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Development dark chocolate enriched with mangrove leaf powder (*Sonneratia alba*): Physico-chemical properties, antioxidant activity, and sensory quality

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Abstract

The incorporation of mangrove leaf powder into food systems offers an emerging strategy for enhancing the functional value of confectionery products. This study evaluated the effects of *Sonneratia alba* (*S. alba*) mangrove-leaf powder on the physicochemical properties, antioxidant capacity, and sensory quality of dark chocolate. Leaves were processed into fine 60-mesh powder and added at concentrations of 0–5.5% (w/w). The analytical assessments included moisture content, total phenolic content (TPC), antioxidant activity using the DPPH method, CIELAB colour parameters, texture hardness, and consumer acceptance. The product underwent enrichment with *S. alba* produced significant ($p < 0.05$) increases in TPC (49.06–64.37 mg GAE/g) and antioxidant activity (60.45–69.45%). A strong linear relationship between TPC and DPPH inhibition (R^2 = 0.934) indicated that phenolics contributed directly to enhanced radical-scavenging performance. Colour measurements showed elevated a* and b* values with increasing leaf concentration, reflecting intensified red–yellow chromaticity from plant pigments. Meanwhile, hardness decreased from 135.33 to 98.95 g/F, suggesting that fibre components disrupted fat crystallisation and softened the chocolate matrix. Sensory evaluation demonstrated that intermediate enrichment levels (4.5%–5.5%) provided the most favourable consumer responses, yielding the highest scores for flavour, texture, and overall acceptance. Collectively, these results indicate that *powder from S. alba leaves* serves as an effective natural fortifying agent capable of improving the functional profile of dark chocolate without compromising sensory desirability. The findings highlight opportunities to use mangrove biomass as a sustainable, phenolic-rich ingredient for developing clean-label, functional chocolate products.

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1. Introduction

Dark chocolate is recognized as a functional food because of its high cocoa polyphenol content, which contributes to antioxidant activity and potential health benefits. However, conventional formulations often rely solely on cocoa solids and sugar, with limited exploration of additional plant-based bioactive. Dark chocolate is regarded as an essential food because of its anti-diabetic, anti-inflammatory, and anti-microbial attributes. It also has a recognised function in weight control and the modification of a lipid profile towards a healthier state. However, the processing of dark chocolate results in the loss of various elements, including polyphenols, flavonoids, ascorbic acid, and thiamine. The distinctive blend of nutritional and hedonic value renders dark chocolate an ideal instance of a food that connects pleasure and health (1–3).

The chocolate production process—comprising fermentation, drying, roasting, grinding, refining, and conching—significantly affects the final composition, as high temperatures can degrade heat-sensitive compounds such as polyphenols, flavonoids, ascorbic acid, and other vitamins. While fermentation is essential for flavour enhancement, it can reduce overall polyphenol levels by up to 80% through enzymatic oxidation, illustrating the trade-off between sensory improvement and nutritional loss (4). To mitigate these losses, research has explored functional fortification with plant-derived bioactive—such as fruit peels, seeds, algae, and herbal extracts—to boost antioxidant activity, enrich flavour complexity, and enhance textural qualities (5,6).

Recent years have seen increasing interest in enriching dark chocolate with phenolic-rich plant ingredients to enhance both functional properties and flavour complexity, with additions such as grape seed powder, matcha, moringa, green coffee, and spirulina being shown to elevate antioxidant levels while introducing distinctive sensory notes (1,2,7,8). This trend aligns with sustainability goals by utilising agro-industrial byproducts and underused plant resources, although excessive fortification can compromise chocolate's delicate flavour balance and smooth texture, making dosage optimisation essential. Within this context, mangrove species—particularly *Sonneratia alba*—have emerged as promising novel sources of polyphenolic antioxidants, as these plants naturally accumulate high levels of flavonoids, tannins, and carotenoids due to their adaptation to saline and oxidative stress. These bioactive metabolites contribute antioxidant, antibacterial, anti-inflammatory, and antidiabetic functions when consumed, broadening their potential as functional food components (9,10). Phytochemical studies further show that *S. alba* leaves contain substantial phenolic content, reaching up to 120 mg GAE/g extract, and display strong DPPH radical-scavenging activity, supporting their suitability for incorporation into functional chocolate formulations (11).

