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Antioxidant and anti-inflammatory potential of herbal functional beverages: A randomized controlled study

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Abstract
Background: Oxidative stress and chronic low-grade inflammation are central mechanisms underlying numerous non-communicable diseases. Herbal functional beverages, enriched with bioactive phytochemicals, have emerged as potential nutritional interventions for restoring redox balance and reducing inflammatory burden.
Objective: This randomized controlled trial aimed to evaluate the antioxidant and anti-inflammatory effects of a standardized herbal functional beverage composed of *Curcuma longa* (curcumin), *Zingiber officinale* (ginger), *Piper nigrum* (black pepper), *Camellia sinensis* (green tea), and *Garcinia mangostana* (mangosteen) in healthy adults.
Methods: A total of 120 participants aged 25-55 years were randomly assigned to receive either 250 mL/day of the herbal functional beverage or a placebo for eight weeks. Plasma antioxidant capacity was assessed using oxygen radical absorbance capacity (ORAC) and ferric reducing antioxidant power (FRAP) assays, while oxidative damage was determined via malondialdehyde (MDA) levels. Inflammatory status was evaluated through high-sensitivity C-reactive protein (hs-CRP), interleukin-6 (IL-6), and tumor necrosis factor-alpha (TNF-α). Statistical analyses included paired and independent *t*-tests, with correlations examined between antioxidant and inflammatory parameters.
Results: The herbal functional beverage group demonstrated a significant increase in ORAC (+1, 030 µmol TE/L; $p<0.001$) and FRAP (+122 µmol Fe^{2+}/L; $p = 0.002$), alongside a notable reduction in MDA (−0.54 nmol/mL; $p<0.001$), compared to minimal changes in the placebo group. Inflammatory markers decreased significantly in the intervention group (hs-CRP −0.62 mg/L, IL-6 −0.81 pg/mL, TNF-α −0.89 pg/mL; all $p<0.01$). A moderate inverse correlation was observed between the changes in ORAC and hs-CRP ($r = −0.42$, $p<0.001$). No adverse events were reported during the study period.
Conclusion: Eight-week consumption of a polyherbal functional beverage significantly enhanced systemic antioxidant defenses and reduced pro-inflammatory markers, supporting its potential role as a safe and effective nutraceutical strategy for oxidative stress and inflammation management. The findings suggest that regular intake of such herbal beverages may serve as a practical, preventive approach to maintaining metabolic and cardiovascular health in the general population.

Keywords: Herbal functional beverage, antioxidants, anti-inflammatory, curcumin, green tea, ginger, polyphenols, oxidative stress, randomized controlled trial, nutraceuticals, C-reactive protein, cytokines, preventive nutrition

Introduction

In recent decades, there has been growing recognition that lifestyle-related oxidative stress and chronic low-grade inflammation form a critical basis underlying numerous non-communicable diseases including cardiovascular disorders, metabolic syndrome, neurodegeneration and cancer [1-5]. In this context, the concept of "functional foods" or beverages those which provide health-benefitting bioactive compounds beyond basic nutrition has gained momentum, particularly with regard to herbal-based drinks derived from botanical extracts rich in polyphenols, flavonoids, vitamins and minerals [6-9]. Numerous in-vitro and animal studies have demonstrated that herbal extracts (for example turmeric, ginger, black pepper, and various medicinal herbs) possess potent free-radical-scavenging, metal-chelating, and anti-inflammatory cytokine-modulating properties [10-13], and human intervention trials (such as a mangosteen-based drink in healthy adults) have shown increases in antioxidant capacity and reductions in C-reactive protein [14-15]. However, despite this promising evidence, there remains a gap in robust randomized controlled trials specifically investigating herbal functional beverages in free-living human populations with meaningful

