

Valorization of over-mature *Moringa oleifera* pod powder as a functional ingredient in sambar powder

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Background: *Moringa oleifera* Lam. (drumstick) pods contain bioactive compounds, including glucosinolates, isothiocyanates, carotenoids, polyphenols, selenium, and sulfur-containing compounds. However, over-mature or firm pods are often underutilized and discarded as low-value agricultural residues. This study explored their potential as a value-added functional ingredient in sambar powder.

Methods: Sambar powder formulations were prepared with *M. oleifera* pod powder (MPP) at graded substitution levels of 0%, 5%, 10%, and 15% (w/w). Proximate composition, mineral content, in vitro antioxidant activity using DPPH radical scavenging and FRAP assays, total phenolic content, and sensory acceptability were evaluated using standard food science protocols and AOAC (2016) methods. Storage stability (moisture content and peroxide value) of the control (T0) and the 15% MPP formulation (T3) was assessed for six months under ambient conditions ($30 \pm 2^\circ\text{C}$ and $65 \pm 5\%$ relative humidity).

Results: The formulation containing 15% MPP (T3) showed significantly ($p \leq 0.05$) higher crude protein (17.86%), dietary fibre (15.33%), calcium (584 mg/100 g), iron (27.3 mg/100 g), and DPPH radical-scavenging activity (89.7%) compared with the control (T0). Sensory evaluation by 25 semi-trained assessors using a 9-point hedonic scale indicated adequate acceptance of T3. Six-month ambient storage data showed that T3 maintained lower moisture content and peroxide values than the control throughout the storage period.

Conclusion: The incorporation of over-mature *M. oleifera* pod powder into sambar powder demonstrates its potential as a value-added functional ingredient, with improvements in nutritional and antioxidant attributes while maintaining sensory acceptability; T3 also showed lower moisture content and peroxide values than the control during storage. The findings support the potential utilization of over-mature Moringa pods for functional food development and agricultural waste valorization.

Keywords: *Moringa oleifera*, functional food, sambar powder formulation, bioactive phytochemicals, antioxidant bioactivity, post-harvest valorization, nutritional enrichment, waste-to-value

Introduction

The global burden of micronutrient deficiency - colloquially termed "hidden hunger" - continues to afflict an estimated 2 billion individuals worldwide, predominantly in low- and middle-income countries across South and Southeast Asia (FAO, 2023). In the Indian subcontinent, dietary inadequacy is compounded by economic barriers to fresh produce consumption and the progressive erosion of traditional dietary diversity. Against this backdrop, functional food design - the deliberate incorporation of bioactive phytochemicals into habitually consumed staple preparations - has emerged as a pragmatic, cost-effective, and culturally acceptable strategy to augment population-level nutritional status (Goyal & Ramzan, 2022). *Moringa oleifera* Lam. (Family: Moringaceae), cultivated extensively across the tropical and subtropical belt of Asia and Africa, occupies a singular position in the ethnobotanical and nutritional pharmacopoeia of India (Fahey, 2005). Every anatomical compartment of this versatile species—leaves, flowers, seeds, bark, and pods has been documented to possess demonstrable therapeutic attributes. The immature pods, marketed as drumsticks in Indian cuisine, represent a routine culinary staple. However, firm or over-mature pods – those that have advanced beyond their commercial harvest window are routinely relegated to agricultural waste streams, despite reportedly containing bioactive compounds such as glucosinolates, isothiocyanates, beta-carotene, vitamin C, calcium, iron, and polyphenolic antioxidants (Anwar et al., 2007; Oyeyinka & Oyeyinka, 2018). Moringa leaves, in particular, have been extensively characterised for their nutrient and phytochemical composition (Leone et al., 2015), whereas pod-specific evidence, particularly for over-mature pods, remains comparatively limited. Sambar powder - a composite spice matrix foundational to South Indian culinary traditions - is consumed daily by hundreds of millions across peninsular India. This spice blend, typically formulated from coriander, red chilli, cumin, pepper, fenugreek, lentils, and aromatic leaves, serves not only as a flavor determinant but also as a dietary source of capsaicin, piperine, and essential minerals (Krishnaswamy, 2008). Leveraging this high daily-frequency consumption pattern to deliver moringa bioactive represents an evidence-based approach to dietary fortification that is aligned with prevailing food systems thinking (Tulchinsky, 2010; WHO, 2022). Despite a substantial body of literature validating the nutritional superiority of moringa leaf and seed preparations (Sreelatha & Padma, 2009; Mbikay, 2012; Jaiswal et al., 2013), the systematic investigation of over-mature moringa pod powder as a functional additive in composite spice matrices remains conspicuously underexplored. The present study addresses this scientific gap through a rigorously designed investigation encompassing proximate composition, mineral profiling, antioxidant bioactivity quantification, sensory evaluation, and six-month ambient storage stability of sambar powder formulations enriched with graded levels of *Moringa oleifera* pod powder. In doing so, this work advances both the applied science of functional food formulation and the broader paradigm of agri-food waste valorization.

