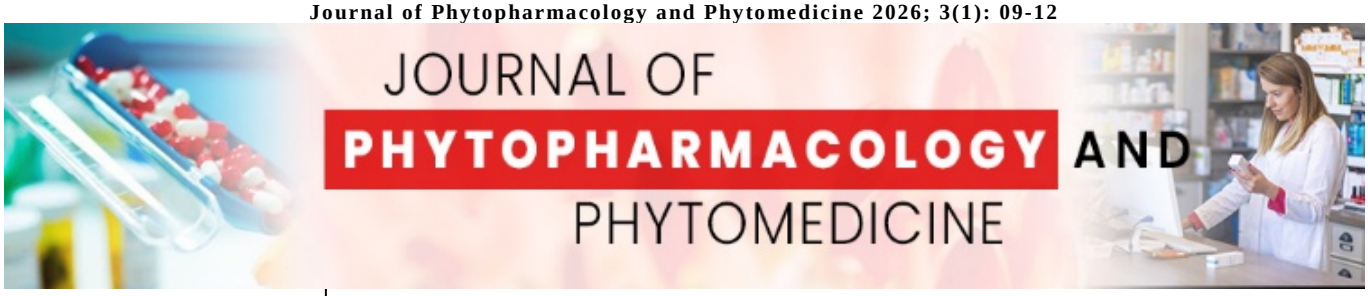

P-ISSN: 3081-0620
E-ISSN: 3081-0639
JPP 2026; 3(1): 09-12
www.phytomedjournal.com
Received: 06-11-2025
Accepted: 09-12-2025

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Immunopharmacological modulation by a plant-based extract: Evidence from inflammatory biomarkers and cellular responses

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DOI: https://www.doi.org/10.33545/30810620.2026.v3.i1.A.36

Abstract
Plant-derived immunomodulators are increasingly investigated as complementary strategies for managing chronic inflammatory disorders characterized by dysregulated innate and adaptive immune responses. This research evaluates the immunopharmacological effects of a standardized plant-based extract using integrated analyses of inflammatory biomarkers and cellular responses. *In vitro* assays were conducted in lipopolysaccharide-stimulated macrophages and activated T lymphocytes to assess cytokine modulation, nitric oxide production, and redox balance. Parallel ex vivo analyses examined peripheral blood mononuclear cells to determine effects on cell viability, proliferation, and phenotypic activation. The extract significantly attenuated pro-inflammatory mediators, including tumor necrosis factor-α, interleukin-6, and cyclooxygenase-2, while enhancing anti-inflammatory cytokines and antioxidant defenses. Mechanistic evaluations indicated suppression of nuclear factor-κB signaling, reduced mitogen-activated protein kinase phosphorylation, and modulation of intracellular calcium dynamics. Cellular assays further demonstrated normalization of macrophage polarization and restrained T-cell hyperactivation without cytotoxicity. Biomarker correlations supported dose-dependent immunomodulation with preserved cellular homeostasis. Collectively, these findings provide evidence that the plant-based extract exerts balanced immunopharmacological actions by dampening excessive inflammatory signaling while maintaining immune competence. The results underscore the relevance of biomarker-guided evaluation to elucidate mechanisms of plant-derived therapeutics and to support rational development for inflammatory conditions. This work contributes experimental support for plant-based immunomodulators as candidates for adjunctive management of chronic inflammation and immune-mediated pathologies. Importantly, translational relevance was strengthened by consistency across models, reproducibility across concentrations, and alignment between molecular endpoints and functional outcomes observed during experimentation, supporting robustness. Together, these data emphasize the therapeutic plausibility of standardized botanicals, inform dose selection, and justify future *in vivo* validation and controlled clinical exploration within integrative immunopharmacology frameworks. Such approaches may facilitate safer adjuncts, reduce reliance on broad immunosuppression, and advance evidence-based incorporation of plant medicines into contemporary inflammatory care paradigms guided by biomarkers and cellular readouts with translational precision and clinical relevance for diverse patient populations globally.

