Ayurveda Sahiti Prabha's
International Journal of Ayurvedic Medicine
ISSN No: 0976-5921

Research Article

Boswellia serrata Gum-Derived Polysaccharide Beads for Enhanced Antioxidant Stabilization and Protection

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Received: 23-01-2026 Accepted: 19-06-2026 Published: 30-06-2026

Abstract

Natural polysaccharides are gaining prominence as sustainable biomaterials for drug delivery and antioxidant protection. *Boswellia serrata* gum polysaccharide (BSP), a biopolymer known for its antioxidant and bioadhesive properties, was isolated and employed to develop polymeric beads for sustained bioactivity of *Andrographis paniculata* (Kalmegh) extract. BSP was extracted using hot-water extraction, ethanol precipitation, and dialysis, yielding 14.3% purified polysaccharide. Polymeric beads were prepared via ionotropic gelation with calcium alginate as the base and varying concentrations of BSP or dextran as co-polymers. The formulations (F1–F6) were evaluated for physicochemical and functional parameters including particle size, swelling index, entrapment efficiency, drug loading, and in vitro antioxidant capacity using DPPH and H_2O_2 assays over ten weeks. BSP-based formulations exhibited smaller particle sizes (0.63–0.70 mm), higher swelling (up to 86.4%), and superior entrapment efficiency (up to 86%) compared with dextran-based beads. Formulation F6 (BSP 20%) showed the highest drug loading (31%) and maintained strong scavenging activity for ten weeks, indicating sustained bioactivity and stability. The findings establish BSP as a natural, biocompatible polymeric carrier capable of extending antioxidant efficacy and suggest its potential application in long-acting nutraceutical and therapeutic formulations.

Keywords: *Boswellia serrata*, Polysaccharide, Polymeric beads, Antioxidant, *Andrographis paniculata*, Ionotropic gelation, Natural biomaterial

Access this article online

Website: https://ijam.co.in

DOI: https://doi.org/10.47552/ijam.v17i2.6981

Introduction

Natural polysaccharides have attracted significant interest as multifunctional biomaterials for drug delivery, tissue engineering, and antioxidant protection owing to their biodegradability, biocompatibility, and structural flexibility. Among them, polysaccharides from *Boswellia serrata* gum (BSP) are an interesting class of naturally occurring polymers possessing high film-forming capacity, mucoadhesive nature, and free radical scavenging ability. Conventionally, *Boswellia serrata*, or Indian frankincense, has been used in Ayurvedic and Unani medicinal practices due to its powerful anti-inflammatory, antioxidant, and immunomodulatory activities largely due to both its resinous terpenoids and hydrophilic polysaccharide fractions. While natural polysaccharides such as guar gum, xanthan gum, and chitosan have been widely explored as drug delivery matrices, the potential of *Boswellia serrata* polysaccharide (BSP) as a multifunctional carrier with inherent antioxidant activity remains largely unexplored (1–3).

Recent development in natural polymer science points out the potential of plant-based polysaccharides as encapsulating matrices to deliver bioactive molecules from degradation and ensure sustained and controlled release (4,5). Yet, the intrinsic instability of a wide range of natural antioxidants, such as those from *Andrographis paniculata* (Kalmegh), subjected to physiological and environmental stress restricts their therapeutic potential (6). In an attempt to overcome this limitation, the production of BSP-based polymeric beads presents a double benefit: utilizing the inherent antioxidant and film-forming properties of BSP, as well as enhancing the stability, bioavailability, and drug release behavior of phytochemicals entrapped (7,8).Ionotropic gelation is still the most effective method for the preparation of such biopolymer beads because of its gentle processing conditions and capacity to maintain the structural integrity of thermally labile natural compounds (9). Incorporation of BSP into matrices of calcium alginate can also stabilize the beads and regulate diffusion-controlled release of active ingredients. This hybrid system not only offers mechanical strength and antioxidant synergy but also complies with the modern drive for sustainable, nature-based materials in pharmaceutical innovation (10).