Materials and Methods

Procurement and preparation of raw materials

Over-mature *Moringa oleifera* pods, identifiable by their characteristic fibrous, rigid texture and yellowing pericarpal surface, were procured from established growers in Sri Sathya Sai District, Andhra Pradesh, India, during the post-harvest season (February–March 2025). Pods were surface-cleaned, deseeded, sliced transversely into uniform segments (approximately 2–3 cm), and subjected to tray drying in a forced-air oven (Narang Medical Instruments, Model: RM-03P) at $55 \pm 2^\circ\text{C}$ for 16–18 h until moisture content reached below 8% (wb). Dried segments were pulverized in a high-speed blender (Preethi Eco-Plus 750W), passed through a 60-mesh ASTM sieve (250 μm aperture), and the resultant fine powder (Moringa pod powder; MPP) was vacuum-sealed in low-density polyethylene pouches pending analysis. Conventional sambar spice ingredients - coriander seeds (*Coriandrum sativum*), red chilies (*Capsicum annuum*), cumin seeds (*Cuminum cyminum*), fenugreek seeds (*Trigonella foenum-graecum*), black pepper (*Piper nigrum*), dried curry leaves (*Murraya koenigii*), Bengal gram dal (*Cicer arietinum*), black gram dal (*Vigna mungo*), and cinnamon bark (*Cinnamomum verum*) - were obtained from certified food-grade suppliers. All ingredients were individually cleaned, moisture-standardized, and dry-roasted to an internal temperature of $80 \pm 5^\circ\text{C}$ in a cast-iron pan on an electric hot plate (Bajaj Platini, 1500 W) under constant stirring to prevent scorching.

Experimental formulation design

Four sambar powder formulations were prepared according to the substitution scheme detailed in Table 1. Each formulation was prepared independently in triplicate—i.e., three separate preparation batches per treatment ($n = 3$ independent batches), each analysed once—so that the independent experimental unit for all subsequent statistical analyses is the batch, and the reported mean $\pm$ SD values reflect batch-to-batch variability rather than repeated analytical measurements on a single batch. The base formulation (T0) comprised: coriander seeds (100 g), red chilies (50 g), chana dal (30 g), MPP (0 g), cumin seeds (10 g), fenugreek seeds (10 g), dried curry leaves (10 g), urad dal (25 g), black pepper (5 g), and cinnamon sticks (2–3, approximately 8 g), giving a fixed total batch weight of 248 g. In treatments T1, T2, and

T3, MPP replaced coriander seeds on a strict weight-for-weight basis at 5%, 10%, and 15% of this fixed total batch weight, respectively (MPP = 12.4, 24.8, and 37.2 g, with coriander correspondingly reduced to 87.6, 75.2, and 62.8 g). All other ingredients (red chilies, chana dal, cumin seeds, fenugreek seeds, dried curry leaves, urad dal, black pepper, cinnamon) were deliberately held constant in absolute weight across T0–T3, so that (i) "% MPP substitution" is unambiguously defined as the percentage of total blend weight contributed by MPP, (ii) total batch weight is identical (248 g) for all four treatments, and (iii) coriander is the sole ingredient displaced by MPP. All roasted ingredients were ground together in a cyclone-type pulverizer (Micro Pulverizer, National Engineering Works, India) and blended homogeneously. Finished powders were stored in airtight amber glass jars (250 mL) prior to analysis.

Table 1. Ingredient composition (g) of sambar powder formulations at graded Moringa pod powder (MPP) substitution levels. MPP replaced coriander seeds on a weight-for-weight basis at 5%, 10%, and 15% of a fixed total batch weight of 248 g (identical across T0–T3); all other ingredients were held constant in absolute weight by design.