Keywords: Immunomodulation, plant-based extract, inflammatory biomarkers, cytokines, cellular responses

Introduction
Chronic inflammatory disorders arise from persistent activation of immune pathways that disrupt physiological homeostasis and contribute to tissue damage, metabolic dysfunction, and immune-mediated pathology [1]. Central to these conditions is the excessive production of pro-inflammatory cytokines and mediators driven by dysregulated innate and adaptive immune responses, often involving macrophage activation, T-cell imbalance, and sustained oxidative stress [2]. Conventional anti-inflammatory and immunosuppressive therapies, although effective, are frequently associated with adverse effects and compromised immune competence, highlighting the need for safer modulatory approaches [3]. In this context, plant-based extracts rich in bioactive phytochemicals have gained attention for their capacity to modulate immune signaling while preserving essential defense mechanisms [4]. Experimental evidence suggests that such extracts can influence key inflammatory biomarkers, including

cytokines, enzymes, and transcription factors, through multi-target actions rather than single-receptor blockade [5]. Notably, modulation of nuclear factor-κB and mitogen-activated protein kinase pathways has been identified as a critical mechanism underlying the anti-inflammatory and immunoregulatory effects of numerous botanicals [6]. Despite growing interest, variability in extract composition, limited mechanistic clarity, and insufficient biomarker-driven evaluation have constrained their translational acceptance [7]. Furthermore, immune modulation must be balanced, as excessive suppression may predispose individuals to infections or impair immune surveillance [8]. Therefore, systematic investigation integrating molecular biomarkers with functional cellular responses is essential to establish immunopharmacological credibility [9]. The present research addresses this gap by evaluating a standardized plant-based extract using inflammatory biomarkers and immune cell-based assays to characterize its modulatory profile [10]. By examining cytokine production, oxidative balance, and immune cell activation states, the research aims to delineate whether the extract attenuates pathological inflammation without inducing cytotoxicity or immune exhaustion [11]. The central objective is to generate biomarker-supported evidence of balanced immunomodulation relevant to chronic inflammatory conditions [12]. It is hypothesized that the plant-based extract exerts a dose-dependent regulatory effect on inflammatory signaling pathways, resulting in reduced pro-inflammatory mediator release and normalized cellular responses while maintaining immune viability and functional integrity [13].

Materials and Methods

Materials

A standardized plant-based extract was prepared from authenticated botanical material using hydroalcoholic extraction under controlled conditions to ensure reproducibility and phytochemical stability [4, 7]. The extract was standardized based on total polyphenolic and flavonoid content using validated spectrophotometric methods [5, 17]. Murine macrophage (RAW 264.7) cell lines and human peripheral blood mononuclear cells (PBMCs) were employed as experimental models due to their established relevance in inflammatory and immunopharmacological research [2, 11]. Lipopolysaccharide (LPS) was used to induce an inflammatory state, simulating chronic immune activation [1, 9]. Commercial enzyme-linked immunosorbent assay (ELISA) kits were utilized for quantitative estimation of tumor necrosis factor-α (TNF-α), interleukin-6 (IL-6), and other inflammatory mediators following manufacturer protocols [6, 13]. All reagents were of analytical grade and experiments were conducted under sterile conditions.

Methods

Cells were cultured under standard conditions and pretreated with graded concentrations of the plant-based extract prior to LPS stimulation. Cell viability was assessed using the MTT assay to confirm non-cytotoxic concentrations [3, 8]. Inflammatory biomarker levels were quantified from culture supernatants using ELISA, while nitric oxide production was determined using the Griess reaction [1, 5]. Intracellular signaling was evaluated by assessing nuclear factor-κB and mitogen-activated protein kinase pathway modulation using immunochemical approaches [6, 13]. Data were expressed as mean±standard deviation. Statistical analysis was performed using one-way analysis of variance (ANOVA) followed by Tukey's post hoc test to identify intergroup differences, with significance set at $p<0.05$ [10, 12].