The incorporation of *S. alba* leaf powder into dark chocolate provides an opportunity to combine health benefits with sustainable resource utilisation, particularly as Indonesia's extensive mangrove ecosystems remain underutilised and much of their biomass is discarded as waste. Converting this biomass into functional food ingredients supports environmental conservation, strengthens coastal communities' livelihoods, and aligns with national and global movements towards plant-based, natural, and clean-label products. Beyond its metabolic advantages, *S. alba* can also influence sensory qualities, as its polyphenols and pigments—such as chlorophyll and carotenoids—intensify chocolate's colour and create a richer visual appearance while contributing subtle herbal aromas that may refine flavour complexity (12,13). Its dietary fibre content has the potential to modify texture by softening the chocolate matrix and enhancing the mouthfeel, making the ingredient valuable for both functional and sensory innovation. These combined effects emphasise the value of evaluating *S. alba* fortification not only for its bioactive contribution but also for its overall impact on consumer acceptability (14,15).

Research on polyphenol fortification in chocolate indicates that modest levels of inclusion can improve overall acceptance by adding complex bitterness and a more robust scent, as long as the concentration stays below the sensory threshold. Previous researchers indicated that the incorporation of phenolic-rich plant powders into chocolate enhanced antioxidant capacity while preserving an advantageous sensory equilibrium, particularly regarding colour and texture (16–18).

This study aims to assess the effect of incorporating *S. alba* leaf powder on the antioxidant capacity and sensory quality of dark chocolate. The study examined total phenolic content (TPC), DPPH radical inhibition, and hedonic sensory attributes—color, texture, taste, scent, and overall acceptance—utilizing a semi-trained panel. The connection between TPC and antioxidant inhibition was assessed to clarify the relationship between bioactive content and functional efficacy. This study's findings aim to offer significant insights into the creation of nutritionally enhanced, sustainable, and consumer-acceptable dark chocolate formulations. This effort not only addresses the necessity for antioxidant enhancement but also promotes local resource valorisation through the unique use of mangrove plants in food systems, thereby contributing to ecological sustainability, food security, and diversity of functional products.

2. Materials and Methods

2.1. Materials

Fresh *S. alba* leaves were collected from Tanjung Jabung Timur Regency, Jambi, Indonesia. Leaves were washed, shade-dried to 10% moisture, ground, and sieved (60-mesh) to obtain fine powder. Additional materials utilised were ethanol, folin-ciocalteu reagent, 7% sodium carbonate (Na_2CO_3), gallic acid, methanol, aluminium chloride ($AlCl_3$), sodium acetate, distilled water, quercetin, DPPH, ascorbic acid. The Instruments and equipment that are used includes Texture analyser with cylindrical probe (type TA10SS, 12.7 mm in diameter), rotary evaporators, hotplates, magnetic stirrers, 60 mesh sieves, Whatman filter paper, analytical balances, and UV-Vis spectrophotometers:

2.2. Production of Mangrove leaf powder

Selected mangrove leaves (*S. alba*) are washed with running water and subsequently sun-dried till their moisture content reaches 10%. The subsequent step involves grinding the mangroves leaves with a blender and filtering the mixture through a 60 mesh sieve to obtain evenly fine mangrove leaves powder.

2.3. Dark Chocolate Production

The production of dark chocolate commenced with the precise measurement of all components in accordance with the previous research (17). The product was formulated with cocoa butter, cocoa powder, sugar, lecithin, and vanilla, incorporating *S. alba* leaf powder at quantities of 0–5.5% (w/w). The preparation method was modified from (17), wherein the fat phase was preheated before the sequential incorporation of cocoa powder, sugar, lecithin, vanilla, and *S. alba* powder. Cocoa butter is initially heated to 50°C for 15 minutes in a stainless steel vessel over boiling water until it transforms into liquid form. Subsequently, all components, including cocoa butter, cocoa powder, vanilla, lecithin, granulated sugar, and the *S. alba* powder, are uniformly combined in a conching machine and agitated until thoroughly homogenised. The resulting mixture goes through to a conching process at 40°C for an average of 5 hours. Upon completion of this operation, the Dark Chocolate mixture subsequently undergoes tempering. The tempering process commences with heating to 45°C for 10 minutes, followed by a reduction to 26°C for 10 minutes, and subsequently an increase to 31°C for 10 minutes, with constant stirring during the tempering. Upon completion of tempering, the chocolate is promptly poured into moulds utilising chocolate moulds. After that, the printing is done with a chocolate mold and the chocolate is cooled in the refrigerator (5°C) until it hardens in a few hours and resulting in the final dark chocolate product.

