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Dentistry Section

Chitosan-based Biocomposite Enriched with *Vaccinium sect. Cyanococcus* and *Zingiber officinale* Extracts: An Ex-vivo Evaluation of Anti-inflammatory and Antioxidant Properties

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ABSTRACT

Introduction: The integration of natural polymers with bioactive botanicals offers a sustainable and multifunctional strategy for developing therapeutic biomaterials. Chitosan, a biodegradable polysaccharide with inherent antioxidant properties, serves as an effective matrix for drug delivery and tissue engineering. *Vaccinium sect*. *Cyanococcus* (blueberry) and *Zingiber officinale* (ginger), both rich in polyphenolic compounds, are known for their potent antioxidant and anti-inflammatory effects. The rationale lies in harnessing their synergistic anti-inflammatory and antioxidant potential to create a bioactive platform for targeted tissue regeneration and oxidative stress modulation in clinical applications.

Aim: To formulate and evaluate a chitosan-based biocomposite enriched with blueberry and ginger extracts for its ex-vivo anti-inflammatory and antioxidant activity.

Materials and Methods: The present laboratory-based ex-vivo study was conducted at the Department of Periodontics, Saveetha Dental College, Chennai, Tamil Nadu, India. from January to March 2025. Powdered blueberry and ginger (2 g each) were extracted in distilled water at 50-60°C, filtered, and condensed. Chitosan was solubilised in 1% acetic acid, and the plant extracts were gradually incorporated under constant mechanical stirring. The resulting biocomposite was evaluated using three anti-inflammatory assays-Bovine Serum Albumin (BSA) protein denaturation, egg albumin denaturation, and Human Red Blood Cell (HRBC) membrane stabilisation- and three antioxidant assays- 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging, hydrogen peroxide scavenging, and Ferric Reducing Antioxidant Power (FRAP). All tests were performed in triplicate. Statistical analysis was conducted using IBM Statistical Package for Social Sciences (SPSS) version 23.0 with independent t-tests between test and control groups where $p<0.05$ was considered to be significant.

Results: The biocomposite demonstrated a pronounced, concentration-dependent anti-inflammatory action, with 83.54±1.2% inhibition at 50 µg/mL in the BSA model. Notable suppression was also observed in albumin denaturation and erythrocyte protection. Antioxidant assessments indicated strong scavenging and reducing capabilities, evidenced by DPPH and FRAP values of 90.36±1.4% and 83.29±1.5%, respectively, and H_2O_2 neutralisation around 80.21±1.3% at the highest concentration.

Conclusion: This phytochemical-enriched chitosan biocomposite demonstrates promising ex-vivo anti-inflammatory and antioxidant properties, supporting its potential for biomedical applications in oxidative stress modulation and tissue regeneration.

Keywords: Blueberry, Ginger, Phytochemicals, Phytotherapy, Polyphenols

INTRODUCTION

Composite materials represent a cornerstone in various scientific innovations, largely due to their ability to blend diverse structural and functional elements into unified systems. These systems, typically comprising a continuous matrix and a discrete reinforcement phase, are crafted to outperform their individual constituents [1]. Although synthetic composites have achieved tremendous success-particularly within industrial and medical technologies-their ecological impact, including persistence in the environment and lack of biodegradability, has necessitated a pivot toward more sustainable alternatives [2]. This ecological consciousness has driven the advancement of biocomposites-materials that not only decompose naturally but also align with principles of biocompatibility and renewable sourcing [3].

Biocomposites often integrate naturally occurring polymers such as chitosan, cellulose, alginate, or starch, frequently enriched with natural fibres or bioactive agents to develop therapeutic constructs tailored for biomedical purposes [4]. These constructs exhibit considerable benefits, including safe degradation within physiological environments, minimal cytotoxicity, and compatibility with host tissues, making them ideal carriers for medicinal agents. As multifunctional platforms, they hold significant promise in drug delivery, antioxidant therapies, and wound care applications [5].