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Therefore, this study focuses on the isolation and characterization of polysaccharides from *Boswellia serrata* gum and the development of BSP-based polymeric beads for the sustained bioactivity and antioxidant protection of *Andrographis paniculata* extract. By combining traditional medicinal resources with modern polymer science, this work aims to establish a green, biocompatible platform for prolonged antioxidant therapy and nutraceutical applications.

Materials and Methods

Materials

Boswellia serrata gum was procured from the Indian Institute of Natural Resins and Gums (IINRG), Namkum, while leaves of *Andrographis paniculata* were obtained from the West Bengal Medicinal Plant Board, Kalyani, India. All other reagents and solvents used in the study were of analytical grade (Nice, Loba Chemie, or Himedia), and deionized water was utilized throughout the experimental procedures.

Extraction of plant materials

Dried leaves of *Andrographis paniculata* (commonly known as Kalmegh) were cut into small fragments and macerated with ethanol. The mixture was then subjected to ultrasonic-assisted extraction at 15 MHz for 50 minutes. The extract was subsequently filtered and concentrated under reduced pressure, and the resulting residue was preserved in an airtight container for further analysis. The obtained extract was a crude (normal) ethanolic extract, which was subsequently utilized for the preparation of BSP-based polymeric beads for encapsulation and sustained bioactivity applications. This combined approach enhances extraction efficiency by improving solvent penetration and facilitating the release of intracellular phytoconstituents. Additionally, ultrasonication accelerates mass transfer and reduces extraction time while preserving thermolabile bioactive compounds (11).

Quantification of Andrographolide

Andrographolide was quantified using a high-performance thin-layer chromatography (HPTLC) system (Aspire Scientific, India) equipped with JustTLC software for densitometric analysis. Separation was achieved using a mobile phase of chloroform:methanol (8:2, v/v), with andrographolide detected at an Rf range of 0.39–0.43 (11).

Evaluation of Antioxidant potential of the extract

The antioxidant activity of the only extract (Control) was assessed using hydrogen peroxide (H_2O_2) and 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assays. **These assays were selected due to their complementary evaluation of free radical scavenging and reactive oxygen species neutralization, providing a rapid and reliable assessment of antioxidant potential.** In the H_2O_2 scavenging assay, 1 mL of the sample solution was combined with 0.6 mL of 40 mM H_2O_2 prepared in phosphate buffer (pH 7.4) and incubated at room temperature for 10 minutes. The absorbance was measured at 230 nm, and the percentage scavenging activity was calculated relative to the blank. For the DPPH assay, 1 mL of 0.1 mM DPPH solution in methanol was mixed with 1 mL of the sample solution and incubated in the dark for 30 minutes. The absorbance was then recorded at 517 nm, and the radical scavenging percentage was calculated with respect to the control. Ascorbic acid served as the reference antioxidant standard for both assays (12).

Isolation of polysaccharide from *B. seratta* gum

Isolation of the polysaccharide was carried out following the method described by Pathak *et al*. (2024) with minor modifications. Briefly, 100 g of dried *Boswellia serrata* gum was crushed and boiled in 900 mL of distilled water using a water bath at 90°C for 8 hours. The resulting mixture was allowed to cool to room temperature and kept overnight. The dispersion was then filtered through a muslin cloth, and the filtrate was centrifuged at 3500 rpm for 15 minutes (R-8C, Remi, India) to remove residual impurities. The supernatant was concentrated to one-sixth of its initial volume and subsequently precipitated with 95% ethanol in a 1:5 (v/v) ratio. The resulting precipitate was collected by centrifugation (3500 rpm, 4 minutes) and dialyzed using a cellulose membrane (HiMedia, 12–14 kDa molecular weight cut-off) for 12 hours at 4 °C to eliminate low molecular weight fractions. The dialyzed fraction was purified further using a Sephadex column and lyophilized to obtain the crude polysaccharide, designated as BSP (13).

