



## Alginate–gum Arabic beads for encapsulation of longan extract: Improving efficiency, stability, and safety

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### ABSTRACT

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#### Keywords

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Phenolic compounds from longan (*Dimocarpus longan* Lour.) extract possess strong antioxidant properties but are highly unstable during processing and storage, limiting their application in functional foods. This study aimed to develop an alginate–gum Arabic encapsulation system to enhance the efficiency, stability, and microbial safety of longan phenolic compounds. Beads were produced using an extrusion technique with 1.5% (w/v) sodium alginate and 4% (w/v) calcium chloride as the optimal gelling condition, and gum Arabic was incorporated as a co-polymer to improve bead performance. The formulation containing gum Arabic exhibited the highest encapsulation efficiency (74.9%), and stability evaluations revealed superior retention of phenolic compounds under acidic conditions (pH 2), with a more controlled release profile compared to neutral and alkaline environments. To address microbial safety, gamma irradiation at 5 and 7.5 kGy was applied; a dose of 5 kGy increased bead firmness, whereas 7.5 kGy achieved complete sterilization without compromising structural integrity or functional properties. These findings indicate that the integration of alginate with gum Arabic significantly enhances both encapsulation performance and bioactive stability, while gamma irradiation serves as an effective non-thermal sterilization method. The developed system demonstrates strong potential for application as a delivery platform in functional food and nutraceutical formulations requiring stability and safety assurance.

**Contribution/Originality:** This study contributes to the existing literature by developing a novel alginate–gum Arabic encapsulation system that improves phenolic compound stability and safety. It is one of the few studies investigating the integration of gamma irradiation with biopolymer-based encapsulation for functional food and nutraceutical applications.

## 1. INTRODUCTION

In recent years, consumers have shown increasing interest in functional foods that not only provide nutrition but also contribute to disease prevention. This trend has encouraged the development of innovative food products with added health benefits. Longan (*Dimocarpus longan* Lour.), a subtropical fruit widely cultivated in Thailand, is one of the country's major economic crops and is also exported to international markets. Despite its appealing taste and aroma, fresh longan is highly perishable. To extend its shelf life, the fruit is commonly processed into canned products,

syrup, or dried longan. These processes, however, generate by-products such as longan seeds, which are often discarded as waste. Notably, longan seeds contain abundant phenolic compounds, including gallic acid, ellagic acid, and corilagin (Sudjaroen et al., 2012), all of which are known for their antioxidant properties.

The functional potential of these bioactive compounds is, however, limited by their rapid metabolism, poor solubility, and instability under heat and light, which together reduce their bioavailability (Walter & Marchesan, 2011). To overcome these drawbacks, encapsulation has been introduced as a strategy to protect sensitive compounds, regulate their release, and improve sensory characteristics (De Souza et al., 2018). Among various encapsulation approaches, extrusion is frequently used because of its simplicity, one-step preparation, and control over particle size. In this method, longan seed extract is incorporated into a hydrocolloid solution, extruded through a nozzle, and solidified in a calcium chloride bath with continuous stirring (Lupo, Maestro, Gutiérrez, & González, 2015). Sodium alginate is the most common encapsulating material due to its non-toxicity, biodegradability, and widespread use in food applications. However, alginate beads are highly porous and unstable under acidic conditions (Pereira et al., 2018). These shortcomings can be mitigated by combining alginate with other polymers, which interact through hydrogen bonding to form stable hydrogel networks (Annisa, Sulaiman, Nugroho, Nugroho, & Kutsyk, 2022).

Gamma irradiation has also gained attention as a sterilization technique. Compared with conventional methods, it provides deep penetration, minimal chemical residues, and low heat generation, making it cost-effective and environmentally friendly (Byun et al., 2008). Moreover, irradiation can modify polysaccharides such as alginate by cleaving glycosidic bonds, which may influence their structural integrity.