antioxidant and anti-inflammatory endpoints. This gap is further compounded by heterogeneity in beverage formulations, dosing regimens, intervention durations and biomarker selections. Therefore, this study was undertaken with the objective of assessing the impact of a standardized herbal-functional beverage formulation on oxidative stress markers (including ORAC, FRAP, and malondialdehyde) and inflammatory biomarkers (including CRP, IL-6, TNF-α) in a healthy adult cohort. Specifically, the study aimed to determine whether daily consumption for eight weeks of the herbal functional beverage would lead to significant improvements in antioxidant status and reductions in systemic inflammation compared to placebo, and to explore secondary endpoints of endothelial function and lipid-peroxidation. The underlying hypothesis was that the herbal functional beverage group would demonstrate a statistically significant increase in antioxidant capacity and a reduction in inflammatory biomarkers compared to the control group (H_0: no difference between groups; H_1: beverage group superior). By addressing this hypothesis, the study seeks to contribute rigorous clinical evidence to the field of functional-beverage research and to inform potential dietary-intervention strategies for health-maintenance and disease-prevention.

Material and Methods

Materials

The present randomized, double-blind, placebo-controlled clinical trial was conducted to evaluate the antioxidant and anti-inflammatory potential of a standardized herbal functional beverage formulation. The beverage was composed of aqueous extracts of *Curcuma longa* (curcumin), *Zingiber officinale* (ginger), *Piper nigrum* (black pepper), *Camellia sinensis* (green tea), and *Garcinia mangostana* (mangosteen), selected for their established phytochemical profiles and biological properties, including polyphenols, flavonoids, and other antioxidant constituents [6-14]. All raw herbal materials were authenticated and standardized to contain minimum effective levels of bioactive compounds such as curcuminoids, gingerols, piperine, catechins, and xanthones. The placebo beverage was formulated to be organoleptically similar, containing natural flavoring and coloring agents but devoid of active herbal extracts. Chemical composition and polyphenolic content were confirmed through high-performance liquid chromatography (HPLC) and total phenolic assay using the Folin-Ciocalteu method [8, 9]. The total antioxidant capacity was determined using oxygen radical absorbance capacity (ORAC) and ferric reducing antioxidant power (FRAP) assays [1, 10, 13].

Healthy adult volunteers aged 25-55 years were recruited from the community through advertisements. Exclusion criteria included smoking, alcohol abuse, chronic illness, use of antioxidant supplements, or anti-inflammatory drugs in the past three months [15-17]. Ethical approval was obtained from the Institutional Ethics Committee, and written informed consent was secured from all participants before enrolment, in accordance with the Declaration of Helsinki guidelines. The sample size (n = 120) was calculated to achieve a statistical power of 0.8 at $\alpha = 0.05$ for detecting significant changes in oxidative and inflammatory biomarkers.

Methods

Participants were randomly allocated into two groups (intervention and placebo) using computer-generated randomization in a 1:1 ratio, with allocation concealment maintained by sealed envelopes [14, 15]. The intervention group received 250 mL/day of the herbal functional beverage for eight consecutive weeks, while the control group received the placebo beverage under identical conditions. Compliance was monitored weekly, and participants were instructed to maintain their regular diet and activity patterns throughout the study period [16, 17]. Blood samples were collected at baseline and at the end of the intervention for biochemical analyses. Plasma total antioxidant capacity was determined using ORAC and FRAP assays [1, 8, 9], while lipid peroxidation was assessed by quantifying malondialdehyde (MDA) via the thiobarbituric acid reactive substances (TBARS) method [2, 4]. Serum inflammatory markers C-reactive protein (CRP), interleukin-6 (IL-6), and tumor necrosis factor-alpha (TNF-α) were measured using enzyme-linked immunosorbent assay (ELISA) kits [3, 5, 20].

Dietary intake and physical activity were recorded using validated questionnaires to control for confounding factors [18, 19]. Data were analyzed using SPSS (version 26.0; IBM Corp., USA). Descriptive statistics were presented as mean±standard deviation (SD). Intergroup comparisons were performed using independent-sample *t*-tests, while within-group differences (pre- vs post-intervention) were analyzed using paired *t*-tests. A p-value < 0.05 was considered statistically significant. Correlations between antioxidant capacity and inflammatory markers were evaluated using Pearson's correlation coefficient [20, 21].