Formulation of polymeric beads

Kalmegh-loaded polymeric beads were formulated by the ionotropic gelation technique. In this method, *Andrographis paniculata* extract was uniformly dispersed in a sodium alginate solution, and the resulting suspension was extruded dropwise through a fine-gauge needle into a gently stirred 0.1 M calcium chloride ($CaCl_2$) solution at a controlled rate of 10–12 drops per minute. The formed beads were allowed to cure in the $CaCl_2$ solution for 12 hours to ensure complete cross-linking. Subsequently, the beads were collected by filtration, rinsed thrice with distilled water, and air-dried for 24 hours at ambient temperature, followed by oven-drying at 45 °C for an additional 24 hours. Various formulations were prepared by incorporating dextran and *Boswellia serrata* polysaccharide (BSP) in different proportions (Table 1) to evaluate their effects on bead characteristics and drug entrapment efficiency (14-16).

Table 1: Formulation of polymeric beads

Ingredients	Formulations (%)					
	F1	F2	F3	F4	F5	F6
Kalmegh	10	10	10	10	10	10
Dextran	10	15	20	-	-	-
BSP Polysaccharide	-	-	-	10	15	20
Sodium alginate	2	2	2	2	2	2
Calcium Chloride	5	5	5	5	5	5

Evaluation of polymeric beads

Particle size

The diameter of the dried polymeric beads was determined using a vernier caliper as well as an optical microscope. Measurements were performed on ten randomly selected beads, and the average bead diameter was expressed as the mean ± standard deviation (SD) (17).

Swelling index

The swelling behavior of the polymeric beads was evaluated in 0.1 M HCl (pH 1.2) and phosphate buffer (pH 6.8) to simulate gastric and intestinal conditions, respectively. A pre-weighed quantity (100 mg) of beads was immersed in 900 mL of each respective medium within dissolution vessels of a USP type II (paddle) dissolution apparatus (Electrolab TDP-08L, India). The study was conducted at 37 ± 0.5 °C with a paddle rotation speed

of 50 rpm. Beads were periodically removed at predetermined intervals, gently blotted with tissue paper to remove surface moisture, and weighed immediately (18). The degree of swelling was determined based on the weight change of the beads, and the swelling index (SI) was calculated using the following equation:

$$\%Swelling = \left(\frac{W_s - W_d}{W_d}\right) \times 100$$

Where, W_s = weight of swollen beads, W_d = weight of dry beads

Microencapsulation efficiency

The entrapment efficiency (EE) of the formulated beads was determined by allowing 100 mg of beads to disintegrate completely in 100 mL of phosphate buffer (pH 6.8) under continuous stirring. The resulting dispersion was filtered, and the drug content in the filtrate was quantified spectrophotometrically at λmax 230 nm using a UV–visible spectrophotometer (UV-160A, Shimadzu Co. Ltd., Kyoto, Japan) (19). All measurements were performed in triplicate, and the entrapment efficiency was calculated using the following equation:

$$\text{Encapsulation efficiency (EE\%)} = \left(\frac{Total Drug - Unencapsulated\ drug}{Total\ Drug}\right) \times 100$$

Structural and Morphological evaluations

The particle size and surface texture of BSP based beads were measured by microscopic analysis methods using Quasmo M02 Microscope at 400X magnification. The average particle sizes and the external texture of different formulations were evaluated.

Evaluation for extension of antioxidant activity of plant materials

DPPH scavenging assay

The free radical scavenging activity of the polymeric bead extract was evaluated using the Blois method based on the DPPH assay. Briefly, 1 mL of 0.1 mM DPPH solution in methanol was mixed with 3 mL of the polymeric bead solution. The mixture was incubated at 37 °C for 30 minutes in the dark, and the absorbance was subsequently measured at 517 nm using a UV–visible spectrophotometer (Shimadzu, Japan). A control sample containing only the DPPH solution without extract was used as reference (20). The percentage of inhibition (I), representing the radical scavenging activity, was calculated using the following equation:

