sites that retain free and bound water, raising equilibrium moisture content of the finished matrix relative to the low-moisture control; because no compensatory drying step followed carrot powder addition, this contribution is expressed directly in the finished product. All values nonetheless remained below the 3% ceiling set by the Codex Alimentarius for chocolate products [24]. The increase is technologically relevant, since elevated moisture raises water activity and may shorten microbiological and textural shelf life, a relationship that requires direct water activity and storage measurements to confirm.

Ash content did not differ significantly among formulations ($F = 1.04$, $p = 0.424$), ranging from 0.89 to 1.79%. Although the enriched formulations were numerically higher than the control, this difference did not reach significance under triplicate sampling. A plausible explanation is that the mineral contribution of carrot powder (6.0% ash; Table 1) is partly masked on a wet-weight basis by the concurrent and proportionally larger increase in moisture described above; expressing ash on a dry-matter basis would help separate a genuine mineral effect from this dilution artefact. This result is more conservative than that of Ramli et al. [14], who reported significantly higher ash values (1.83 to 2.11%) in chocolates enriched with Nypa fruticans sugar, and than Al-Marazeeq [15], who found that wheat germ enrichment significantly increased ash in dark chocolate. The discrepancy may reflect the smaller mineral contribution of carrot powder relative to those ingredients, the moisture dilution effect, or the limited power of a triplicate design. Msaddak et al. [17] similarly reported no significant change in protein, moisture, fat or total carbohydrate upon enrichment of biscuits with prickly pear cladode powder, but did observe a significant increase in ash and dietary fibre, a pattern the present chocolates did not reproduce.

Lipid content differed significantly among formulations ($F = 589.17$, $p < 0.001$), with the control lowest (37.89%), F1 intermediate (43.22%) and F2 and F3 highest (43.90% and 43.86%, not significantly different from each other). This pattern parallels cocoa butter content (100 g in F1 versus 150 g in the control, F2 and F3; Table 2) far more closely than carrot powder level, indicating that cocoa butter rather than carrot powder is the principal driver of lipid variation among the enriched formulations. Because cocoa butter crystallises predominantly as symmetrical monounsaturated triglycerides, mainly POP, POS and SOS species built on palmitic, oleic and stearic acids, its proportion governs not only total lipid content but also the crystalline polymorphism determining snap, gloss and melting behaviour [25], providing a mechanistic link to the sensory results discussed in Section 3.2. All lipid values remained within the range reported by Afoakwa et al. [25] for dark chocolate (34 to 45%).

Protein content differed significantly among all four formulations ($F = 718.15$, $p < 0.001$), every pairwise comparison being significant, and ranked control (10.11%) above F3 (9.32%), F1 (9.04%) and F2 (8.54%). This ordering is not monotonic with carrot powder level and instead follows milk powder content (247, 197, 147 and 147 g respectively), with which protein was very strongly correlated ($r = 0.945$). Whole milk powder, at approximately 25 to 26% protein, is by a wide margin the most protein-dense component of the recipe, so formulations receiving less of it are correspondingly lower in protein. That F1 nevertheless exceeded F2 despite identical milk powder contents is explained by the additional protein contributed by its larger carrot powder addition, since carrot powder supplies 10.0% protein (Table 1) whereas the cocoa butter it displaced supplies effectively none.

The direction of this effect merits emphasis for formulation

practice: because carrot powder is markedly less protein-dense than the milk powder and cocoa mass it partly displaces, its incorporation lowers rather than raises the protein content of the finished chocolate. This contrasts with Angor et al. [16], who reported significantly increased protein, ash and fibre when cactus stem powder was added to chocolate, and with Al-Marazeeq [15], who observed higher protein following wheat germ fortification of dark chocolate. In both of those studies the plant material was protein-rich relative to the matrix, whereas here the substitution operates in the opposite direction, illustrating that the nutritional consequence of plant powder enrichment depends on the composition of the ingredient displaced as much as on that of the ingredient added.

Carbohydrate content, calculated by difference and therefore inclusive of dietary fibre, was significantly lower in all three enriched formulations (44.04, 44.10 and 43.48% for F1, F2 and F3) than in the control (50.70%; $F = 55.31$, $p < 0.001$), with no significant differences among the enriched samples. This reduction of approximately 7 percentage points is accounted for principally by the concurrent rise in lipid content, which increased by 5.3 to 6.0 percentage points across the same formulations, together with smaller contributions from the increases in moisture and protein-bearing ingredients. Sugar addition was held constant at 300 g in every batch, so the decrease reflects dilution of the sugar and lactose fraction by the fat phase rather than any reduction in added sugar.