Among these polymers, chitosan has emerged as particularly advantageous due to its mucoadhesiveness, antimicrobial efficacy, degradability, and ability to form cohesive films [6]. Chemically, it comprises β-(1→4)-linked units of D-glucosamine and N-acetyl-D-glucosamine, providing reactive sites for conjugation with phytochemicals to create advanced delivery vehicles [7]. Its native antioxidant property, associated with radical scavenging and metal ion chelation, positions chitosan as a suitable base for hybrid biomaterials incorporating polyphenol-rich plant derivatives [8]. The integration of herbs has become an integral aspect of medical applications; therefore, studies are increasingly focusing on assessing various in-vivo plant-based formulations [9-13].

Blueberries (*Vaccinium sect. Cyanococcus*) are widely recognised for their high content of health-promoting compounds such as phenolic acids, anthocyanins, and flavanols. These phytochemicals have demonstrated anti-inflammatory properties via the suppression of pro-inflammatory markers. Their antioxidant prowess is primarily due to their capability to neutralise reactive oxygen species, crucial in modulating oxidative stress implicated in chronic disorders and impaired wound healing [14]. Incorporating blueberry extracts into biocomposite matrices may therefore potentiate therapeutic effects.

Zingiber officinale (ginger) is another extensively researched botanical known for its rich content of gingerols, shogaols, and zingerone. These compounds exert therapeutic influence by attenuating inflammatory signalling pathways and reducing prostaglandin biosynthesis. Additionally, their antioxidant capacity derives from direct radical neutralisation and the stimulation of endogenous antioxidant enzymes [15]. When embedded in a chitosan-based structure, ginger's phytochemicals benefit from prolonged stability and a controlled release profile.

By merging blueberry and ginger phytochemicals within a chitosan framework, a multifunctional, synergistically enhanced biomaterial can be crafted. This composite not only facilitates sustained delivery but also shields delicate bioactives from degradation, thereby amplifying their bioefficacy. The present study presents a novel biocomposite system integrating chitosan with polyphenol-rich *Vaccinium* and *Zingiber* extracts, targeting both oxidative stress and inflammatory pathways. Unlike conventional scaffolds, this composite leverages synergistic phytochemical interactions for enhanced therapeutic efficacy. Its dual functionality positions it as a sustainable, bioactive candidate for periodontal tissue regeneration. This research aimed to develop and comprehensively characterise a novel chitosan biocomposite integrated with *Vaccinium* and *Zingiber* extracts, focusing on ex-vivo analysis of its anti-inflammatory and antioxidative attributes.

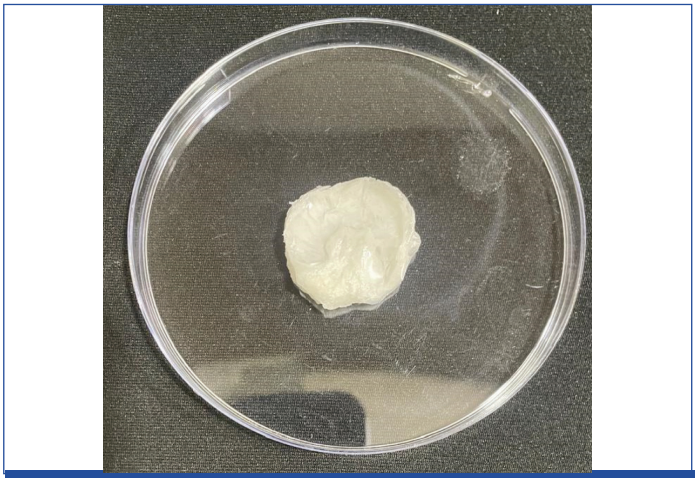
MATERIALS AND METHODS

The present ex-vivo study was conducted at the Department of Periodontics, Saveetha Dental College, Chennai, Tamil Nadu, India, from January 2025 to March 2025. The study protocol was approved by the Institutional Ethics Committee (IEC Approval No:SRB/SDC/PERIO-2302/25/023). All experimental assays were performed in three replicates (n=3) to ensure statistical accuracy and reproducibility of results.