$$\%\ DPPH\ scavenging\ assay = \left(\frac{A_C - A_S}{A_C}\right) \times 100$$

H_2O_2 scavenging assay

A hydrogen peroxide (H_2O_2) solution (40 mM) was freshly prepared in phosphate buffer (pH 7.4). The concentration of H_2O_2 was verified spectrophotometrically by measuring absorbance at 230 nm using a UV–visible spectrophotometer (Shimadzu, Japan). Polymeric bead samples dispersed in distilled water were added to 0.6 mL of the H_2O_2 solution (40 mM), and the mixture was incubated for 10 minutes at room temperature. The absorbance of H_2O_2 at 230 nm was then recorded against a blank solution containing phosphate buffer without H_2O_2 (21). The percentage of H_2O_2 scavenging activity of the extract or α-tocopherol (used as reference standard) was calculated using the following equation:

$$\%H2O2\ scavenging\ activity = \left(\frac{A_C - A_S}{A_C}\right) \times 100$$

Where, A_c = absorbance of control, A_s = absorbance of sample

Statistical analysis

All data are presented as mean ± SEM (n = 3). Statistical significance was assessed using one-way ANOVA, with $p < 0.05$ considered significant.

Results

Quantification of andrographolide

Andrographolide was successfully identified and quantified by HPTLC, exhibiting a well-resolved and reproducible peak at an Rf value of approximately 0.42 under the optimized chromatographic conditions. Quantitative densitometric analysis revealed an andrographolide content of 1.47%, indicating efficient extraction and reliable analytical performance. The stack but distinct band at this Rf further confirms the specificity of the method and suggests minimal interference from co-eluting phytoconstituents, supporting its suitability for routine standardization of *Andrographis paniculata* extracts (11).

Antioxidant activity of Kalmegh

The concentration-dependent DPPH radical scavenging activity of *Andrographis paniculata* (Kalmegh) extract and ascorbic acid was systematically assessed, and the findings are summarized in Table 2. Ascorbic acid, employed as the reference antioxidant, demonstrated markedly superior free-radical quenching capacity at all tested concentrations, as reflected in its lower IC_{50} value (33.57 ± 0.38 µg/mL) compared with that of the Kalmegh extract (41.09 ± 0.47 µg/mL). Despite this difference, the extract exhibited considerable antioxidant potential, indicating its ability to neutralize reactive oxygen species effectively. Such activity highlights the potential therapeutic role of *A. paniculata* in mitigating oxidative stress–associated pathologies, including cardiovascular and neoplastic disorders. Nevertheless, the relatively shorter duration of its antioxidant effect may limit its pharmacological applicability. Incorporation of the extract into a polysaccharide-based carrier system could provide a sustained bioactivity, thereby prolonging its antioxidant action and enhancing its overall bioefficacy (22,23).

Table 2: Anti oxidation activity of *A. paniculata* extract

Sample	Concentration (µg/ml)	% Scavenging	IC50 Value (µg/ml)
Ascorbic Acid	0	28.690± 0.19	33.57 ± 0.38
	10	34.927± 0.12	
	20	45.738± 1.21	
	40	54.677± 0.37	
	60	67.983± 0.37	
	80	77.754± 0.37	
	100	84.407± 0.37	
A. paniculata extract	0	12.910± 0.45	41.09± 0.47
	10	26.860± 0.78	
	20	37.329± 0.66	
	40	49.924± 0.91	
	60	58.715± 0.91	
	80	63.819± 0.91	
	100	79.110± 0.91	

Yield of polysaccharide

A previously uncharacterized polysaccharide, designated as BSP, was isolated from the dried gum of *Boswellia serrata* through a sequential process involving hot-water extraction, ethanol

precipitation, dialysis against distilled water, and subsequent lyophilization. The extraction yielded approximately 14.3% (w/w, based on the lyophilized weight of the crude gum), which represents a notably higher recovery compared with previously reported polysaccharide yields from other *Boswellia* species, typically averaging around 6.8%. This enhanced yield underscores the efficiency of the optimized extraction protocol and suggests that *B. serrata* gum may serve as a rich source of bioactive polysaccharides for further structural and pharmacological evaluation (24). Further the polysaccharide the polysaccharide was structurally a glucomannan (←4) -Glcp-(1←3) -Manp-(1→) reported by Mondal et al., 2026. (25)