Considering these aspects, the present study aimed to (i) investigate the encapsulation efficiency of phenolic compounds from longan seed extract, (ii) evaluate the pH stability of the encapsulated beads, and (iii) explore the application of gamma irradiation as a sterilization method for longan-based encapsulated products.

Despite the widespread use of alginate for encapsulating plant phenolics, evidence is limited on whether blending gum Arabic with alginate can concurrently improve encapsulation efficiency, pH-dependent stability/release, and microbial safety over alginate alone (Annisa et al., 2022; Pereira et al., 2018). Integrating gamma irradiation as a non-thermal sterilization method is also underexplored (Byun et al., 2008). We therefore hypothesize that gum Arabic–alginate beads increase encapsulation efficiency, that acidic pH (~2) enhances retention with slower, controlled release, and that gamma irradiation improves bead firmness at 5 kGy and enables sterilization at 7.5 kGy without impairing structure or function. The remainder of the paper is organized as follows: Section 2, methods; Section 3, results and discussion; Section 4, conclusions.

### 1.1. Literature Review

Phenolic constituents from longan by-products, especially peel and seeds, exhibit strong antioxidant potential but face rapid metabolism, poor aqueous solubility, and processing-induced degradation that limit bioavailability in foods (Sudjaroen et al., 2012; Walter & Marchesan, 2011).

Ionic gelation of alginate is widely adopted to protect sensitive actives and enable pH-responsive release because  $\text{Ca}^{2+}$  cross-links form hydrated networks with tunable permeability. Nonetheless, standalone alginate beads can be porous and acid-labile; blending alginate with complementary biopolymers such as gum Arabic can reinforce gel networks via hydrogen bonding, reduce diffusion under gastric pH, and improve retention and mechanical integrity (Annisa et al., 2022; De Souza et al., 2018; Lupo et al., 2015). Recent reports further document advances in alginate-based carriers and polymer-blend strategies that enhance phenolic stability and bioaccessibility and modulate release behavior (González, Pérez, Gómez, & Rodríguez, 2025; Lai et al., 2024; Martinović et al., 2024).

In parallel, gamma irradiation has emerged as a non-thermal preservation option offering deep penetration and minimal thermal load; controlled dosing can ensure microbial safety while maintaining hydrocolloid functionality and, in some cases, altering alginate chain characteristics relevant to gel performance (Al-Sharif et al., 2025; Aly & Maraie, 2024; Byun et al., 2008).

However, few studies have jointly examined an alginate–gum Arabic system for phenolic stabilization and release, together with a terminal irradiation step for safety, particularly for longan phenolics, leaving acid-phase performance and post-irradiation integrity insufficiently resolved. These gaps motivate the present study.

## 2. MATERIALS AND METHODS

### 2.1. Materials Preparation

Dried longans were sourced from the pilot plant at Maejo University, Chiang Mai, Thailand. The fruit flesh and seeds were blended into powder and subsequently dried at 45°C for 20 hours. The dried material was further milled to obtain a 40-mesh powder (as shown in Figure 1). To ensure sterility, the samples were placed in aluminum trays and irradiated with UV light (254 nm) for 60 minutes inside a type-II laminar flow cabinet (ESCO). Finally, the sterilized powders were sealed in aluminum foil bags and stored in desiccators until analysis.



Figure 1. Longan powder.

### 2.2. Extraction Procedure by Microwave-Assisted Extraction

Microwave-assisted extraction (MAE) was employed to obtain phenolic compounds and evaluate antioxidant activity from longan powder. Approximately 1 g of the powder was mixed with 30 mL of distilled water in a round-bottom flask. The extraction was performed using a modified microwave oven (Samsung MS23F300EEK) connected to a Soxhlet condenser and a cooling system maintained at 10 °C (Coolab, WBCI-15) (as shown in Figure 2). Extraction was carried out for 15 min at 700 W. After extraction, the flask was removed from the microwave and allowed to cool at ambient temperature.