Materials: Dry ginger and blueberry powders, along with pharmaceutical-grade chitosan, were procured from Himalayan Nutraceuticals Pvt., Ltd., India. Analytical-grade chemicals, including BSA, Dimethyl Sulfoxide (DMSO), egg albumin, Phosphate-Buffered Saline (PBS), 2,2- DPPH, 2-deoxy-2-ribose, ferric chloride, Ethylenediaminetetraacetic Acid (EDTA), acetate buffer, and 2,4,6-Tris(2-Pyridyl)-S-Triazine (TPTZ) were obtained from Sigma-Aldrich®, USA. Diclofenac sodium,which was used as the reference standard, was supplied by TO Chemicals Ltd., Thailand. Absorbance was measured using a UV- Visible Spectrophotometer (Model: UV-1800, Shimadzu Corporation, Kyoto, Japan).

Study Procedure

Preparation of the biocomposite: For the formulation, two grams each of powdered *Vaccinium sect. Cyanococcus* (blueberry) and *Zingiber officinale* (ginger) were dissolved in 100 mL of distilled water and gently heated at 50-60°C to facilitate the extraction of bioactive compounds while preserving thermolabile constituents. The resulting mixture was filtered using Whatman No.1 filter paper, and the filtrate was condensed to a final volume of 5 mL to yield a concentrated extract. In parallel, chitosan was dissolved in 1% acetic acid under continuous magnetic stirring to produce a viscous, gel-like matrix. The concentrated phytochemical extract was then gradually incorporated into the chitosan solution under sustained mechanical stirring to ensure uniform dispersion. This process resulted in a stable, homogenous chitosan-based biocomposite [Table/Fig-1] enriched with blueberry and ginger phytoconstituents, suitable for subsequent in-vitro evaluations [16].



[Table/Fig-1]: Macroscopic image of the formulated chitosan-based biocomposite enriched with *Vaccinium sect. Cyanococcus* and *Zingiber officinale* extract.

Anti-inflammatory activity: The anti-inflammatory activity was evaluated using the following three assays. Each assay was performed in triplicate, and the mean values of the three samples were calculated and used for statistical analysis.

BSA denaturation assay: A 0.45 mL aliquot of BSA solution was mixed with 0.05 mL of the biocomposite extract at concentrations ranging from 10 to 50 µg/mL The mixture's pH was adjusted to 6.3 and incubated at room temperature for 10 minutes, followed by heating at 55°C for 30 minutes. Diclofenac sodium and DMSO were used as positive and negative controls, respectively [17].

Absorbance (Abs) was recorded at 660 nm, and inhibition was calculated as:

$$\% \text{ Inhibition} = \{(\text{Abs Control} - \text{Abs Sample})/\text{Abs Control}\} \times 100$$

Egg albumin denaturation assay: Fresh egg albumin (0.2 mL) was added to 2.8 mL of PBS and treated with different concentrations of biocomposite (10–50 µg/mL). Samples were subjected to identical heating and incubation as the BSA assay [17].

The percentage inhibition of protein denaturation at 280 nm was calculated as:

$$\% \text{ Inhibition} = \{(\text{Abs Control} - \text{Abs Sample})/\text{Abs control}\} \times 100$$

Membrane stabilisation assay: The HRBC were isolated from fresh blood by centrifugation at 3000 rpm and washed three times with PBS. A 10% RBC suspension was prepared. One millilitre of RBC suspension was combined with 1 mL of biocomposite extract (diluted in Tris-HCl buffer) and incubated at 37°C for 30 minutes. Post-centrifugation, supernatants were analysed at 540 nm. Diclofenac served as the positive control and DMSO as the negative control [17].