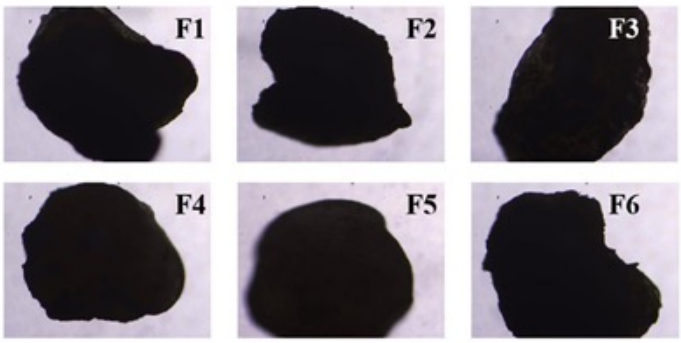
Particle size and surface morphology

Particle size analysis of six alginate bead formulations (F1–F6) demonstrated diameters ranging from 0.66 mm to 0.79 mm. Among them, formulation F3 produced the largest beads (0.79 mm), possibly due to its higher alginate concentration or slower droplet detachment during ionic gelation. Conversely, F6 generated the smallest beads (0.66 mm), likely resulting from reduced solution viscosity or accelerated crosslinking kinetics (Table 3; Fig. 1). These findings highlight the critical role of polymer concentration and gelation dynamics in determining the morphological characteristics of alginate-based bead systems (26). Morphologically, the beads were irregular in shape resembling oval structure. Although, the surface appeared to be creased there were little to no observed cracks or pores observed.

Table 3: Particle size of the polymeric beads

Formulation	Particle Size (mm)
F1	0.79±0.011
F2	0.76±0.005
F3	0.70±0.01
F4	0.69±0.02
F5	0.68±0.015
F6	0.63±0.02

Figure 1: Minimized exterior pictogram six formulations



Swelling index

The swelling behavior of polymer bead formulations (F1–F6) was monitored at 1-hour intervals over a 6-hour period. Among the tested formulations, F6 exhibited the highest swelling index (86.4% at 6 h), followed by F4 (84.6%) and F3 (83.4%). The pronounced swelling in these formulations suggests a relatively open or less crosslinked polymeric network, facilitating greater water penetration and diffusion of the encapsulated *Andrographis paniculata* (Kalmegh) extract. In contrast, F2 demonstrated the lowest swelling index (66.22% at 6 h) across all time points, indicative of a denser matrix structure and higher polymer concentration that restricts fluid uptake (Table 4). The enhanced swelling observed in F3, F4, and F6 may therefore be attributed to formulation-specific modifications that increased the porosity and hydrophilicity of the bead matrices, improving their water absorption capacity (27).

Table 4: Swelling indices of polymeric beads

Time (h)	Swelling Index (%) of the polymeric beads					
	F1	F2	F3	F4	F5	F6
0	0	0	0	0	0	0
1	9.63± 0.456	7.01± 0.2	11.45± 0.167	13.46± 0.304	14.93± 0.310	16.21± 0.132
2	24.25± 0.286	20.64± 0.219	21.86± 0.148	26.23± 0.268	26.92± 0.233	27.6± 0.134
3	37.44± 0.207	31.83± 0.148	37.46± 0.089	36.82± 0.192	37.61± 0.35	40.39± 0.203
4	48.84± 0.109	42.69± 0.219	56.84± 0.258	52.61± 0.207	54.68± 0.151	57.63± 0.151
5	59.08± 0.223	52.26± 0.164	72.29± 0.178	71.42± 0,114	77.18± 0.122	71.20± 0.086
6	71.43± 0.167	66.22± 0.363	83.43± 0.207	84.64± 0.313	89.21± 0.192	86.41± 0.169