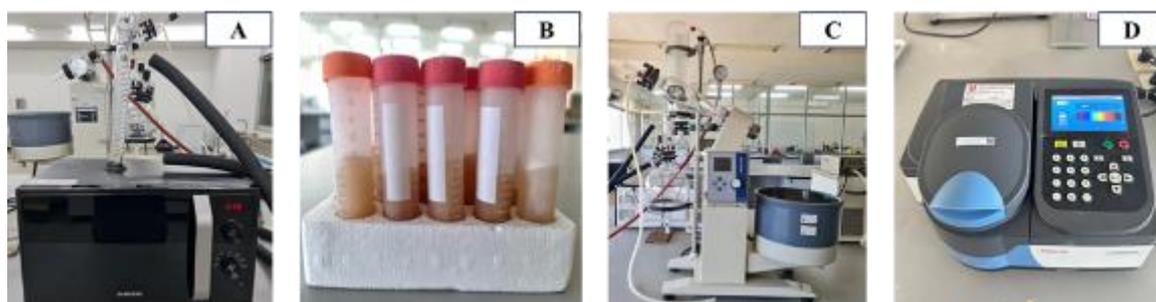


Figure 2. Extraction procedure by Microwave-Assisted Extraction (A) Microwave oven with a Soxhlet extractor set, (B) Longan extracts, (C) Evaporator, (D) Spectrophotometer.

The resulting mixture was centrifuged at 3500 rpm for 15 minutes (Dynamica Velocity 18R), and the supernatant was filtered to obtain a clear extract. The final extract volume was recorded and stored in amber-colored bottles at room temperature to minimize light-induced degradation until analysis (Narkprasom, Narkprasom, & Upara, 2015). Preliminary evaluation showed that the crude extract possessed antioxidant activity of 40.89% and contained 20.14 mg GAE/g of total phenolic compounds. Concentration of the extract by vacuum evaporation increased the soluble

solids to 15 °Brix and raised the total phenolic content to 62.42 mg GAE per sample, representing a threefold increase compared with the initial value.

### 2.3. Encapsulation Procedure

The extrusion technique, with slight modifications from Chatterjee and Bhattacharjee (2015), was applied for bead formation. Preliminary trials were conducted using an Encapsulator B390 (BUCHI Labortechnik AG, Flawil, Switzerland) (as shown in Figure 3) to determine the most suitable operational parameters. Optimal bead stability was achieved at a flow rate of 3 mL/min, a vibration frequency of 1440 Hz, and an electrode voltage of 440 V.

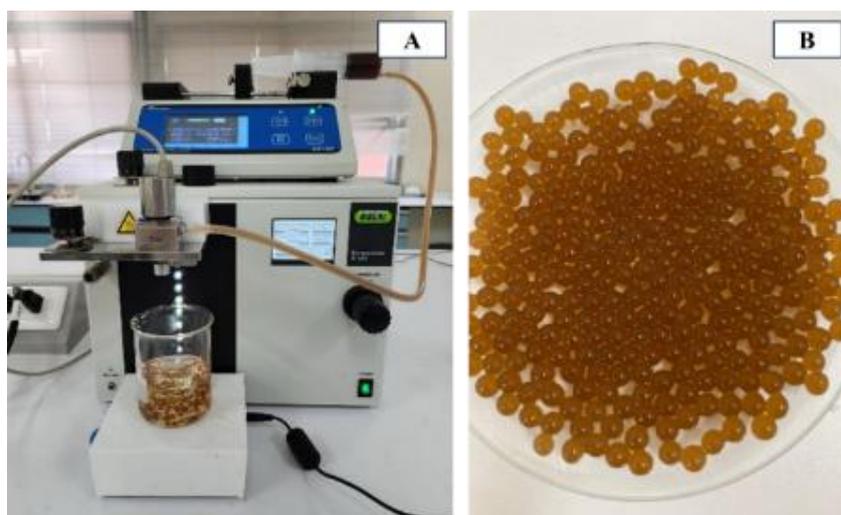


Figure 3. Encapsulation procedure by extrusion method (A) Encapsulator B390, and (B) Longan beads.