2.4. Moisture Content

The moisture content in the blanched samples was tested with the oven method (19). A total of 2 g of the samples was placed in a cup and dried in an air dryer to a constant weight (105 °C). The content of the powder was calculated using the formula:

$$\text{The moisture content}=\frac{B-C}{B-A}x100\% \qquad (1)$$

Information:
A = weight of the cup (g)
B = weight of cup and sample before drying (g)
C = weight of cup and sample after drying (g)

2.5. Determination Total Phenol

Total phenol content was measured using the colorimetric method Folin-Ciocalteu (20) with modified. the sample of 200 µl was put into the test tube. Then 1 mLof Folin-Ciocalteu 10% solution was added and leave it for 1 minute, next 3 mL of Na_2CO_3 20 % was added. Furthermore, stored in a dark room at room temperature for 2 hours. Finally, the absorbance was measured with a UV-Vis spectrophotometer at a wavelength of 760 nm. Total phenol is determined based on a standard curve of gallic acid and expressed as mg gallic acid equivalent per gram of chocolate (mg GAE / g sample).

2.6. Determination Antioxidant Activity

The test was carried out according to Todorovic *et al*., (21) with some modifications by weighing 4 g of dark chocolate sample using an analytical balance, then heating it using a tempering tool and placing it in a screw tube. The sample is dissolved with 96% ethanol. Then the solution was homogenized using a vortex. After that, the solution was centrifuged for 10 minutes at 3000 rpm. Take as much as 0.2 mL of the supernatant and put it in a closed test tube that has been filled with 3.8 mL of DPPH solution. The mixed solution was then homogenized using a vortex and stored for 30 minutes in a dark room. Absorption was measured using a UV-Vis spectrophotometer at a wavelength of 517 nm. The absorbance data obtained is used to determine the % inhibition. The DPPH ability of the extract is calculated by the following formula:

$$AA(\%)=\frac{(A_{control}-A_{sample})}{A_{control}}x100\% \qquad (2)$$

Information:
AA = Antioxidant Activity Value (%) *dark chocolate* sample solution in 96% ethanol reacted with DPPH solution in 96% ethanol
A control = Absorbance of standard solution

2.7. Determination of Color profile

Colour measurements were conducted via a CR-20 Minolta colorimeter (Tokyo, Japan). The device assesses colour characteristics according to the sample's surface reflectance. For each measurement, a dark chocolate sample was positioned on the receptor region, and the measurement button was activated to acquire colour values. The recorded characteristics comprised L* (lightness), a* (redness/greenness), and b* (yellowness/blueness), adhering to the CIE Lab* colour space standard. In this colour space, L* denotes lightness, spanning from 0 (black) to 100 (white); a* signifies the red-green axis, where negative values denote green and positive values denote red; and b* indicates the yellow-blue axis, with negative values representing blue and positive values representing yellow.

All measurements were conducted in triplicate. The acquired L*, a*, and b* values were subsequently utilised to ascertain the associated hue and colour description via the Colour Hexa database (www.colorhexa.com). This method facilitates the objective quantification of colour differences arising from the incorporation of *S. alba* powder in dark chocolate compositions (22).

2.8. Texture Analysis

The hardness of dark chocolate samples was assessed using a texture analyser (Stable Micro Systems, 2005). Hardness was quantified in gram force (gF), signifying the pressure necessary to distort the material. Each dark chocolate sample was positioned on the support table plate, and the start button was engaged during the measurement. The cylindrical probe (type TA10SS, 12.7 mm in diameter) autonomously identified the sample surface prior to exerting compression at a constant velocity of 5 mm/s to a penetration depth of 5 mm. The peak force measured during compression was shown on the instrument panel and indicated in gF units, denoting the sample's hardness value (23).

2.9. Sensory Analysis

Sensory attributes are critical variables of the acceptability and consumer preference for a food product. The evaluation of these characteristics is conducted through the integrated perception of the five human senses—sight, touch, smell, taste, and, to a lesser degree, hearing—facilitating a thorough assessment of product quality characteristics. This study employed sensory evaluation through hedonic (liking) and hedonic quality tests to assess panellist responses to the colour, texture, taste, and aroma of dark chocolate enhanced with *S. alba* leaf powder. A questionnaire functioned as the evaluative tool, comprising predefined rating scales that panellists utilised to assess their level of preference.

Twenty-five semi-trained panellists from the students of Agricultural Product Technology Study Program, Faculty of Agriculture at Universitas Jambi participated in the test. All panellists were habitual chocolate consumers and had become familiar with the evaluation protocol before testing. The sensory evaluation utilised a 7-point hedonic scale, with 1 indicating extremely disliking and 7 indicating extreme liking, as per the guidelines of ISO 4121:2003 and ASTM E1871-09 for consumer acceptability assessment. Each panellist assessed the coded samples in regulated conditions (temperature 25 ± 2 °C; neutral white illumination) to reduce bias (24).