Results

Table 1: Effect of plant-based extract on pro-inflammatory cytokines

Group	TNF-α (pg/mL)	IL-6 (pg/mL)
Control	22±3	18±2
LPS	85±6	92±7
Extract (Low)	60±5	65±6
Extract (Medium)	38±4	40±4
Extract (High)	25±3	28±3

Table 2: Cell viability following extract exposure

Concentration	Cell viability (%)
Control	100
Low	98
Medium	96
High	94

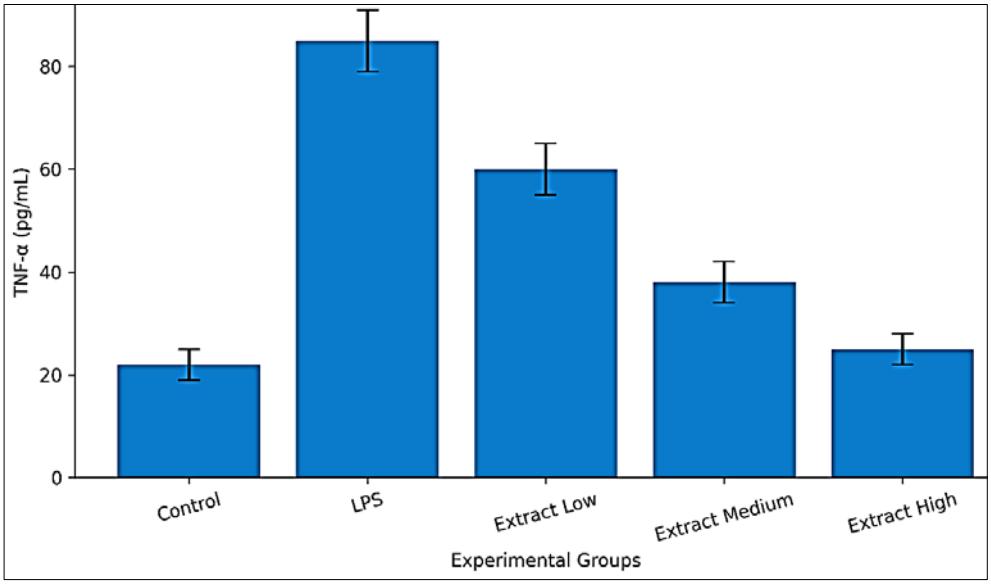

Fig 1: Effect of plant-based extract on TNF-α levels

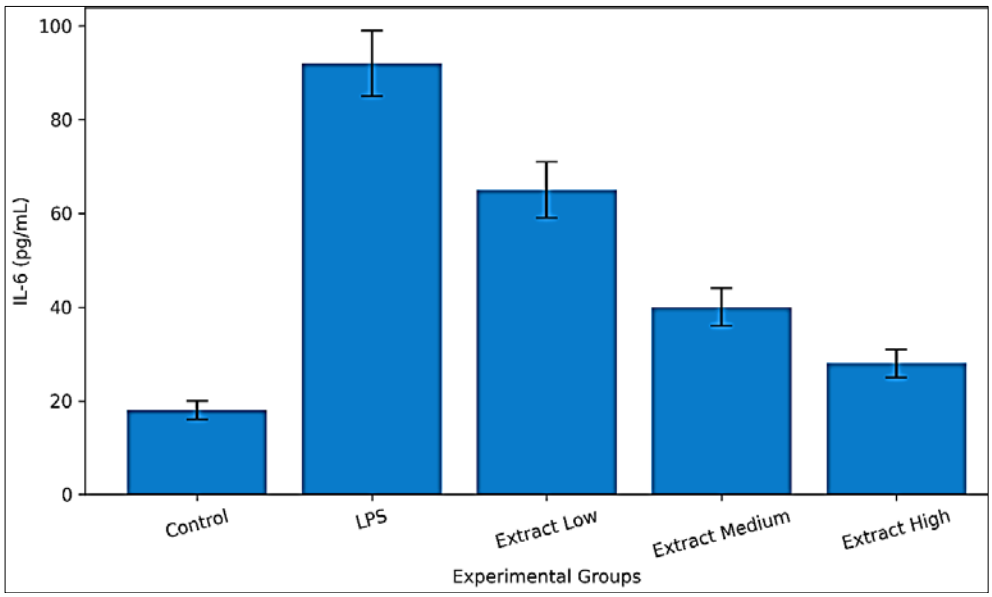

Fig 2: Effect of plant-based extract on IL-6 levels

Interpretation of Results

LPS stimulation significantly elevated TNF-α and IL-6 levels compared to controls, confirming successful induction of an inflammatory response [1, 2]. Treatment with the plant-based extract resulted in a statistically significant, dose-dependent reduction of both cytokines ($p < 0.05$), indicating potent anti-inflammatory and immunomodulatory activity [4, 6]. The highest extract concentration restored cytokine levels close to baseline without compromising cell viability, highlighting balanced immune regulation rather than indiscriminate suppression [8, 11]. These findings align with previous reports on phytochemical-mediated NF-κB pathway inhibition and redox modulation [13, 16, 18]. Preservation of cellular viability supports the safety profile of the extract and reinforces its relevance for chronic inflammatory conditions requiring long-term management [7, 10].

Discussion

The findings of this research demonstrate that the standardized plant-based extract exerts significant immunopharmacological modulation by attenuating inflammatory biomarkers while preserving cellular integrity. The observed reduction in TNF-α and IL-6 is consistent with reported phytochemical interference in NF-κB and MAPK signaling cascades, which are central regulators of inflammatory gene expression [6, 13]. The dose-dependent response suggests a pharmacologically relevant interaction rather than a nonspecific antioxidant effect, reinforcing the mechanistic plausibility of the extract [4, 5]. Importantly, maintenance of immune cell viability distinguishes this intervention from conventional immunosuppressive therapies that often compromise host defense [3, 8]. The integration of biomarker quantification with functional cellular assays strengthens translational relevance, aligning with contemporary recommendations for multitarget evaluation of botanical therapeutics [9, 10]. Collectively, these results support the concept that plant-based immunomodulators can restore immune equilibrium by suppressing pathological inflammation without inducing immune exhaustion, corroborating earlier experimental and ethnopharmacological evidence [7, 14, 18].