Ingredient	T0 (Control)	T1 (5% MPP)	T2 (10% MPP)	T3 (15% MPP)
Coriander seeds (g)	100	87.6	75.2	62.8
Red chilies (g)	50	50	50	50
Chana dal (g)	30	30	30	30
Urad dal (g)	25	25	25	25
Cumin seeds (g)	10	10	10	10
Fenugreek seeds (g)	10	10	10	10
Dried curry leaves (g)	10	10	10	10
Black pepper (g)	5	5	5	5
Cinnamon sticks (g)	8	8	8	8
Moringa pod powder (g)	0	12.4	24.8	37.2

Analytical methods

Proximate composition (moisture, crude protein, crude fat, crude fibre, ash, and carbohydrate by difference) was determined following the Association of Official Analytical Chemists (AOAC, 2016) official methods. Mineral concentrations (calcium, iron, zinc, potassium, magnesium, and phosphorus) were quantified using Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES; Perkin-Elmer Optima 7000 DV) following acid digestion with concentrated $\text{HNO}_3\text{:HClO}_4$ (4:1, v/v). Total phenolic content (TPC) was estimated by the Folin-Ciocalteu colorimetric method (Singleton et al., 1999) and expressed as gallic acid equivalents (GAE) per gram of dry weight. *In vitro* antioxidant activity was assessed by DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay (Brand-Williams et al., 1995) and ferric reducing antioxidant power (FRAP) assay (Benzie & Strain, 1996). Storage stability of T0 and T3 (moisture content and peroxide value) was evaluated at 0, 1, 2, 3, 4, 5, and 6 months under ambient conditions ($30 \pm 2^\circ\text{C}$, $65 \pm 5\%$ relative humidity) in a controlled stability chamber (Thermo Scientific, Model: SHKE4000). Peroxide value (PV) of T0 and T3 was determined at each storage interval by iodometric titration following AOAC Official Method 965.33 (AOAC, 2016). Lipid was first extracted from the powder by cold extraction with n-hexane (1:5, w/v; 30 min at room temperature with intermittent shaking), dried over anhydrous sodium sulphate, and the solvent was removed under reduced pressure at below 40°C . An aliquot of the extracted fat (5.0 ± 0.05 g) was dissolved in 30 mL of glacial acetic acid–chloroform mixture (3:2, v/v) in a 250 mL stoppered conical flask, 0.5 mL of saturated potassium iodide solution was added, and the flask was swirled for exactly 1 min and kept in the dark. Distilled water (30 mL) was then added and the liberated iodine was titrated against 0.01 N sodium thiosulphate solution using 1% (w/v) starch solution as the indicator until the blue colour disappeared. A reagent blank was run in parallel. PV was calculated as $\text{PV (meq O}_2\text{/kg fat)} = [(S - B) \times N \times 1000] / W$, where S is the sample titre (mL), B is the blank titre (mL), N is the normality of the sodium thiosulphate solution, and W is the weight of the fat sample (g). PV is expressed as milliequivalents of active oxygen per kg of fat (meq $\text{O}_2\text{/kg}$). Moisture content during storage was determined by the AOAC oven-drying method described above for proximate composition.

Sensory evaluation

Sensory acceptability was assessed by a panel of 25 semi-trained assessors (age: 20–45 years; sex ratio: 12 male, 13 female) recruited from within the university campus. Assessors were requested to prepare a standardized volume of sambar broth (200 mL) using each formulation (5 g per serving) and evaluate the products on a 9-point hedonic scale (1 = extremely dislike, 9 = extremely like) for six attributes: colour, aroma, flavour, taste, texture, and overall acceptability. Assessments were conducted in individual booths under standardized white fluorescent light, and palate-cleansing water

was provided between samples. Ethical clearance for human subjects' participation was obtained from the Institutional Ethical Review Committee (IERC/BESTUNI/2025/047).

Statistical analysis

For proximate composition, mineral profile, total phenolic content, and antioxidant assay data, each of the three independent preparation batches per treatment ($n = 3$ batches; the independent experimental unit) was analysed once, and results are expressed as mean $\pm$ standard deviation (SD) across batches. One-way analysis of variance (ANOVA) followed by Duncan's Multiple Range Test (DMRT) was performed on these batch-level values using IBM SPSS Statistics (Version 27.0, IBM Corp., Armonk, NY, USA) to determine significant differences among treatments at $p \leq 0.05$. Because the 25 sensory assessors each rated all four formulations, sensory hedonic scores constitute repeated measures within assessor rather than independent observations; these data were therefore analysed using a repeated-measures (mixed-model) ANOVA with treatment as a fixed effect and assessor as a repeated/random factor, followed by pairwise comparisons with Bonferroni correction, rather than a one-way ANOVA that treats every rating as independent. Storage stability data (moisture content and peroxide value recorded repeatedly on the same batches at 0, 1, 2, 3, 4, 5, and 6 months) were likewise analysed using a repeated-measures/mixed-model ANOVA with treatment, storage time, and their interaction as fixed effects and batch as a random effect, rather than by comparing time points as independent one-way contrasts. Pearson's correlation analysis was conducted to examine bivariate relationships between key nutritional and antioxidant parameters.