2.10. Statistical Data Analysis

The data were collected and tabulated in Microsoft Excel 2013. ANOVA was applied to obtain the effect of the treatment. The ANOVA tests were followed by Duncan New Multiple Range Test (DNMRT) post-test if the significant difference was presented at ($p < 0.05$).

2. Results and Discussion

3.1. Moisture Content

The incorporation of *S. alba* leaf powder did not significantly affect ($p > 0.05$) the moisture content of dark chocolate samples, which remained stable within the range of 2.16–2.53%. Table 1 presents the moisture content of dark chocolate with incorporating various quantities of mangrove leaf powder.

The average moisture content demonstrated a reduction in the resultant dark chocolate as the concentration of mangroves leaf powder increased. Nevertheless, the treatment with mangroves leaf powder did not significantly influence the moisture content of the dark chocolate.

The reduction of moisture content in dark chocolate is attributed to the active compounds in mangroves leaves, including tannins, flavonoids, and saponins, which have water-binding properties. Thus, an increased concentration of mangroves leaf correlates with a heightened release of water in the dark chocolate. A slight decrease at higher enrichment levels may be attributed to the water-binding capacity of polyphenolic compounds and dietary fibers present in *S. alba* leaves (25,26). Similar studies on phenolic-rich plant powders also reported reduced free moisture in chocolate matrices, indicating potential benefits for shelf-life stability.

Table 1. Moisture content of dark chocolate with incorporating various quantities of *S. alba* leaf powder

Addition *S. alba* Leaf Powder (%)	Moisture Content (%)
0	4.89 ± 3.06
1.5	2.46 ± 0.65
2.5	2.53 ± 0.39
3.5	2.23 ± 0.18
4.5	2.16 ± 0.06
5.5	2.50 ± 0.77

*ns = non-significant at 5% level of significance, * = Significant at 5% level of significance*

Moisture content is a crucial factor influencing chocolate quality and shelf life, as excessive water facilitates sugar bloom, fat migration, and microbiological proliferation, especially mould contamination. The Codex Alimentarius Standard for Chocolate and Chocolate Products (CODEX STAN 87-1981) provides that the maximum allowable moisture level in chocolate must not surpass 1.5–2.0%, based on formulation and processing circumstances. Maintaining low moisture guarantees product stability, prevents stickiness, and keeps optimal texture and lustre (26).

This study found that dark chocolate samples incorporating *S. alba* leaf powder at substitution levels of 1.5%, 2.5%, 3.5%, 4.5%, and 5.5% maintained moisture contents within an acceptable range, suggesting that the inclusion of mangrove leaf powder did not negatively impact the chocolate's physicochemical stability. The intrinsic fibre and polyphenol composition of *S. alba* may have facilitated modest water retention without undermining product dryness or integrity. Comparable results were reported by other researchers, who noted that the incorporation of phenolic-rich plant powders preserved satisfactory moisture levels in dark chocolate while improving its functional attributes (27). These results suggest that the inclusion of *S. alba* leaf powder may offer shelf-life benefits by limiting free water availability without compromising the structural integrity of the chocolate.

3.2. Total Phenol

The investigation indicates that the incorporation of *S. alba* leaf powder influences the total phenolic content of dark chocolate. The total phenolic content of dark chocolate with varying amounts of mangroves leaf powder is presented in Table 2 below.

Total phenolic content increased significantly ($p < 0.05$) from 49.06 mg GAE/g in the control to 64.37 mg GAE/g at 5.5% enrichment. This linear increment aligns with reports on the fortification of chocolates with polyphenolic compounds from fruits and plant-based powders, which enhance the functional bioactive profile (28). Given that *S. alba* leaves are rich in flavonoids, tannins, and phenolic acids, their incorporation substantially improves the nutraceutical value of the final product (28,29).

Table 2. Total Phenol content of dark chocolate with incorporating various quantities of *S. alba* leaf powder.

Addition *S. alba* Leaf Powder (%)	Total Phenol Content (mg GAE/g)
0	49.06 ± 1.98[a]
1.5	51.97 ± 1.29[b]
2.5	53.59 ± 0.96[c]
3.5	58.05 ± 1.38[d]
4.5	59.89 ± 2.03d[de]
5.5	64.37 ± 1.09[e]

Description: Numbers followed by different lowercase letters the same column, significantly different at the 5% level according to the Duncan multiple range test (DNMRT)

3.3. Antioxidant Activity

Antioxidant analysis of dark chocolate with *S. alba* leaf powder was performed utilising the DPPH method. The analysis of variance indicated that the incorporation of mangroves leaf powder considerably influenced the antioxidant activity of dark chocolate. The antioxidant activity values of dark chocolate with different concentrations of mangroves leaf powder are presented in Table 3.