To further refine the process, a three-level full factorial design was employed, focusing on two key formulation variables: the sodium alginate concentration (1.0, 1.5, and 2.0 g/mL; Tokuyama Corporation, Japan) and the calcium chloride concentration (3.0, 4.0, and 5.0 g/mL). The response variables included encapsulation efficiency of total phenolic compounds and antioxidant activity. Once the optimal encapsulation conditions were identified, alginate was blended with other natural polymers to evaluate improvements in encapsulation efficiency.

### 2.4. Sizes and Shapes

The particle size of the encapsulated beads was evaluated by randomly selecting 20 beads from each formulation batch. Their diameters were measured using a digital vernier caliper (Model 500-196-30, Mitutoyo, Japan), and the results were reported as mean values with corresponding standard deviations (mean  $\pm$  SD) to reflect size distribution.

### 2.5. Mechanical Properties

Mechanical properties of the beads were assessed using texture profile analysis (TPA) with a TA.XT-PLUS Texture Analyzer (Stable Micro Systems, UK). A total of ten beads were randomly selected and compressed at ambient temperature using a cylindrical P/50 probe. The test parameters included a pre-test speed of 1.0 mm/s, test and post-test speeds of 5.0 mm/s, and a trigger force of 5 g. Each bead was compressed to 75% of its initial height to evaluate textural attributes.

### 2.6. Surface Morphology Analysis

Longan beads were freeze-dried prior to analysis. Surface morphology was examined using scanning electron microscopy (SEM; JEOL JMS-5410LV, Japan). To enhance conductivity, dried samples were affixed to aluminum

stubs with double-sided carbon tape and coated with a 10–20 nm layer of gold using a sputter coater (JEOL JFC-1200). Imaging was performed under high-vacuum conditions at an accelerating voltage of 15 kV.

### 2.7. Encapsulation Efficiency (EE%)

Encapsulation efficiency (EE%) was determined by comparing the total phenolic content retained within the beads (TPC<sub>b</sub>) to that of the initial solution used for bead formation (TPC<sub>s</sub>), following the method adapted from Sudjaroen et al. (2012). Beads were dissolved in 5% (w/v) sodium citrate and centrifuged at 7,500 rpm for 30 minutes at 25°C. The resulting supernatant was analyzed for phenolic compounds, and EE% was calculated accordingly, Equation 1.

$$EE(\%) = \frac{TPC_b}{TPC_s} \times 100 \quad (1)$$

Where TPC<sub>b</sub> is the amount of total phenolic compounds encapsulated in the beads, and TPC<sub>s</sub> is the total phenolic content in the initial solution.

### 2.8. Stability at Different pH Values

The stability of the encapsulated phenolic compounds was evaluated under varying pH conditions. Beads were immersed in buffer solutions adjusted to pH 2, 5, and 8 and incubated for 2 hours with continuous magnetic stirring. After incubation, the released phenolic compounds were quantified, and the release percentage was calculated using Equation 2.

$$\text{Total phenolic release (\%)} = \frac{E}{E_0} \times 100 \quad (2)$$

Where E represents the amount of phenolic compounds released into the medium, and E<sub>0</sub> denotes the total phenolic content initially encapsulated in the beads.

### 2.9. Quantitative Total Phenolic Compound Analysis

The total phenolic content of microwave-assisted longan extracts was determined using the Folin–Ciocalteu method, adapted from Namjouyan, Azemi, and Rahmanian (2010), with gallic acid serving as the calibration standard. Briefly, 0.1 mL of extract was mixed with 2 mL of 2% (w/v) sodium carbonate (Na<sub>2</sub>CO<sub>3</sub>) in a test tube, followed by the addition of 0.1 mL of Folin–Ciocalteu reagent. The mixture was vortexed, covered with aluminum foil, and kept in the dark at room temperature for 30 minutes. Absorbance was then recorded at 750 nm using a UV–Vis spectrophotometer. Results were expressed as milligrams of gallic acid equivalent per gram of sample (mg GAE/g), based on a gallic acid calibration curve.