The percentage inhibition of haemolysis is calculated using the following formula:

$$\% \text{ Inhibition}=\{(\text{Abs control} - \text{Abs sample})/\text{Abs control}\}\times 100$$

Antioxidant activity: The antioxidant activity was evaluated using the following three assays. Each assay was performed in triplicate, and the mean values of the three samples were calculated and used for statistical analysis.

DPPH radical scavenging assay: Various concentrations (10-50 µg/mL) of the biocomposite were mixed with DPPH solution (20 µM in methanol). The reaction mixture was kept in the dark for 30 minutes at room temperature. Absorbance was read at 517 nm. Ascorbic acid (1 mg/mL) served as the standard [18].

$$\% \text{ Scavenging}=\{(\text{Abs control} - \text{Abs sample})/\text{Abs control}\}\times 100$$

H2O2 scavenging assay: Each 1 mL reaction mixture contained 28 mM 2-deoxy-2-ribose, 200 µM ferric chloride, EDTA, ascorbic acid, and biocomposite at different concentrations. Incubation was carried out at 37°C for one hour, and absorbance was measured at 532 nm [18].

The percentage scavenging activity was calculated using the following formula:

% Scavenging = {(Abs Control - Abs Sample)/Abs Control} × 100

FRAP assay: A freshly prepared FRAP reagent (acetate buffer, TPTZ, and FeCl in 10:1:1 ratio) was mixed with water and biocomposite extract, incubated at 37°C for 10 minutes. The formation of a ferrous- TPTZ complex was measured at 593 nm [18].

The percentage scavenging activity was calculated using the following formula:

% Scavenging = {(Abs control - Abs sample)/Abs control} × 100

STATISTICAL ANALYSIS

The collected data were compiled and analysed statistically using the IBM-SPSS software, version 23.0. Statistical evaluation was performed using the independent t-test. A p-value of less than 0.05 was considered to indicate statistical significance.

RESULTS

Anti-inflammatory Activity

BSA denaturation assay: A marked concentration-dependent inhibition of protein denaturation was observed. At the highest concentration of 50 µg/mL, the biocomposite demonstrated 83.54±1.2% inhibition, closely matching the standard (84.96±1.1%). Even at 10 µg/mL, notable inhibition of 44.12±1.4% was recorded, showcasing its strong anti-inflammatory capacity. Statistical analysis revealed no significant difference (p>0.05) between the biocomposite and standard across all tested concentrations, indicating comparable anti-inflammatory efficacy [Table/Fig-2].

Concentration (µg/mL)	Standard (% Inhibition, Mean±SD)	Biocomposite (% Inhibition, Mean±SD)	p-value	t-value
10	45.82±1.5	44.12±1.4	0.137	1.56
20	58.34±1.6	57.26±1.3	0.162	1.09
30	70.48±1.3	69.12±1.2	0.198	1.61
40	78.92±1.2	77.84±1.1	0.219	1.56
50	84.96±1.1	83.54±1.2	0.248	2.02

[Table/Fig-2]: Bovine Serum Albumin (BSA) denaturation assay comparing chitosan biocomposite and standard at various concentrations. Data are presented as mean±standard deviation (n=3).
#Independent t-test applied for comparison between standard and test groups at each concentration. p<0.05 is considered statistically significant. SD: Standard deviation; µg/mL: Micrograms per millilitre; t: Student's t-value.

Egg albumin denaturation assay: This assay similarly revealed a progressive inhibition pattern. Maximum inhibition of 78.65±1.6% was recorded at 50 µg/mL, slightly below the standard (81.12±1.3%). At the lowest concentration, inhibition reached 52.24±1.5%, reaffirming the biocomposite's protective effect against protein denaturation. Statistical analysis revealed no significant difference (p>0.05) between the biocomposite and standard across all tested concentrations, indicating comparable anti-inflammatory efficacy [Table/Fig-3].