Results and Discussion

Proximate composition

The proximate composition of all sambar powder formulations is presented graphically in Figure 1. The incorporation of moringa pod powder at progressively higher substitution levels was associated with statistically significant ($p \leq 0.05$) improvements in the nutritional composition of the spice blend. The crude protein content of T3 (15% MPP) was recorded at 17.86%, representing an increase of 25.7% over the control (T0: 14.21%), a finding consistent with the documented protein richness of *M. oleifera* pod tissue (Anwar et al., 2007; Oyeyinka & Oyeyinka, 2018). This elevation is likely to reflect the protein contributed by MPP; a protein-rich composition has also been described for Moringa leaves (Teixeira et al., 2014).

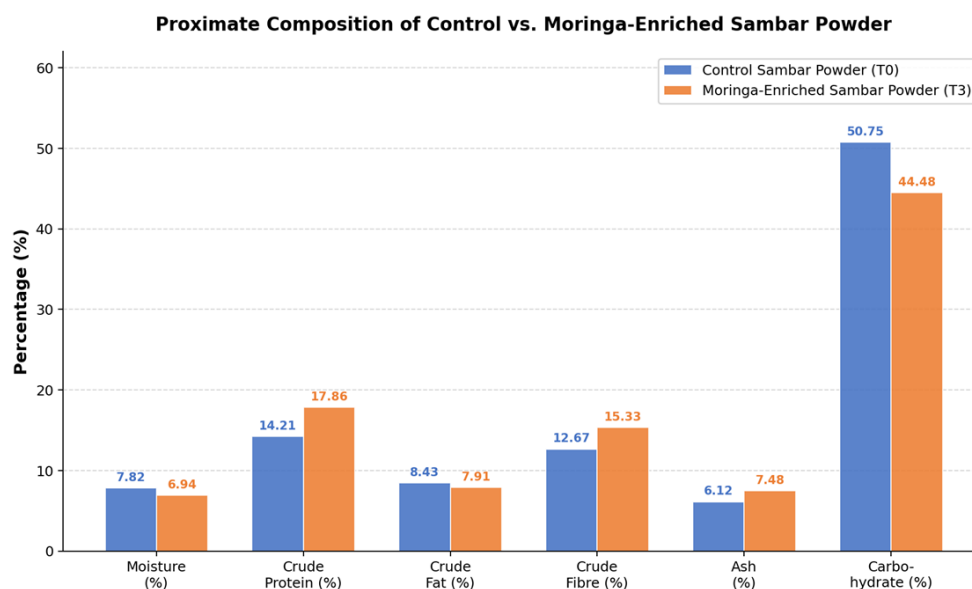


Figure 1. Proximate composition (%) of sambar powder formulations (T0–T3). Values represent mean $\pm$ SD ($n=3$ independent batches). Significant differences between treatments were determined by one-way ANOVA followed by Duncan's Multiple Range Test ($p \leq 0.05$).

Dietary fibre content exhibited a pronounced upward trajectory with increasing MPP substitution, reaching 15.33% in T3 compared to 12.67% in T0 - a statistically significant increment of 21.0% ($p \leq 0.05$), consistent with reports that Moringa

Pods are a source of dietary fibre (Sánchez-Machado et al., 2010). Dietary fibre is nutritionally important, as higher fibre intake has been associated with a lower risk of non-communicable diseases (Slavin, 2013; Reynolds et al., 2019). These findings indicate a potential nutritional contribution of MPP-enriched sambar powder and warrant further investigation of its health relevance. The crude fat content demonstrated a modest but significant decline with increasing MPP substitution (T0: 8.43% vs T3: 7.91%), consistent with the comparatively low lipid content reported for Moringa pods (Sánchez-Machado et al., 2010) and the partial replacement of coriander seeds in the control blend.