Table 3. Antioxidant activity of dark chocolate with incorporating various quantities of *S. alba* leaf powder.

Addition *S. alba* Leaf Powder (%)	Inhibition (%)
0	60.45 ± 2.50[a]
1.5	63.79 ± 3.48[b]
2.5	64.86 ± 0.90[bc]
3.5	65.32 ± 0.77[cd]
4.5	67.78 ± 0.16d[de]
5.5	69.45 ± 0.21[e]

Description: Numbers followed by different lowercase letters the same column, significantly different at the 5% level according to the Duncan multiple range test (DNMRT)

Antioxidant capacity, assessed via the DPPH radical scavenging assay, rose significantly ($p < 0.05$) from 60.45% (control) to 69.45% (5.5% enrichment). Table 3 shows that the highest inhibition percentage, 69.45%, was observed with the addition of 5.5% mangroves leaf powder, whilst the lowest inhibition percentage, 60.45%, was observed with 0% *S. alba* leaf powder.

The antioxidant activity of the sample, regardless high or low, is determined by its inhibition percentage using the DPPH radical scavenging method. A greater inhibition percentage value of the sample correlates with increased antioxidant activity. This enhancement strongly correlates with TPC values since phenolic compounds act as hydrogen donors and free radical scavengers. Similar findings in phenolic-enriched chocolates confirm that antioxidant activity increases proportionally with polyphenol content (30,31,34). The antioxidant activity of dark chocolate increased with higher levels of *S. alba* leaf powder, indicating enhanced radical-scavenging capacity. Regression analysis between Total Phenolic Content (TPC) and % DPPH inhibition showed a strong positive correlation ($R^2 = 0.9662$; $y = 0.0025x+0.1641$), confirming that samples with higher phenolic content exhibited greater antioxidant activity. This relationship suggests that phenolic compounds—mainly flavonoids and tannins—derived from *S. alba* contributed significantly to the antioxidant potential of the product. Comparable findings were reported in phenolic-enriched chocolates (29,30,32).

3.4. Colour profile determination

Increasing *S. alba* levels significantly decreased lightness (L*) while enhancing redness (a*) and yellowness (b*) values ($p < 0.05$), producing a darker hue. These changes are attributed to natural pigments such as chlorophylls and carotenoids in *S. alba* leaves. Comparable studies have shown that plant-based additives darken chocolate color profiles, thereby influencing consumer perception and product appearance (31,34). The colour properties of dark chocolate with different concentrations of mangroves leaf powder are presented in Table 4 below.

Table 4. Color Value of dark chocolate with incorporating various quantities of *S. alba* leaf powder.

Addition Mangrove leaf Powder (%)	Value			Colour	Description
	L	a	b		
0	35.17	7.87^{c}	7.33^{c}		*Very Dark Grayish Orange*
1.5	32.00	5.93^{b}	5.93^{c}		*Very Dark Grayish Orange*
2.5	31.87	5.37^{b}	5.37^{b}		*Very Dark Grayish Orange*
3.5	29.60	4.93^{ab}	4.97^{b}		*Very Dark Grayish Orange*
4.5	29.27	4.37^{ab}	4.10^{ab}		*Very Dark Grayish Red*
5.5	27.80	2.27^{a}	3.80^{a}		*Very Dark Grayish Red*

Description: Numbers followed by different lowercase letters the same column, significantly different at the 5% level according to the Duncan multiple range test (DNMRT).

The analysis of colour variation indicated that treatment with *S. alba* leaf powder significantly influenced the a* (reddishness) and b* (yellowness) values of dark chocolate ($p < 0.05$). Nonetheless, it produced no significant effect ($p <0.05$) on the L* (brightness) value. The colour characterisation of dark chocolate, both without and with the incorporation of *S.*

alba leaf powder (1.5g, 2.5g, and 3.5g), was a very dark greyish orange. The colour characterisation of dark chocolate, enhanced with 4.5g and 5.5g of *S. alba* leaf powder, was a very dark greyish red.

The brightness value (L*) signifies the luminosity level of a product, where 0 denotes black and 100 denotes white. The lightness value denotes the darkness (brightness) of a colour. According to previous research (31). The hue of chocolate significantly influences its overall appearance and acceptance among consumers.