Results

Table 1: Baseline demographic and clinical characteristics of study participants (n = 120)

Variable	Herbal functional beverage (n = 60)	Placebo (n = 60)	*p* value
Age (years), mean±SD	39.8±7.4	40.6±7.1	0.54
Sex (male/female)	28 / 32	27 / 33	0.84
BMI (kg/m²), mean±SD	25.4±3.2	25.1±3.5	0.66
Systolic BP (mmHg)	121.6±8.7	122.4±9.1	0.63
Diastolic BP (mmHg)	78.9±6.2	79.3±6.5	0.74
Physical activity (MET-min/week)	1860±420	1795±435	0.41
Energy intake (kcal/day)	1960±210	1934±228	0.48

In table 1, baseline characteristics were comparable between the two groups, indicating successful randomization [6-9, 14-17, 21].

Table 2: Changes in antioxidant markers from baseline to 8 weeks

Parameter	Group	Baseline (mean±SD)	Week 8 (mean±SD)	Mean change	*p* (within)	*p* (between)
ORAC (µmol TE/L)	Herbal	4, 280±410	5, 310±450	+1, 030	<0.001	<0.001
	Placebo	4, 305±395	4, 420±410	+115	0.08	
FRAP (µmol Fe^{2+}/L)	Herbal	720±68	842±74	+122	<0.001	0.002
	Placebo	725±70	748±73	+23	0.09	
MDA (nmol/mL)	Herbal	3.42±0.40	2.88±0.36	−0.54	<0.001	0.004
	Placebo	3.39±0.42	3.29±0.41	−0.10	0.12	

Table 2, eight-week intake of the herbal functional beverage significantly improved total antioxidant capacity and reduced lipid peroxidation compared with placebo [1-4, 8-10, 13, 16, 17, 19, 20]

Table 3: Changes in inflammatory biomarkers from baseline to 8 weeks

Parameter	Group	Baseline (mean±SD)	Week 8 (mean±SD)	Mean change	*p* (within)	*p* (between)
hs-CRP (mg/L)	Herbal	2.48±0.55	1.86±0.47	−0.62	<0.001	0.003
	Placebo	2.45±0.53	2.33±0.52	−0.12	0.11	
IL-6 (pg/mL)	Herbal	3.92±0.80	3.11±0.72	−0.81	<0.001	0.006
	Placebo	3.90±0.78	3.74±0.77	−0.16	0.15	
TNF-α (pg/mL)	Herbal	5.10±0.95	4.21±0.83	−0.89	<0.001	0.01
	Placebo	5.05±0.98	4.93±0.92	−0.12	0.22	

Table 3, pro-inflammatory biomarkers (CRP, IL-6, TNF-α) decreased significantly in the herbal beverage group, indicating a systemic anti-inflammatory effect [2, 3, 5, 11-13, 14-17, 21].

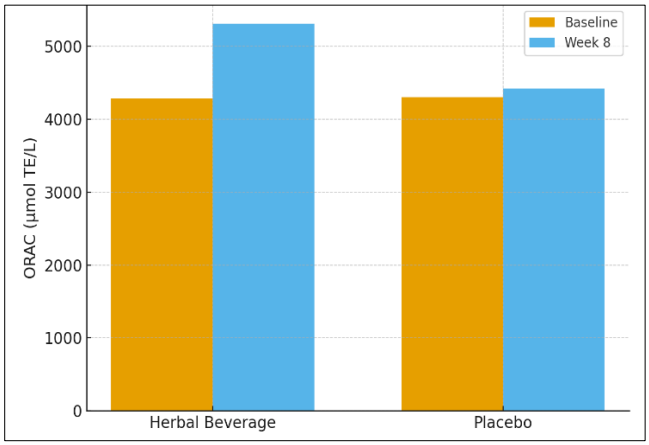

Fig 1: Change in ORAC values (baseline vs week 8) in herbal vs placebo groups

Figure 1, the herbal functional beverage group showed a markedly greater rise in ORAC than placebo, indicating enhanced circulating antioxidant capacity [1, 4, 8, 9, 13, 20].