Mineral composition

Table 2 and Figure 2 present the mineral profiles of all four formulations as determined by ICP-OES. The results reveal a consistent, progressive enrichment of macro- and micromineral concentrations with increasing MPP substitution levels. Calcium content increased from 312 mg/100 g in T0 to 584 mg/100 g in T3 - an 87.2% increment - attributable to the mineral content of MPP; elevated calcium has been reported for Moringa leaves (Leone et al., 2015), whereas pod-specific calcium data for over-mature pods are limited and were not independently examined here. Given that inadequate calcium intake is a recognised nutritional concern in India (IOF, 2022), these findings indicate a potential nutritional contribution of MPP-enriched sambar powder and warrant further investigation of its health relevance. Iron content increased from 14.2 mg/100 g (T0) to 27.3 mg/100 g (T3), representing a 92.3% enhancement. Given that iron-deficiency anaemia remains endemic across rural Andhra Pradesh and the broader Indian subcontinent - particularly among women of reproductive age and children under five (International Institute for Population Sciences, 2021) - this mineral augmentation may be nutritionally relevant, although iron bioavailability from the enriched matrix was not assessed in the present study. Zinc concentrations likewise improved substantially (T0: 3.8 mg/100 g vs T3: 7.1 mg/100 g), with comparable patterns observed for potassium, magnesium, and phosphorus. Direct comparison with pod-specific mineral data is limited; Sánchez-Machado et al. (2010) characterised the nutritional composition of edible parts of *M. oleifera*, including leaves, flowers, and immature pods, and reported substantial nutritional value.

Table 2. Mineral profile (mean $\pm$ SD, n=3 independent batches) of sambar powder formulations. Superscript letters (a–d) denote significantly different means within each row (DMRT, $p \leq 0.05$).

Mineral Parameter	T0 (Control)	T1 (5% MPP)	T2 (10% MPP)	T3 (15% MPP)
Calcium (mg/100 g)	312 $\pm$ 4.2 ^d	398 $\pm$ 5.1 ^c	486 $\pm$ 6.3 ^b	584 $\pm$ 7.8 ^a
Iron (mg/100 g)	14.2 $\pm$ 0.31 ^d	18.7 $\pm$ 0.44 ^c	22.4 $\pm$ 0.58 ^b	27.3 $\pm$ 0.72 ^a
Zinc (mg/100 g)	3.8 $\pm$ 0.09 ^d	4.6 $\pm$ 0.11 ^c	5.9 $\pm$ 0.14 ^b	7.1 $\pm$ 0.19 ^a
Potassium (mg/100 g)	621 $\pm$ 8.6 ^d	689 $\pm$ 9.4 ^c	742 $\pm$ 10.1 ^b	812 $\pm$ 11.3 ^a
Magnesium (mg/100 g)	98 $\pm$ 1.8 ^d	124 $\pm$ 2.2 ^c	157 $\pm$ 2.7 ^b	193 $\pm$ 3.4 ^a
Phosphorus (mg/100 g)	278 $\pm$ 3.9 ^d	305 $\pm$ 4.3 ^c	334 $\pm$ 4.8 ^b	368 $\pm$ 5.2 ^a

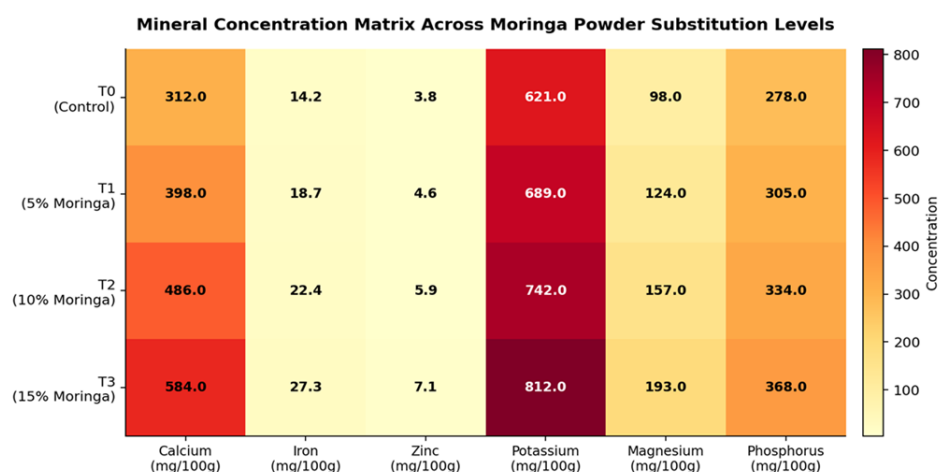


Figure 2. Mineral concentration matrix (ICP-OES) across sambar powder formulations at graded Moringa pod powder substitution levels (0%, 5%, 10%, 15%). Colour intensity gradient (yellow to red) reflects increasing mineral concentration. All values are expressed in mg/100 g dry weight.