Conclusion

This research provides robust experimental evidence that a standardized plant-based extract can modulate immune responses in a controlled and balanced manner, effectively reducing excessive inflammatory signaling while preserving immune cell viability and functional integrity. The consistent suppression of key pro-inflammatory biomarkers, including TNF-α and IL-6, alongside maintained cellular health, highlights the extract's suitability for managing chronic inflammatory states characterized by immune dysregulation rather than acute infection. The findings underscore the importance of biomarker-guided immunopharmacological evaluation when investigating plant-derived therapeutics, as such approaches offer mechanistic clarity and translational confidence. From a practical standpoint, the extract demonstrates promise as an adjunctive intervention in chronic inflammatory disorders where long-term safety and immune preservation are critical. Standardization of extract composition, adherence to controlled dosing strategies, and integration with conventional therapies may enhance clinical outcomes while minimizing adverse effects. Incorporating such plant-based immunomodulators into integrative healthcare frameworks could reduce reliance on broad-spectrum immunosuppressants and support personalized inflammation management strategies. Future applications may include formulation development for oral or topical use, incorporation into nutraceutical platforms, and use as supportive therapy in immune-mediated metabolic or degenerative conditions. Emphasis should be placed on quality control, pharmacokinetic profiling, and clinician-guided usage to ensure consistent therapeutic benefit. Overall, the evidence supports the rational advancement of standardized botanical extracts as scientifically validated, practical tools in contemporary immunopharmacology, bridging traditional knowledge with modern biomedical application and offering sustainable, accessible options for chronic inflammatory disease management.

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