The colour profile of dark chocolate enriched with *S. alba* leaf powder showed a consistent darkening trend, as reflected by the decreasing L* values from 35.17 (control) to 27.80 at the highest enrichment level. Although the statistical analysis indicated that changes in L* were not significant ($p > 0.05$), the numerical decline suggests a downward tendency that aligns with visual darkening of the product. This apparent discrepancy between statistical insignificance and observable numerical change likely reflects variability within sample replicates that exceeded the threshold for statistical difference. Nonetheless, the direction of change is fully consistent with the known pigment composition of *S. alba* leaves, particularly chlorophylls and carotenoids, which absorb light and impart deeper green-brown tones to the chocolate matrix. In contrast, the a* and b* values showed statistically significant reductions, indicating decreased redness and yellowness that further contribute to the overall darker hue. Taken together, the instrumental colour data and the botanical pigment properties confirm that leaf powder incorporation systematically shifts the chocolate toward a darker and more muted colour, even where the L* changes did not reach statistical significance.

3.5. Texture Analysis

Texture greatly impacts the quality and consumer preference for dark chocolate. Hardness was quantified using a texture analyser that incrementally applies uniform pressure to the sample surface until penetration occurs. The maximum force necessary to deform the sample is indicative of its hardness value, measured in grammes of force (gF). This method reflects conventional instrumental techniques employed in food research, specifically for assessing chocolate texture. Table 5 below shows the texture test results for dark chocolate including varying amounts of *S. alba* leaf powder.

Table 5. Texture value of dark chocolate with incorporating various quantities of *S. alba* leaf powder.

Addition *S. alba* Leaf Powder (%)	Texture (gF)
0	135.33 ± 4.69^{e}
1.5	107.77 ± 2.77^{d}
2.5	102.43 ± 1.88^{cd}
3.5	101.67 ± 1.78^{bc}
4.5	$100.77 \pm 0.16d^{ab}$
5.5	98.95 ± 2.52^{a}

Description: Numbers followed by different lowercase letters the same column, significantly different at the 5% level according to the Duncan multiple range test (DNMRT)

The analysis of variance in the texture test showed that the addition of *S. alba* leaf powder significantly affected ($p < 0.05$) the texture of dark chocolate. Table 5 shows that the control treatment devoid of *S. alba* leaf powder exhibited the highest average texture value at 135.33 gF, while the treatment including 5.5 g of *S. alba* leaf powder recorded the lowest average texture value at 98.95 gF.

From Table 5 shows also that the texture score of dark chocolate generally decreases as the concentration of mangroves leaf powder increases. The reduction in the texture score is due to the decreased smoothness of the product resulting from the incorporation of mangroves leaf powder. The variation in texture is due to the incorporation of mangroves leaf, leading to various final product textures. An increased amount of mangroves leaf powder results in decreased smoothness of the dark chocolate. Texture hardness decreased significantly ($p < 0.05$) from 135.33 gF (0%) to 98.95 gF (5.5%), indicating a softer chocolate matrix at higher enrichment levels. This softening effect is likely due to leaf fiber particles disrupting the fat crystal network within the chocolate structure (31,33,34).

The reduction in hardness observed with increasing concentrations of *S. alba* leaf powder can be explained by the interaction of leaf-derived fibre particles with the cocoa butter crystal network. Although the powder was finely milled to a 60-mesh size, its incorporation increases the solid-phase volume fraction during the conching process described in Section 2.3, thereby elevating the yield stress and viscosity of the chocolate mass (though not measured in this study). This increases particle–particle interactions and reduces the efficiency of fat coating around solids during conching. As tempering proceeds, the presence of insoluble fibre interferes with the orderly formation of stable cocoa butter polymorphs—particularly the desirable β(V) crystals—by disrupting nucleation and inhibiting uniform crystal growth. Consequently, the final chocolate matrix becomes less cohesive, producing lower hardness values despite the increased viscosity observed during processing. This mechanistic explanation aligns with previous findings showing that plant fibres weaken the fat-crystal network and soften the final chocolate structure, even when processed using standard conching and tempering protocols (27,28,34).

3.6. Sensory Analysis

The acceptability of an ingredient by consumers is shaped by multiple criteria, with panellist acceptance serving as the ultimate evaluation for determining overall acceptance for colour, texture, and flavour. This evaluation seeks to determine the panellists' degree of acceptability about the incorporation of leaf powder into dark chocolate.

Research results and variance analysis show that the sensory attributes of dark chocolate enhanced with varying quantities of leaf. Table 6 shows the mean sensory test scores for the flavour, taste, colour, texture and overall acceptance of dark chocolate supplemented with *S. alba* leaf powder.

The sensory attributes of dark chocolate augmented with *S. alba* leaf powder were assessed via hedonic testing, including flavour, taste, colour, texture, and overall acceptance. The mean values in Table 6 and depicted on the radar chart (Figure 1) indicate that elevating the concentration of *S. alba* leaf powder led to a systematic improvement in all sensory qualities. The polygon expansion from P0 (control) to P5 (5.5%) on the radar map demonstrates that the addition of mangrove leaf powder enhanced product acceptability.