Antioxidant bioactivity

In vitro antioxidant capacity increased progressively with MPP substitution level, with significant differences among treatments ($p \leq 0.05$), as illustrated in Figure 3. DPPH radical scavenging activity escalated from 62.4% inhibition in T0

to 89.7% in T3, while FRAP values increased from 18.6 $\mu\text{mol Fe}^{2+}$ eq./g dw (T0) to 36.8 $\mu\text{mol Fe}^{2+}$ eq./g dw (T3), representing 43.8% and 97.8% increments, respectively. These results indicate an improved in vitro antioxidant capacity of the MPP-enriched formulations, which may be related to phenolic and other bioactive constituents reported in *M. oleifera* leaf extracts (Vongsak et al., 2013). Individual phenolic compounds were not quantified in the present study, and the cited evidence relates to leaf rather than pod tissue. Total phenolic content followed a parallel trend, increasing from 42.3 ± 1.8 mg GAE/g dw (T0) to 78.6 ± 2.4 mg GAE/g dw (T3). For context, Siddhuraju & Becker (2003) reported the phenolic content of *M. oleifera* leaf extracts, although direct comparison is limited by differences in plant part, extraction, and expression basis. Pearson's correlation analysis across the four treatment means revealed a strong positive association between TPC and DPPH scavenging activity ($r = 0.987$). Antioxidant-rich foods are of interest in relation to oxidative stress (Lobo et al., 2010); however, the present in vitro assays do not establish health effects. These findings indicate a potential nutritional contribution of MPP-enriched sambar powder and warrant further investigation of its health relevance.

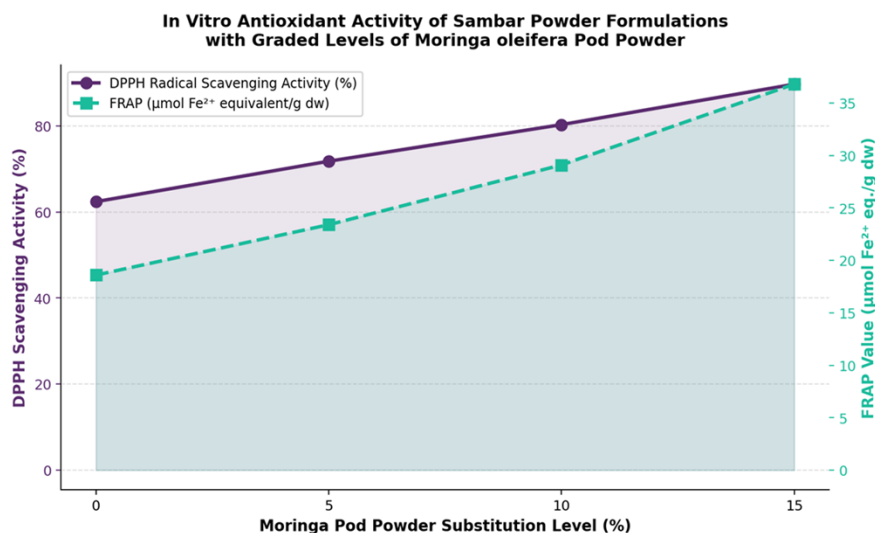


Figure 3. In vitro antioxidant activity (DPPH radical scavenging activity and FRAP value) of sambar powder formulations as a function of *Moringa oleifera* pod powder (MPP) substitution level. DPPH values expressed as % inhibition (left axis); FRAP expressed as $\mu\text{mol Fe}^{2+}$ equivalent per gram dry weight (right axis). Each data point represents mean $\pm$ SD of $n = 3$ independent batches.