Membrane stabilisation assay: The membrane stabilisation assay showed consistent erythrocyte protection. At 50 µg/mL, hemolysis inhibition peaked at 82.45±1.5%, approaching the standard's efficacy (85.67±1.4%). Even at 10 µg/mL, the biocomposite provided considerable protection (55.62±1.3%). Statistical analysis revealed no significant difference (p>0.05) between the biocomposite and standard across all tested concentrations, indicating comparable anti-inflammatory efficacy [Table/Fig-4].

Concentration (µg/mL)	Standard (% Inhibition, Mean±SD)	Biocomposite (% Inhibition, Mean±SD)	p-value	t-value
10	55.41±1.4	52.24±1.5	0.163	2.68
20	62.36±1.3	59.78±1.4	0.129	2.34
30	68.57±1.5	66.12±1.3	0.138	2.14
40	73.92±1.4	71.45±1.6	0.147	2.01
50	81.12±1.3	78.65±1.6	0.158	2.08

[Table/Fig-3]: Egg albumin denaturation assay comparing chitosan biocomposite and standard at various concentrations. Data are presented as mean±standard deviation (n=3).
#Independent t-test applied for comparison between standard and test groups at each concentration. p<0.05 is considered statistically significant. SD: Standard deviation; µg/mL: Micrograms per millilitre; t: Student's t-value.

Concentration (µg/mL)	Standard (% Inhibition, Mean±SD)	Biocomposite (% Inhibition, Mean±SD)	p-value	t-value
10	58.71±1.2	55.62±1.3	0.162	3.03
20	66.84±1.4	63.45±1.5	0.174	2.86
30	73.27±1.3	70.62±1.2	0.183	2.59
40	79.44±1.6	76.93±1.4	0.196	2.04
50	85.67±1.4	82.45±1.5	0.188	2.72

[Table/Fig-4]: Membrane Stabilisation Assay comparing chitosan biocomposite and standard at various concentrations. Data are presented as mean±standard deviation (n=3).
#Independent t-test applied for comparison between standard and test groups at each concentration. p<0.05 is considered statistically significant. SD: Standard deviation; µg/mL: Micrograms per millilitre; t: Student's t-value.

The results of all three different anti-inflammatory assays revealed that the comparison between the standard and the biocomposite showed no statistically significant difference (p>0.05).

Antioxidant Activity

DPPH radical scavenging assay: The chitosan-based biocomposite exhibited dose-dependent DPPH radical scavenging activity, reaching 90.36±1.4% inhibition at 50 µg/m. Although the standard showed marginally higher activity at all concentrations, the difference diminished at higher doses, and the statistical analysis revealed no significant difference (p>0.05) between the biocomposite and standard across all tested concentrations, indicating comparable anti-oxidant activity [Table/Fig-5].

Concentration (µg/mL)	Standard (% Inhibition, Mean±SD)	Biocomposite (% Inhibition, Mean±SD)	p-value	t-value
10	68.42±1.6	65.74±1.7	0.148	1.99
20	76.32±1.5	73.68±1.6	0.163	2.08
30	83.29±1.4	81.24±1.3	0.189	1.86
40	89.15±1.3	87.59±1.2	0.174	1.53
50	91.87±1.2	90.36±1.4	0.183	1.42

[Table/Fig-5]: DPPH radical scavenging assay comparing chitosan biocomposite and standard at various concentrations. Data are presented as mean±standard deviation (n=3).
#Independent t-test applied for comparison between standard and test groups at each concentration. p<0.05 is considered statistically significant. SD: Standard deviation; µg/mL: Micrograms per millilitre; t: Student's t-value.

H_2O_2 scavenging assay: The chitosan-based biocomposite demonstrated concentration-dependent hydrogen peroxide scavenging activity, achieving a maximum inhibition of 80.21±1.3% at 50 µg/mL, Although the standard antioxidant consistently exhibited slightly higher inhibition across all concentrations, and the statistical analysis revealed no significant difference (p>0.05) [Table/Fig-6] between the biocomposite and standard across all tested concentrations, the biocomposite showed efficient and progressive neutralisation of reactive oxygen species, highlighting its promising antioxidant potential.