Table 6. The sensory attributes of dark chocolate with incorporating various quantities of *S. alba* leaf powder.

Addition *S. alba* Leaf Powder (%)	Flavour	Taste	Colour	Texture	Overall acceptance
0	3.96a ± 0.79	4.12a ± 0.93	4.36a ± 1.11	4.04a ± 0.79	4.12a ± 0.83
1.5	4.44b ± 0.65	4.36ab ± 0.76	5.04b ± 0.84	4.80b ± 0.82	4.40ab ± 0.91
2.5	4.72bc ± 0.54	4.60bc ± 1.00	5.36bc ± 0.57	5.24b ± 0.97	4.56bc ± 0.71
3.5	5.16c ± 0.47	4.84cd ± 0.80	5.60cd ± 0.76	5.76c ± 0.83	5.12d ± 0.93
4.5	5.36 cd± 0.86	5.20de ± 0.91	5.84de ± 0.90	6.04cd ± 0.73	5.24de ± 0.83
5.5	5.84d ± 0.90	5.56e ± 0.92	6.08e ± 0.86	6.28d ± 0.84	5.60e ± 1.00

Description: Numbers followed by different lowercase letters the same column, significantly different at the 5% level according to the Duncan multiple range test (DNMRT)

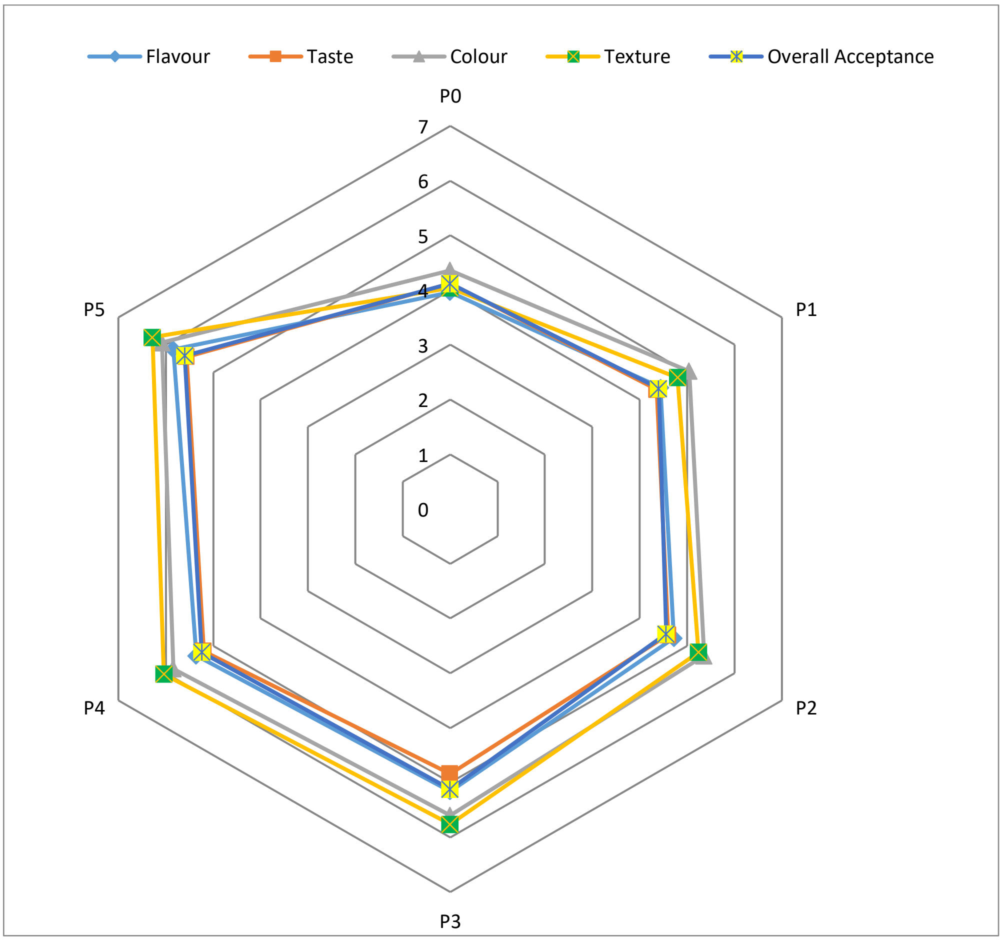

Figure 1. Spider web of sensory Attributes of dark chocolate supplemented with *S. alba* Leaf powder