Drug entrapment efficiency

The encapsulation efficiency of the six polymer bead formulations (F1-F6) was quite diverse and ranged from 78.5% to 86%. F6 presented the highest (86%) entrapment efficiency and was closely followed by F3 (85%) and F2 (82.5%). This implies that drug was more trapped within the polymer matrix. The least efficient formulation was F1 (78.5%), suggesting that the formulation was not optimum. Both dextran (F1–F3) and BSP (F4–F6) formulations presented as potential candidates for optimum drug encapsulation (Table 5; Fig. 2); however, the results suggested that entrapment efficacy is largely dependent on specific formulation variables, such as polymer concentration, and drug to polymer ratios. It may be that in some cases BSP can package chemical agents as well or better than dextran, possibly reflected by the enhanced efficiency seen with F6 under ideal conditions (28).

Table 5: Drug loading efficiency and entrapment efficiency of the polymeric bead formulations

Formulation	Free Drug		Entrapment Efficiency (%)	Drug Loading Efficiency (%)
	Absorbance (nm)	Concentration (µg/ml)		
F1	0.754	8.584524	78.538± 0.089	21.816± 0.212
F2	0.625	7.048810	82.377± 0.108	25.425± 0.148
F3	0.539	6.025000	84.937± 0.166	23.398± 0.177
F4	0.637	7.191667	82.020± 0.321	26.458± 0.263
F5	0.671	7.596429	81.008± 0.122	27.002± 0.045
F6	0.504	5.608333	85.979± 0.303	30.706± 0.209

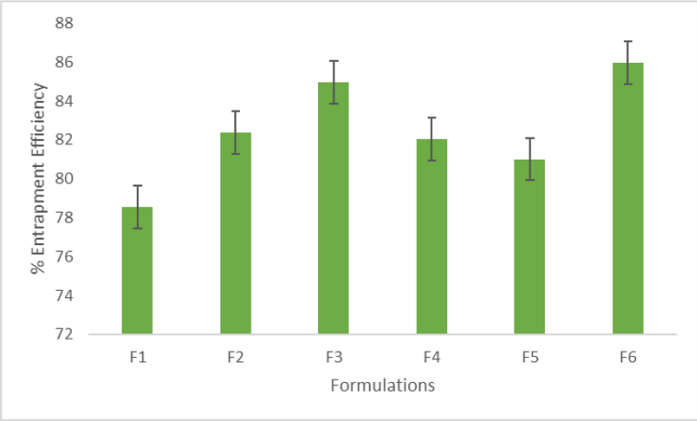
The specificity of the UV spectrophotometric method was ensured by analyzing appropriate blank and placebo matrices, which

confirmed negligible interference from other phytoconstituents at the selected wavelength, that is, 230 nm.

% Drug loading

The polymeric bead formulations (F1–F6) demonstrated drug loading efficiencies ranging from 22% to 31%. Among these, formulation F6 exhibited the highest drug loading (30.70%), followed by F5 (27.002%) and F4 (26.458%), indicating a strong potential for efficient drug entrapment within these matrices. In contrast, F1 showed the lowest loading efficiency (21.816%), suggesting that its composition or preparation parameters were suboptimal for effective drug encapsulation. The progressive increase in drug loading from F1 to F6 reflects the influence of polysaccharide type and formulation optimization. Specifically, beads formulated with Boswellia serrata polysaccharide (F4–F6) demonstrated slightly higher loading efficiencies compared with dextran-based systems (F1–F3) (Table 5), likely due to favorable physicochemical interactions between BSP and the active constituent. These findings suggest that BSP serves as a promising polymeric matrix for enhancing drug entrapment and retention in controlled-release formulations (29).