Concentration (µg/mL)	Standard (% Inhibition, Mean±SD)	Biocomposite (% Inhibition, Mean±SD)	p-value	t-value
10	54.38±1.2	47.13±1.4	0.224	1.42
20	63.59±1.3	57.26±1.3	0.188	1.57
30	71.18±1.4	66.48±1.2	0.172	1.63
40	78.72±1.2	75.39±1.1	0.241	1.36
50	84.03±1.5	80.21±1.3	0.203	1.48

[Table/Fig-6]: H_2O_2 radical scavenging assay comparing chitosan biocomposite and standard at various concentrations. Data are presented as mean±standard deviation (n=3).
#Independent t-test applied for comparison between standard and test groups at each concentration. p<0.05 is considered statistically significant. SD: Standard deviation; µg/mL: Micrograms per millilitre; t: Student's t-value.

FRAP assay: The FRAP assay confirmed the biocomposite's dose-dependent antioxidant efficacy, with inhibition values ranging from 74.02±1.3% at 10 µg/mL to 83.29±1.5% at 50 µg/mL. Although the statistical analysis revealed no significant difference (p>0.05) between the biocomposite and standard across all tested concentrations [Table/Fig-7], the biocomposite exhibited strong ferric ion reduction, comparable to the standard.

The results of all three different antioxidant assays revealed that the comparison between the standard and the biocomposite showed no statistically significant difference (p>0.05).

Concentration (µg/mL)	Standard (% Inhibition, Mean±SD)	Biocomposite (% Inhibition, Mean±SD)	p-value	t-value
10	76.12±1.4	74.02±1.3	0.268	1.21
20	78.39±1.3	76.18±1.2	0.231	1.34
30	80.72±1.2	78.44±1.4	0.253	1.27
40	82.91±1.5	80.63±1.6	0.276	1.18
50	85.45±1.4	83.29±1.5	0.259	1.25

[Table/Fig-7]: FRAP assay comparing chitosan biocomposite and standard at various concentrations. Data are presented as mean±standard deviation (n=3).
#Independent t-test applied for comparison between standard and test groups at each concentration. p<0.05 is considered statistically significant. SD: Standard deviation; µg/mL: Micrograms per millilitre; t: Student's t-value.

DISCUSSION

The development of biocomposites incorporating plant-based bioactive compounds into biopolymeric matrices represents a promising frontier in biomedical material science. In the present study, a chitosan-based biocomposite loaded with *Vaccinium sect. Cyanococcus* (blueberry) and *Zingiber officinale* (ginger) extracts were synthesised and evaluated for their anti-inflammatory, and antioxidant potential.

The findings demonstrated anti-inflammatory potential similar to the standard. This enhanced performance is attributed to the synergistic interactions between the plant-derived phytoconstituents and the chitosan matrix, offering a multifunctional platform with superior therapeutic outcomes.A study by Xie C et al., reported that blueberry supplementation reduced serum levels and gene expression of pro-inflammatory cytokines TNF-α and IL-6 in ApoE$^{-/-}$ mice [19]. Polyphenol-enriched extracts inhibited LPS-induced inflammation in macrophages. This effect was mediated through suppression of NF-κB, MAPK, and JNK pathways. Similarly, a systematic review and meta-analysis by Jalali M et al., showed that ginger contains bioactive compounds such as gingerols, shogaols, and zingerone that exert anti-inflammatory effects by inhibiting cyclooxygenase-2 and suppressing prostaglandin synthesis [20].