Peroxide values differed significantly among formulations ($F = 12.46$, $p = 0.002$) but did not follow a pattern attributable to carrot powder content. Formulation F1, which contained the highest carrot powder level, grouped with the control at the lower end (1.25 and 1.74 meq O_2/kg), whereas F2 and F3, containing less carrot powder, formed a significantly higher group (4.24 and 3.74 meq O_2/kg). This ordering tracks cocoa butter content rather than carrot powder level. Mechanistically, lipid autoxidation proceeds through a free-radical chain reaction in which unsaturated fatty acyl chains, chiefly the oleic and linoleic moieties of cocoa butter triglycerides, undergo hydrogen abstraction and react with molecular oxygen to form the hydroperoxides quantified by this assay [26]. A larger cocoa butter fraction therefore supplies a proportionally larger pool of oxidisable substrate, which accounts for the higher values in F2 and F3. A secondary hypothesis is that the carotenoid pigments concentrated in F1 exerted a radical-scavenging effect partly offsetting its oxidative substrate load, consistent with the established capacity of carotenoids to quench peroxyl radicals [26]; distinguishing this from simple substrate dilution would require a direct antioxidant capacity assay such as DPPH or FRAP. Since the present formulations were not designed as a single-variable substitution series, these data establish that the chocolates differ significantly in oxidative status along a cocoa-butter-dependent pattern, but cannot isolate a causal contribution of carrot powder. Peroxide value and moisture were determined once, immediately after production, so these results describe initial oxidative and hygroscopic status rather than behaviour over storage.

Total carotenoid content, expressed as β-carotene equivalents, increased significantly and dose-dependently with carrot powder addition ($F = 3512.72$, $p < 0.001$), reaching 4.55, 3.08 and 1.45 mg/100 g in F1, F2 and F3 against none detected in the control, with every pairwise comparison significant. Referring these contents to the carotenoid concentration of the raw powder (36.33 ± 0.10 mg/100 g; Table 1) and to the carrot powder mass fraction of each batch gives apparent processing retentions of 83.5%, 84.8% and 79.8% for F1, F2 and F3 respectively, a mean of 82.7 ± 2.6%. Retention showed no systematic trend with incorporation level, indicating that pigment loss is governed by the thermal and oxidative history shared by all three batches rather than by the quantity of powder added. The mean loss near 17% is consistent with thermal isomerisation of all-trans β-carotene to less bioactive cis isomers together with oxidative degradation of the conjugated polyene chain during conching and tempering, mechanisms analogous to the autoxidation pathway discussed above and consistent with the established thermolability and photolability of carotenoids in processed foods [22]. That recovered pigment tracks added pigment closely across a threefold range of incorporation further indicates homogeneous dispersion of the powder through the fat-continuous matrix.

Converting these contents to retinol activity equivalents requires the composition of the carotenoid fraction to be taken into account. Applying the 12: 1 conversion factor for dietary β-carotene from plant sources [27] to the whole carotenoid fraction, a 30 g portion of F1, F2 and F3 would supply approximately 113.8, 77.0 and 36.2 μg RAE. These figures are upper bounds, since they treat every measured carotenoid as β-carotene. In orange carrot, α-carotene typically accounts for roughly 30% of the provitamin A carotenoids by mass [28, 29] and carries half the provitamin A activity of β-carotene, a 24: 1 conversion factor [27], while γ-carotene and lutein contribute little or nothing. Weighting the fraction accordingly lowers the estimates by about 15%, to approximately 97, 66 and 31 μg RAE per 30 g portion, equivalent to roughly 11 to 14%, 7 to 9% and 3 to 4% of the adult recommended dietary allowance (900 μg RAE per day for men, 700 μg RAE per day for women) [27]. Weighting the fraction in this way avoids the systematic overestimation of vitamin A activity that arises when a mixed carotenoid pool is treated as pure β-carotene, and these composition-weighted estimates are the ones cited elsewhere in this work. Both calculations estimate ingested rather than absorbed dose. Because chocolate is a lipid-continuous matrix, carotenoids released during digestion are expected to partition efficiently into mixed micelles, the step widely reported to be rate-limiting for carotenoid absorption from plant foods [11, 12]; the finished chocolate may therefore support a higher fractional bioavailability of β-carotene than raw carrot powder or an aqueous carrot-based food, a proposition testable by in vitro digestion assay. These results provide the first direct analytical support for the provitamin A rationale motivating carrot powder incorporation.

Table 3. Proximate composition and oxidative status of the chocolates produced.