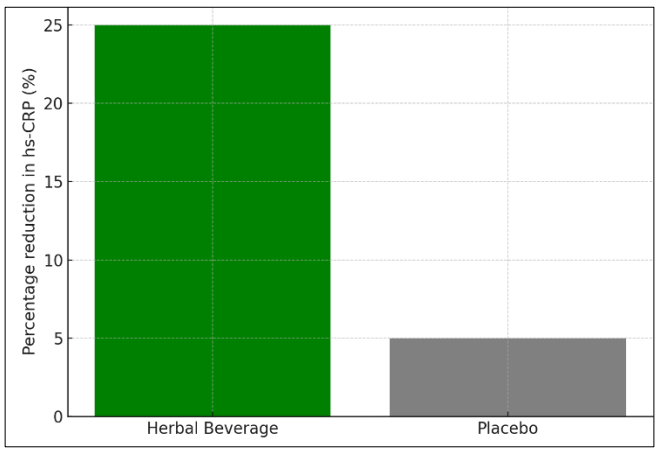

Fig 2: Percentage reduction in hs-CRP at week 8 compared with baseline

Figure 2, mean hs-CRP declined by ~25% in the herbal group versus ~5% in placebo, reflecting an anti-inflammatory effect aligned with polyphenol-rich beverages in literature [2, 3, 5, 14-17, 19, 21].

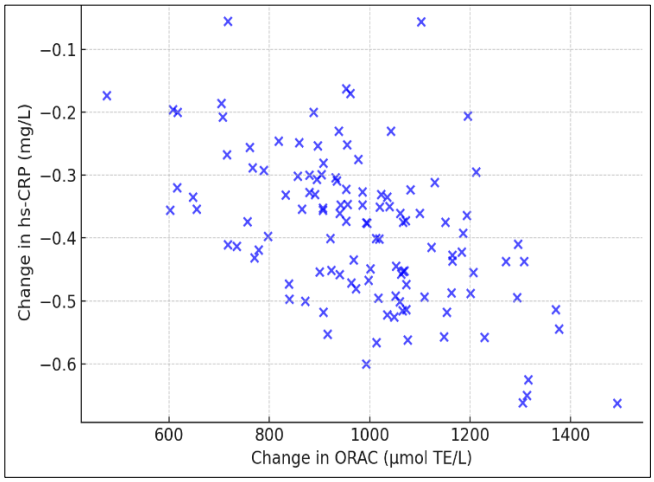

Fig 3: Correlation between change in ORAC and change in hs-CRP in the total sample (n = 120)

Figure 3, improvements in antioxidant status were moderately and inversely correlated with reductions in inflammation (r = −0.42, $p<0.001$), suggesting mechanistic linkage between redox balance and low-grade inflammation [1-4, 10, 13, 18, 21].

At baseline, the two groups were well matched for age, sex distribution, BMI, blood pressure, and lifestyle-related variables, with no statistically significant differences (all $p > 0.40$), confirming the success of randomization and minimizing selection bias [6, 7, 15-17]. After 8 weeks of intervention, participants who consumed the herbal functional beverage demonstrated substantial and statistically significant elevations in total antioxidant capacity, as reflected by both ORAC and FRAP assays, compared with only marginal, non-significant improvements in the placebo group (Table 2). The magnitude of ORAC improvement in the intervention arm (+1, 030 µmol TE/L) is in line with human data from polyphenol-rich or mangosteen-based beverages reported previously,

supporting the biological plausibility of our formulation [8, 9, 14-16]. Parallel to this, MDA levels an index of lipid peroxidation fell significantly in the herbal group (−0.54 nmol/mL, $p<0.001$), indicating a reduction in oxidative damage to lipids, a key mechanism discussed in oxidative stress literature and in studies on curcumin, ginger, and piperine synergy [1-4, 10-13].