Sensory evaluation

Sensory Profile Comparison of Sambar Powder Formulations (9-Point Hedonic Scale)

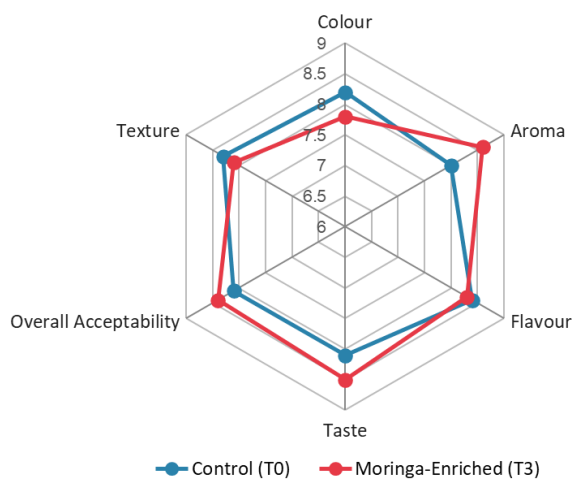


Figure 4. Sensory profile comparison (9-point hedonic scale) of control sambar powder (T0) and Moringa pod powder-enriched formulation (T3), evaluated by 25 semi-trained panelists across six sensory attributes. Values represent mean scores; higher values indicate greater acceptance.

Consumer acceptability is a non-negotiable determinant of functional food viability, irrespective of demonstrated nutritional or bioactive superiority (Granato et al., 2010). As visualized in Figure 4, the sensory profile of the Moringa-enriched formulation (T3) compared favourably with the control across most hedonic dimensions. Aroma scores for T3 (8.6 ± 0.3) marginally exceeded those of T0 (8.0 ± 0.4), reflecting the characteristic earthy, slightly grassy volatile signature of Moringa that the panelists found complementary to the established sambar spice bouquet. Similarly, taste scores for T3 (8.5 ± 0.2) were statistically comparable to T0 (8.1 ± 0.3), suggesting no significant taste dilution effect from the MPP incorporation. Colour scores showed a modest decline in T3 (7.8 ± 0.4 vs 8.2 ± 0.3 for T0), likely due to the slight greenish-brown pigmentation imparted by Moringa pod chlorophyll and tannin degradation products. However, this difference did not translate into diminished overall acceptability - the T3 formulation achieved an overall acceptability score of 8.4 ± 0.3 on the 9-point scale, statistically comparable to T0 (8.1 ± 0.2), and well above the acceptability threshold of 7.0 recommended by Meilgaard et al. (2016). These findings align with those of Dhakar et al. (2011), who reported sustained consumer acceptance of Moringa leaf-incorporated food products at comparable supplementation levels.

Storage stability

Storage stability monitoring was restricted to the two bounding formulations—T0 (control, 0% MPP) and T3 (maximum substitution, 15% MPP)—rather than all four treatments, in order to characterise the extremes of the substitution gradient within the available six-month ambient monitoring capacity; the intermediate formulations (T1, T2) were not carried through the full storage protocol. The preservation of nutritional quality and physicochemical integrity during ambient storage constitutes a critical determinant of commercial viability for composite spice powders. As illustrated in Figure 5, both moisture content and peroxide value exhibited progressive increases over the six-month ambient storage period in both T0 and T3 formulations. However, T3 demonstrated consistently lower moisture absorption throughout the storage period (6-month moisture: 8.16% vs 9.04% for T0), possibly related to the lower initial moisture content and comparatively higher fibre density of MPP, which may contribute to reduced hygroscopicity (Rao & Balasubramanyam, 2017). These observations apply to T0 and T3 only; the storage behaviour of T1 and T2 was not evaluated.

Lipid oxidation, as indexed by peroxide value, remained within the permissible limit of 10 meq O₂/kg prescribed by the Food Safety and Standards Authority of India (FSSAI, 2020) for spice powders throughout the observation period for both formulations. Notably, T3 exhibited peroxide values consistently below those of T0 at all time points (6-month PV: T3 = 1.78 meq O₂/kg vs T0 = 2.31 meq O₂/kg), which may reflect antioxidant compounds reported in other Moringa tissues (Atawodi et al., 2010, based on leaf, stem-bark, and root-bark extracts); this was not directly tested in the present study.