Figure 2: Drug entrapment efficiency of the bead formulations

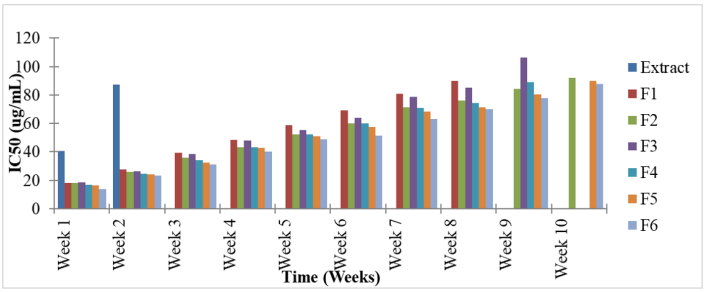


Extended time-based antioxidant properties of polysaccharides

DPPH scavenging assay

The DPPH radical scavenging assay demonstrated that Kalmegh-based formulations effectively preserved antioxidant activity over a 10-week period, continuing upto 3 months in accelerated environmental conditions. All six formulations (F1–F6) were compared with the crude extract, revealing distinct differences based on polymer type. The dextran-based formulations (F1–F3) exhibited moderate to strong antioxidant activity, maintaining efficacy for approximately 8–9 weeks, with a slight improvement observed at higher dextran concentrations. In contrast, formulations incorporating Boswellia serrata polysaccharide (BSP) (F4–F6) displayed superior scavenging activity, particularly at later stages (Weeks 8–10), suggesting enhanced stability and protection of bioactive constituents of Kalmegh. Among them, F5 (BSP 15%) and F6 (BSP 20%) recorded the lowest IC_{50} values, indicating greater antioxidant potency (Fig. 3), which even continued for next two weeks, upto 3 months of time. This improvement may be attributed to favorable physicochemical interactions between BSP and Kalmegh phytochemicals, facilitating sustained bioactivity. Overall, both dextran and BSP matrices effectively extended the antioxidant lifespan of Kalmegh, with BSP showing a slight advantage, potentially due to its natural resinous composition that enhances bioadhesion and moderates degradation kinetics (30). BSP-based polymeric beads enhance DPPH scavenging by **encapsulating and protecting phytoconstituents while enabling controlled, sustained release,** thereby maintaining prolonged antioxidant availability. Additionally**, hydrogen bonding interactions between BSP and phenolics stabilize bioactives,** and the **intrinsic radical scavenging property of BSP produces a synergistic effect.** Consequently, BSP formulations (F5–F6) exhibit **lower IC_{50} and extended antioxidant activity compared to dextran systems (31).**

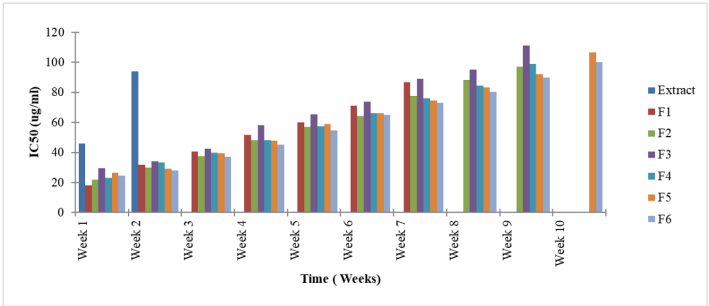
Figure 3: DPPH scavenging assay of extracts and formulations



H_2O_2 scavenging assay

Based on the experimental findings, the antioxidant potential of polymeric bead formulations (F1–F6) was evaluated over a 10-week period with extension upto in comparison with the crude extract to assess the sustained bioactivity of the encapsulated *Andrographis paniculata* (Kalmegh) extract. Among the formulations, F2 (dextran-based) demonstrated promising antioxidant activity during the initial weeks, achieving a substantial IC_{50} value by the eighth week, followed by a rapid decline thereafter. In contrast, formulations F4, F5, and F6, incorporating *Boswellia serrata* polysaccharide (BSP)—exhibited a progressive and sustained increase in antioxidant activity throughout the study period, with F6 showing the most consistent performance up to week 10 (IC_{50} = 92.31 ± 0.83) (Fig. 5). This steady antioxidant response suggests a controlled and prolonged release profile in BSP-based formulations. The extended activity observed in these formulations indicates enhanced stability of the encapsulated bioactives and improved release modulation compared to the dextran-based systems. BSP-based polymeric beads enhance H_2O_2 scavenging by **protecting encapsulated phytoconstituents from oxidative degradation and enabling sustained release,** ensuring prolonged interaction with hydrogen peroxide. Additionally, **the inherent antioxidant activity of BSP and its stabilizing polymer–drug interactions contribute to improved and extended reactive oxygen species neutralization** (32).