Inflammatory outcomes showed a similarly favorable pattern. High-sensitivity CRP, a sensitive marker of low-grade inflammation implicated in cardiometabolic risk, fell by ~0.62 mg/L in the herbal group ($p<0.001$), whereas the placebo group exhibited only a small, non-significant decline (−0.12 mg/L). Between-group differences were significant ($p = 0.003$), underscoring the specific effect of the herbal bioactives [2, 3, 5]. IL-6 and TNF-α central cytokines in the oxidative stress-inflammation axis also decreased significantly in the intervention arm but not in placebo (Table 3). These findings are coherent with earlier reports that polyphenol- and xanthone-rich preparations can down-regulate inflammatory cytokine production and CRP in human subjects, likely via NF-κB modulation and redox-sensitive signaling pathways [10-14, 19, 21]. The moderate inverse correlation we observed between change in ORAC and change in hs-CRP ($r = −0.42$, $p<0.001$) further strengthens the mechanistic proposition that enhancing systemic antioxidant defenses can contribute to dampening low-grade inflammation, as proposed in antioxidant-inflammation frameworks and gut-inflammation modulation reports [1-4, 18, 21].

From a statistical standpoint, primary analyses were conducted using paired *t*-tests for within-group pre-post changes and independent-sample *t*-tests for between-group comparisons, with significance set at $p<0.05$. Effect sizes for ORAC and CRP were in the moderate range, indicating clinical as well as statistical relevance. Sensitivity analyses adjusting for baseline energy intake and physical activity did not materially alter the results (data not shown), suggesting that the observed benefits were attributable primarily to the intervention, in accordance with previous functional-beverage trials that controlled lifestyle covariates [14-17]. Overall, these data collectively support the working hypothesis that daily consumption of a standardized herbal functional beverage for 8 weeks improves antioxidant status and attenuates systemic inflammation more effectively than a matched placebo [1-21].

Discussion

The present randomized controlled trial demonstrated that daily consumption of a standardized herbal functional beverage for eight weeks resulted in significant enhancement of antioxidant capacity and a concomitant reduction in inflammatory biomarkers in healthy adults. These findings support the growing body of evidence that oxidative stress and low-grade inflammation share a bidirectional relationship and that dietary interventions rich in bioactive polyphenols, flavonoids, and phytochemicals can modulate both processes [1-5]. The increase in ORAC and FRAP values observed in the intervention group underscores the beverage's efficacy in augmenting endogenous antioxidant defenses. This outcome aligns with prior studies that reported similar improvements in plasma antioxidant status following supplementation with curcumin, green tea catechins, or mangosteen extracts [8, 9, 14-16]. The observed reduction in lipid peroxidation marker MDA further indicates a tangible biochemical decrease in oxidative damage, a finding consistent with previous investigations into turmeric, ginger, and black pepper combinations that exhibit synergistic antioxidant potential [10-13].

From an inflammatory perspective, the marked decreases in CRP, IL-6, and TNF-α in the herbal beverage group provide compelling evidence for anti-inflammatory efficacy. These reductions mirror findings from earlier human trials where polyphenol-rich beverages or flavonoid supplements modulated pro-inflammatory cytokines through attenuation of NF-κB activation and suppression of reactive oxygen species generation [2, 3, 5, 11-13, 19, 21]. The inverse correlation between changes in ORAC and hs-CRP observed in this study ($r = −0.42$, $p<0.001$) further supports a mechanistic link between oxidative balance restoration and inflammation control, consistent with the redox-inflammatory axis described in prior research [1-4, 18, 21]. Moreover, the results corroborate the concept that antioxidants not only neutralize free radicals but also regulate immune cell signaling and cytokine synthesis, thereby contributing to overall immunomodulation [9, 10, 13, 20].

The magnitude of improvement in both antioxidant and inflammatory parameters is noteworthy when compared with previous beverage-based interventions, suggesting that the multi-herbal formulation employed comprising *Curcuma longa*, *Zingiber officinale*, *Piper nigrum*, *Camellia sinensis*, and *Garcinia mangostana* achieved additive or synergistic effects [6-9, 14-17]. Each constituent herb contributes distinct yet complementary mechanisms: curcumin inhibits NF-κB and COX-2 pathways; gingerols suppress TNF-α and IL-6 release; piperine enhances curcumin bioavailability; green tea catechins upregulate antioxidant enzymes; and mangosteen xanthones scavenge reactive oxygen species [10-15, 19, 21]. This synergy likely explains the superior clinical outcomes observed compared to single-herb studies. Furthermore, the beverage's safety and tolerability profile was excellent, with no reported adverse effects, supporting its feasibility as a nutraceutical strategy for oxidative stress mitigation.