Parameter	Control	F1	F2	F3	F	p
Moisture (%)	0.41 ±0.31 b	1.91 ±0.28 a	1.77 ±0.33 a	2.15 ±0.11 a	24.87	< 0.001
Ash (%)	0.89 ±0.87 a	1.79 ±0.71 a	1.69 ±0.39 a	1.19 ±0.81 a	1.04	0.424
Lipid (%)	37.89 ±0.21 c	43.22 ±0.31 b	43.90 ±0.12 a	43.86 ±0.13 a	589.17	< 0.001
Protein (%)	10.11 ±0.06 a	9.04 ±0.04 c	8.54 ±0.04 d	9.32 ±0.02 b	718.15	< 0.001
Carbohydrate (%)	50.70 ±0.95 a	44.04 ±0.82 b	44.10 ±0.53 b	43.48 ±0.83 b	55.31	< 0.001
Peroxide (meq O_2/kg)	1.74 ±0.76 b	1.25 ±0.91 b	4.24 ±0.41 a	3.74 ±0.71 a	12.46	0.002
Total carotenoids (mg/100 g)	0.00 ±0.00 d	4.55 ±0.06 a	3.08 ±0.09 b	1.45 ±0.04 c	3512.72	< 0.001

Values are means ± standard deviation (n = 3). Within a row, means sharing at least one common letter do not differ significantly (Tukey's HSD, $\alpha = 0.05$). F statistics have 3 and 8 degrees of freedom. Carbohydrate was calculated by difference and includes dietary fibre; its dispersion was obtained by propagation of the standard deviations of the measured fractions. Total carotenoids are expressed as β-carotene equivalents (Section 2.4).

3.2. Sensory Acceptability

All samples scored above the sensory indifference threshold of 5 on the nine-point hedonic scale, with mean scores ranging from 5.66 ±0.34 to 7.66 ±0.23 (Table 4), confirming that carrot powder incorporation did not impair overall perception of the chocolate. Colour and texture did not differ significantly among the four samples, indicating that carrot powder at the levels tested did not detectably alter these attributes. This is consistent with the pale orange hue contributed by β-carotene being largely masked by the dominant brown of the cocoa solids, and with the modest mass fractions of carrot powder (5 to 15%) relative to the total recipe.

For aroma, taste, crispness and overall liking, formulation F2 achieved the highest mean score in every case and was significantly superior to F1 on all four attributes, while the control and F3 occupied intermediate positions not significantly different from either. Formulation F2 recorded the highest overall liking (7.35 ± 0.24), significantly above F1 (6.27 ± 0.29) and statistically indistinguishable from the control (6.85 ±0.27). A plausible technological explanation is that F2 combines a high cocoa butter content, equal to the control, with a moderate carrot powder level: the cocoa butter fraction supports the polymorphic crystallisation responsible for a crisp bite and clean melt [25], while moderate carrot powder addition delivers a measurable β-carotene and fibre contribution without the higher moisture load observed in F1.

Formulation F1, which combined the highest carrot powder level with the lowest cocoa butter level, obtained the lowest or joint-lowest score on most attributes. Because moisture interferes with the crystalline network and mouthfeel of chocolate, and because a reduced cocoa butter fraction independently limits crisp, glossy structuring, this sensory pattern is at least as consistent with F1's lower cocoa butter content and higher moisture as with its carrot powder level. Formulation F3, despite the second-highest peroxide value, was not sensorially distinguishable from the control on any attribute, indicating that the oxidative differences described in Section 3.1 were not perceptible at this time point, most likely because the absolute peroxide values recorded remained well below the level at which secondary oxidation products become organoleptically detectable as rancidity.

Table 4. Sensory acceptability scores of the chocolates produced.

Attribute	Control	F1	F2	F3
Aroma	6.83 ±0.27 ab	5.86 ±0.34 b	7.00 ±0.30 a	6.53 ±0.26 ab
Colour	7.30 ±0.18 a	6.76 ±0.24 a	7.40 ±0.18 a	6.96 ±0.21 a
Taste	6.80 ±0.28 a	5.66 ±0.34 b	7.46 ±0.23 a	6.73 ±0.24 a
Texture	7.00 ±0.28 a	6.60 ±0.28 a	7.23 ±0.26 a	6.30 ±0.24 a
Crispness	6.30 ±0.32 b	6.47 ±0.25 b	7.66 ±0.23 a	6.83 ±0.27 ab

Attribute	Control	F1	F2	F3
Overall liking	6.85 ±0.27 ab	6.27 ±0.29 b	7.35 ±0.24 a	6.67 ±0.24 ab

Values are means ± standard error (n = 30 assessors). Within a row, means sharing at least one common letter do not differ significantly (Tukey's HSD, α = 0.05).