In addition to its anti-inflammatory effects, the biocomposite exhibited robust antioxidant activity, a crucial attribute for therapeutic applications involving oxidative stress, such as chronic inflammation, tissue injury, and wound healing. The antioxidant potential was evaluated using DPPH, H_2O_2, and FRAP radical scavenging assays, which revealed significantly higher free radical scavenging capacity in the blueberry-ginger-loaded chitosan composite. Dudek A et al., explained that anthocyanins from blueberries are potent antioxidants due to their ability to donate hydrogen atoms and stabilise free radicals through delocalised conjugated systems [21]. Ginger-derived compounds, particularly 6-shogaol, formed by dehydration of 6-gingerol, exhibit potent anti-inflammatory and antioxidant effects. Preclinical studies have demonstrated that 6-shogaol suppresses leukocyte infiltration, reduces oedema, and downregulates inflammatory mediators, including COX-2 and iNOS, by modulating the NF-κB, MAPK, and Nrf2/HO-1 pathways, as noted by Bischoff-Kont I et al., [22].

Comparative analysis with other chitosan-based antioxidant systems highlights the superior performance of the current biocomposite. For instance, Mittal A et al., highlighted that chitosan–green tea composites containing epigallocatechin gallate showed notable antioxidant activity; however, their stability under light and pH variations is limited, often resulting in rapid degradation of catechins [23]. Chitosan–turmeric composites by Li H et al., exhibited strong antioxidant potential due to curcumin, but curcumin's low water solubility and poor bioavailability hinder consistent activity in aqueous or physiological environments [24]. In contrast, the co-loading of blueberry and ginger extracts provides both hydrophilic and lipophilic antioxidant constituents, enhancing solubility and bioavailability while enabling sustained release from the chitosan matrix. This dual-phase antioxidant protection contributes to a prolonged scavenging effect, which is particularly beneficial in biological systems where oxidative stress persists over time.

The observed multifunctionality of the chitosan-blueberry-ginger biocomposite arises from synergistic phytochemical interactions, where compounds such as anthocyanins and gingerols exhibit amplified bioactivity when integrated. Clinically, chitosan is extensively employed in wound healing due to its multifunctional properties, including potent haemostatic activity, intrinsic antimicrobial effects, and ability to stimulate fibroblast proliferation. It enhances angiogenesis, accelerates epithelial regeneration, and is widely used in surgical dressings, burn management, and periodontal procedures, reflecting its strong translational value [25,26]. From a materials perspective, the inclusion of these bioactives into the chitosan matrix not only enhances biological functionality but also contributes to mechanical stability and controlled release properties. This biocomposite, with its proven antioxidant and anti-inflammatory profiles, offers significant potential for biomedical applications such as wound healing, antioxidant therapy, drug delivery systems, promising alternative to synthetic biomaterials in periodontal therapy and tissue engineering. Through systematic evaluation, the study supports the advancement of environmentally responsible, phytochemical-augmented biomedical solutions aligned with modern therapeutic expectations.

Limitation(s)

This investigation was confined to ex-vivo conditions, which may not fully replicate the complexity of in-vivo biological responses. Pharmacokinetic behaviour, degradation profile, and potential immunogenicity of the biocomposite were not assessed. Additionally, the absence of long-term exposure studies limits understanding of sustained biocompatibility. Future studies should emphasise in-vivo validation, pharmacokinetic profiling, and long-term therapeutic evaluations to substantiate the translational potential of this phytochemical-enriched, eco-friendly biomaterial.

CONCLUSION(S)

The chitosan-based biocomposite incorporating *Vaccinium sect. Cyanococcus* (blueberry) and *Zingiber officinale* (ginger) extracts demonstrated potent anti-inflammatory and antioxidant effects ex-vivo, highlighting the synergistic bioactivity of natural polymers and plant-derived phytochemicals. Enhanced cellular compatibility,

suppression of pro-inflammatory mediators, and free radical scavenging confirm its potential as a biologically active, eco-friendly material for therapeutic applications. These findings support its promising role in periodontal regenerative strategies and biomedical formulations, paving the way for further in-vivo and translational research.

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