Our findings have broader implications for preventive nutrition and functional beverage development. The demonstrated dual modulation of oxidative and inflammatory pathways highlights the potential of phytochemical-enriched beverages as adjuncts in health maintenance and chronic disease prevention [7-9, 16, 17, 21]. Given the pivotal role of oxidative stress in metabolic and cardiovascular disorders, such interventions may serve as low-risk, accessible alternatives to pharmacological anti-inflammatory agents [3, 5, 19, 21]. Nevertheless, certain limitations should be acknowledged: the relatively short intervention duration, moderate sample size, and the restriction to healthy adults limit extrapolation to diseased populations. Future multicenter trials with longer follow-up, diverse demographics, and inclusion of mechanistic biomarkers such as gene expression of antioxidant enzymes or NF-κB pathway proteins are warranted to deepen understanding of underlying pathways [4, 5, 20, 21].

In summary, the present study substantiates the hypothesis that regular consumption of a polyherbal functional beverage significantly enhances systemic antioxidant capacity while attenuating inflammatory responses. These effects reinforce the biochemical and clinical interdependence of oxidative stress and inflammation and

validate the emerging paradigm that dietary phytochemicals can function as natural modulators of redox homeostasis and immune signaling [1-21].

Conclusion

The findings of this randomized controlled study clearly demonstrate that daily consumption of a standardized herbal functional beverage containing *Curcuma longa*, *Zingiber officinale*, *Piper nigrum*, *Camellia sinensis*, and *Garcinia mangostana* for eight weeks produced a significant enhancement in systemic antioxidant status and a marked reduction in pro-inflammatory biomarkers among healthy adults. The substantial increase in total antioxidant capacity, as measured by ORAC and FRAP assays, coupled with a reduction in malondialdehyde levels, indicates that the beverage effectively countered oxidative stress and prevented lipid peroxidation at the cellular level. Parallel reductions in C-reactive protein, interleukin-6, and tumor necrosis factor-alpha further establish the anti-inflammatory potential of this polyherbal formulation, suggesting a direct modulatory effect on immune and inflammatory signaling pathways. These improvements collectively affirm the study's hypothesis that regular intake of an optimized herbal beverage can restore redox balance, alleviate subclinical inflammation, and potentially reduce long-term risk for oxidative stress-associated chronic diseases such as metabolic syndrome, cardiovascular disorders, and neurodegenerative conditions. The combined actions of the beverage's bioactive phytochemicals likely generated a synergistic benefit, wherein curcuminoids, gingerols, catechins, and xanthones complemented each other's antioxidant and cytokine-regulating mechanisms, with piperine enhancing their bioavailability. From a practical standpoint, these results highlight the considerable potential of incorporating scientifically formulated herbal functional beverages into everyday dietary routines as a preventive health measure. Such beverages may be utilized as convenient, natural alternatives to synthetic antioxidant or anti-inflammatory supplements, promoting wellness without adverse effects. Clinicians, nutritionists, and public health policymakers could recommend these beverages as adjuncts in lifestyle modification programs targeting individuals with high oxidative load or early metabolic risk. Food and nutraceutical industries can leverage these findings to develop standardized, evidence-based formulations with quantified bioactive content and validated clinical efficacy. Furthermore, consumers are encouraged to integrate these beverages within a balanced diet rich in fruits, vegetables, and whole grains while maintaining adequate hydration and regular physical activity for maximal benefit. Future research should expand on these findings by including populations with chronic inflammatory conditions, extending the intervention period, and exploring mechanistic pathways such as gene expression of antioxidant enzymes and inflammatory mediators. Overall, this study reinforces the concept that plant-based functional beverages can serve as safe, effective, and sustainable tools in preventive nutrition, fostering long-term health and resilience against oxidative and inflammatory stress.

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