Figure 4: H_2O_2 scavenging assay of extracts and formulations



Discussion

The current study illustrates the successful isolation of *Boswellia serrata* gum polysaccharide (BSP) and its application in developing polymeric beads with prolonged antioxidant protection. BSP provided extraction yields (14.3%) much higher than those reported for other Boswellia species indicating the selected gum material can yield relatively high polysaccharide content and extractability. The physicochemical characteristics of BSP including high hydrophilicity, capability to form films, and intermolecular hydrogen bonding complex, provide significant potential for its application in encapsulation systems designed for natural bioactives (33).

Formulations of polymeric beads produced containing BSP displayed particle size ranges of 0.63mm-0.79 mm consistent with previously reported ionotropically gelled based systems. Particle size appeared to vary proportionately to polymer viscosity and rate of droplet detachment from the impeller during gelation. F6 was observed to have the smallest particle size and uniformity in bead size indicating a successful optimization for the polymer-crosslinker interaction. As expected, the swelling index exhibited a gradual increase across formulations containing higher quantities of BSP suggesting the inclusion of BSP improved hydration of the gel matrix and subsequent pore expansion, which are beneficial factors for sustained bioactivity. The efficiency of entrapment and drug loading in formulations containing BSP (F4-F6) was markedly higher than that of dextran-based beads (F1-F3). This may be attributed to the presence of hydroxyl and carboxyl functional groups in BSP, which formed hydrogen bonds and electrostatic interactions with the phenolic components of Andrographis paniculata extract, thereby enhancing encapsulation. A similar enhancement effect has been reported for other natural polysaccharide systems such as matrices containing guar gum and xanthan gum (34).

In the extended antioxidant studies, it was found that beads based on BSP achieved stable scavenging activity over 10 weeks, whereas the dextran-based system appeared to lose activity by week 8. This suggests that BSP offers relatively better protection against oxidative degradation, likely because of its inherent radical scavenging capacity and polymeric viscosity, which would hinder reactive oxygen species diffusion . Formulation F6, containing the highest amount of BSP, produced the lowest IC_{50} values in both DPPH and H_2O_2 assays over an extended period of storage, supported improved controlled release and increased antioxidant synergies. Such sustained bioactivity effects are particularly desirable for formulations developed for the treatment of disorders mediated by chronic inflammation and oxidative stress (35, 36).

The combination of BSP with Andrographis extract illustrates a synergistically-based application—a traditional pharmacological capacity of phytoconstituents with modern polymer engineering. The process of ionotropic gelation helped ensure structural stability without thermal degradation and produced beads that may serve as a biofriendly alternatives to synthetic polymers. Collectively the data propose that BSP may act as both a stabilizing matrix and as an active antioxidant compound, reinforcing its dual use in natural polymer-based delivery systems. Overall, these findings are consistent with current trends for eco-sustainable, biocompatible carriers for the functional food and pharmaceutical industry applications (35).

Conclusion

The gum polysaccharide of *Boswellia serrata* was successfully used to create polymeric beads that effectively encapsulated and stabilized *Andrographis paniculata* extract. The BSP-based formulations showed higher entrapment efficiency, controlled swelling, and longer antioxidant activity compared to dextran-based formulations. Therefore, BSP is a powerful natural polymer and offers sustained bioactivity and antioxidant protection, providing a new and exciting platform for future nutraceutical and therapeutic formulations.

Acknowledgement

The authors would like to thank Central Instrumental facility, Brainware University, Kolkata for providing the facilities in completion of research in this manuscript.

Funding: No

Conflict of interest: The authors declare that there is no conflict of interests regarding the publication of this article.

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