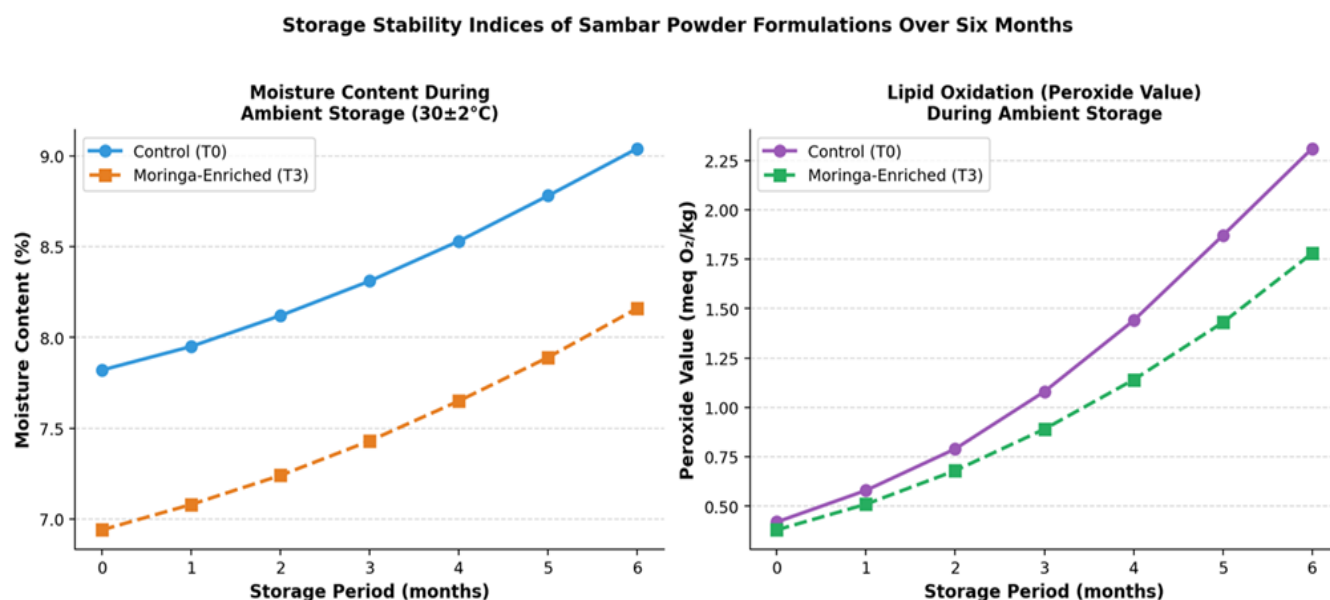


Figure 5. Storage stability profiles of control (T0) and Moringa-enriched sambar powder (T3) over six months under ambient conditions ($30 \pm 2^\circ\text{C}$, $65 \pm 5\%$ RH). Left panel: Moisture content (%); Right panel: Peroxide value (meq O₂/kg). Data points represent mean values ($n=3$); FSSAI permissible limits are indicated.

Conclusion

The present investigation provides experimental evidence that over-mature *Moringa oleifera* pod powder, hitherto regarded as agricultural waste, can be effectively valorized as a functional ingredient in sambar powder formulations with acceptable sensory scores in this culturally entrenched spice blend. The formulation with the highest tested MPP substitution level, 15% (T3), achieved statistically significant enhancements in crude protein, dietary fibre, calcium, iron, zinc, and in vitro antioxidant capacity relative to the control, while maintaining adequate sensory acceptability on a 9-point hedonic scale. Six-month ambient storage data showed that T3 maintained lower moisture content and peroxide values than the control throughout the storage period. From a translational perspective, this approach suggests potential benefits in three areas: (i) nutritional - enhancing micronutrient and antioxidant density in a daily-consumption food vehicle; (ii) economic - generating value-added revenue from discarded post-harvest biomass and supporting rural livelihoods; and (iii) ecological - reducing agri-food waste and associated environmental burden. The scalability of this technology to small and medium food enterprises, as well as its potential integration into government nutrition supplementation programmes such as the Mid-Day Meal Scheme and the Integrated Child Development Services, warrants further evaluation. Future research directions should encompass: (a) in vivo bioavailability studies to quantify the bioaccessibility of mineral and polyphenolic fractions from the enriched matrix under simulated gastrointestinal digestion conditions; (b) techno-economic analysis of industrial-scale MPP production; and (c) clinical intervention trials to quantify biomarker responses in nutritionally vulnerable populations consuming the Moringa-enriched preparation.

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Author contributions

C.S.B. conceived the study, supervised experimental design, data analysis, and manuscript preparation, conducted proximate and mineral analyses. R.M. performed antioxidant assays and storage stability studies, coordinated sensory evaluation and statistical analyses. All authors reviewed and approved the final manuscript.

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Conflict of interest

The authors declare no conflict of interest. The patent application (No. 202641031666) was filed by the same research team; however, no commercial funding was received for this research.

Ethics approval

Ethical clearance for sensory evaluation with human participants was granted by the Institutional Ethical Review Committee, BESTIU (Ref. No. IERC/BESTUNI/2025/047).

AI tool usage declaration

We declare that we did not use any AI tools in the preparation of this manuscript.

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