Flavour and taste are critical factors influencing customer opinion of dark chocolate quality. The findings indicated a consistent increase in flavour and taste scores with the incorporation of *S. alba* powder, rising from 3.96 ± 0.79 and 4.12 ± 0.93 in the control group to 5.84 ± 0.90 and 5.56 ± 0.92 at the 5.5% concentration. This improvement is due to the polyphenolic compounds—such as flavonoids, tannins, and phenolic acids—in *S. alba* leaves, which interact with cocoa polyphenols to enhance the bitterness and aromatic complexity characteristic of premium dark chocolate. Comparable synergistic flavour enhancement was observed when phenolic-rich plant powders were included into chocolate compositions, augmenting depth and perceived antioxidant flavour without introducing off-notes. The moderate bitterness from *S. alba* phenolics enhances cocoa's inherent bitterness, resulting in a more sophisticated flavour profile that corresponds with consumer preferences for dark chocolate (35,36).

Colour significantly influences first consumer perception and is intricately associated with expectations of chocolate intensity. The hedonic colour scores rose from 4.36 ± 1.11 in the control group to 6.08 ± 0.86 at 5.5% substitution. The radar map corroborates this tendency, illustrating an outward displacement of the colour axis with each successive level. This enhancement is linked to the natural pigments—specifically chlorophylls and carotenoids—found in *S. alba* leaves, which contribute to a richer brown-green colouration. Prior research indicated that including chlorophyll-rich plant components enhanced the colouration of cocoa-based products while bolstering customer perceptions of naturalness and functional benefits (6). Furthermore, consumers frequently associate darker chocolate tones with elevated cocoa content and enhanced antioxidant properties (59). Consequently, the visual impact of *S. alba* leaf powder improves both the aesthetic appeal and perceived nutritional value of the product.

Texture indicates the tactile aspect of sensory assessment and profoundly affects overall acceptability. The average texture score rose from 4.04 ± 0.79 at P0 to 6.28 ± 0.84 at P5. The radar map indicates texture as a significantly growing parameter, denoting substantial enhancement. The dietary fibre content of *S. alba* leaves serves as a natural stabiliser and bulking agent in chocolate preparation. Fibres engage with fat and moisture, augmenting viscosity and facilitating the more uniform distribution of cocoa particles during conching. Similar findings by previous researchers who discovered that plant-derived fibres enhanced the consistency and mouthfeel of chocolate systems by stabilising the fat matrix. The fiber's ability to retain water enhances a creamy and dense texture, reducing the occurrence of fat bloom (36,37).

Overall acceptability encompasses consumer assessment of all sensory characteristics. The findings indicated a steady increase from 4.12 ± 0.83 in the control group to 5.60 ± 1.00 at 5.5% substitution, as corroborated by the expanded polygon on the radar graph. This pattern suggests that moderate to high levels of *S. alba* inclusion improved the overall sensory balance of dark chocolate without overshadowing its inherent cocoa essence. Excessive inclusion above this threshold may add herbal or astringent overtones, a limitations also identified in dark chocolate research (37,38). Thus, a concentration of roughly 4.5–5.5% ensures an ideal equilibrium between sensory enhancement and product stability.

The Spider web chart visualisation enhances the statistical analysis by demonstrating that *S. alba* supplementation yields balanced multidimensional enhancements across all sensory dimensions. These findings illustrate the dual capability of mangrove leaf powder as both a functional and sensory enhancer, confirming its application in sustainable confectionary innovation.

3. Conclusions

The addition of *S. alba* leaf powder in dark chocolate formulations considerably enhanced the sensory quality across all evaluated parameters. These enhancements arise from the presence of bioactive compounds that augment aromatic complexity and colouration, while dietary fibre facilitates a smoother texture and uniform mouthfeel. The antioxidant characteristics of these substances may enhance flavour stability and oxidative resistance, so augmenting both sensory enjoyment and functional significance. The ideal incorporation level ranges from 4.5% to 5.5%, providing a rich, balanced sensory profile clear of unpleasant bitterness. Thus, S. alba leaf powder exhibits significant potential as a natural, locally obtained functional component for sustainable confectionery innovation.

Further studies might investigate the relationship between specific polyphenol fractions and sensory chemistry, the antioxidant- flavour stability correlation during storage, and the industrial scalability of *S. alba* incorporation in chocolate systems.

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Author Contributions

A.N., M.M., M.L., and H.H. conceived and designed the experiments, and wrote the paper; I.L.T., R.A performed the experiments, analysed the data, interpreted the data and wrote the paper; R.I. performed the experiments; F.A, Y.C, B.B, H.W and E.K.S supported the writing of the paper.

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No conflict of interest.

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