3.3. Relationship Between Formulation Variables, Composition and Sensory Response

Because carrot powder, cocoa butter and milk powder varied simultaneously across formulations, Pearson correlation coefficients were computed across formulation means to identify which variable best accounted for the observed responses (Table 5). Cocoa butter mass correlated strongly and positively with aroma (r = 0.92), taste (r = 0.90) and overall liking (r = 0.77), whereas carrot powder mass correlated negatively and more weakly with the same attributes (r = -0.63, -0.47 and -0.31 respectively). This supports the interpretation developed in Section 3.2, namely that the lower sensory scores of F1 more plausibly reflect its comparatively low cocoa butter content than a direct sensory penalty attributable to carrot powder.

Milk powder mass and protein content, by contrast, were weak or negative covariates of the hedonic attributes, protein correlating negatively with crispness (r = -0.81) and showing essentially no relationship with overall liking (r = -0.28). Protein content in this system is therefore a marker of the milk phase rather than a determinant of sensory quality, and the significant compositional differences in protein reported in Section 3.1 carried no detectable hedonic penalty.

Peroxide value correlated positively with crispness (r = 0.87), taste (r = 0.80) and overall liking (r = 0.73), indicating that formulations with higher peroxide values were, at this initial time point, also the better liked. This apparent paradox resolves once peroxide value is recognised as a proxy for cocoa butter content in the present design: panel preference was driven by texture and flavour attributes associated with cocoa butter crystallisation, not by any perceptible rancidity. It nonetheless underscores that oxidative and sensory quality must be tracked independently, and over time, since the favourable initial sensory profile of the higher-fat formulations coexists with a larger pool of oxidisable substrate. β-Carotene content, being set by carrot powder mass at formulation (r = 0.9997), closely mirrored the carrot powder correlations.

Taken together, these relationships indicate that carrot powder can be incorporated at up to 10% of the total batch mass, equivalent to 18.2% of the cocoa phase, without sensory penalty, provided cocoa butter is not reduced concurrently. Isolating the effect of carrot powder itself will require a single-variable substitution series in which cocoa butter and milk powder are held constant, complemented by direct antioxidant capacity assays, in vitro bioaccessibility measurement and storage trials monitoring peroxide value, water activity and β-carotene retention over shelf life.

Table 5. *Pearson correlation coefficients between formulation and physicochemical variables and sensory attributes.*

Variable	Aroma	Taste	Crispness	Overall liking
Carrot powder (g)	-0.63	-0.47	0.29	-0.31
Cocoa butter (g)	0.92	0.90	0.38	0.77
Milk powder (g)	0.36	0.16	-0.58	0.01
Moisture (%)	-0.41	-0.17	0.46	-0.19
Protein (%)	0.07	-0.16	-0.81	-0.28
Peroxide value	0.63	0.80	0.87	0.73
Total carotenoids (mg/100 g)	-0.61	-0.46	0.29	-0.29

Coefficients computed on formulation means (control, F1, F2, F3; n = 4) and interpreted as descriptive pattern indicators.

4. Conclusion

Carrot powder incorporation increased total carotenoid content in milk chocolate dose-dependently, at a mean apparent processing retention of 82.7 ±2.6% that was independent of incorporation level, alongside a significant increase in moisture and no significant change in ash. Protein decreased significantly with enrichment, tracking the milk powder fraction rather than the carrot powder itself and confirming that plant powder enrichment lowers protein whenever the added ingredient is less protein-dense than the material it displaces. Lipid content and peroxide value likewise tracked cocoa butter rather than carrot powder level, and correlation analysis identified cocoa butter mass as the stronger covariate of aroma, taste and overall liking, indicating that the sensory differences among formulations arose principally from fat phase composition rather than from the added vegetable powder. Incorporation at 10% of the total batch mass delivered the best sensory performance, statistically indistinguishable from the non-enriched control while supplying an estimated 7 to 9% of the adult recommended dietary allowance for vitamin A per 30 g portion. Carrot powder therefore represents a technologically

feasible and sensorially acceptable provitamin A carrier for functional confectionery aimed at populations vulnerable to vitamin A deficiency, with the fat-continuous chocolate matrix offering a potential bioaccessibility advantage that warrants direct measurement.

Abbreviations

ANOVA	Analysis of Variance
AOAC	Association of Official Analytical Chemists
HSD	Honestly Significant Difference
RAE	Retinol Activity Equivalent
RDA	Recommended Dietary Allowance
SD	Standard Deviation

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Data Availability Statement

The data supporting the outcome of this research work has been reported in this manuscript. Additional data are available upon request to the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

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