### 2.10. Quantitative Antioxidant Activity

The antioxidant capacity of the samples was assessed using a modified DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging method, adapted from Shimada, Fujikawa, Yahara, and Nakamura (1992). A stock solution of DPPH (5 mM) was prepared by dissolving 0.1972 g of the reagent in methanol and adjusting the volume to 100 mL. Prior to analysis, a working solution of 0.1 mM DPPH was freshly obtained by diluting the stock with methanol.

For each test, 0.1 mL of the sample extract was combined with 2.9 mL of the DPPH working solution and briefly vortexed. The mixture was then incubated in the absence of light at ambient temperature for 30 minutes. A control sample containing only the DPPH solution was treated under identical conditions. Absorbance readings of both the test and control solutions were recorded at 515 nm using a UV–Vis spectrophotometer. The percentage of radical scavenging activity was calculated using Equation 3.

$$\% \text{Inhibition} = \frac{(A_{\text{control}} - A_{\text{sample}})}{A_{\text{control}}} \times 100 \quad (3)$$

Where  $A_{\text{control}}$  is the absorbance of the control and  $A_{\text{sample}}$  is the absorbance of the sample.

### 2.11. Sterilization by Gamma Irradiation

Gamma irradiation was performed using a  $60\text{Co}$  source in a Gamma Chamber 5000 irradiator (India), facilitated by the Thailand Institute of Nuclear Technology (Public Organization). The absorbed dose rate was maintained at 2.0 kGy/h. For treatment, longan beads suspended in solution were placed in glass bottles and subjected to four irradiation levels: 2.5, 5.0, 7.5, and 10.0 kGy. Post-irradiation, all samples were refrigerated to suppress microbial proliferation. The treated beads were subsequently analyzed for textural characteristics and screened for bacterial and fungal contamination.

### 2.12. Statistical Analysis

To evaluate the significance of differences among treatments, this study employed analysis of variance (ANOVA), a widely used statistical method for comparing means across multiple groups. ANOVA is particularly suitable for experimental designs involving more than two treatments, as it controls for Type I error and provides a robust framework for detecting overall effects. Following ANOVA, Duncan's New Multiple Range Test (DMRT) was applied to identify specific pairwise differences at a 95% confidence level. This post hoc test is known for its sensitivity in detecting differences among group means, especially in food and agricultural research contexts.

All statistical analyses were performed using IBM SPSS Statistics version 26.0 (IBM Corp., Armonk, NY, USA). Results are presented as mean  $\pm$  standard deviation (SD). Unlike previous studies that relied solely on ANOVA or used less discriminative post hoc tests such as Tukey's HSD or LSD, the use of DMRT in this study allowed for more nuanced differentiation between treatment effects. This approach provided greater clarity in interpreting the impact of formulation variables on encapsulation efficiency and bead characteristics.

## 3. RESULTS AND DISCUSSION

### 3.1. Optimization of Encapsulation of Longan Extracts Beads by Extrusion Method

Encapsulation conditions were optimized by varying the concentrations of sodium alginate (1, 1.5, and 2 %w/v) and calcium chloride (3, 4, and 5 %w/v). The encapsulation efficiency of phenolic compounds and antioxidant activity was subsequently evaluated. No bead formation occurred when alginate and calcium chloride concentrations were below 1 and 3 (%w/v), respectively. At alginate levels above 2 (%w/v), bead formation was hindered by high viscosity, resulting in irregular, non-spherical structures. Stable spherical beads were obtained at alginate concentrations of 1 (%w/v) or higher, consistent with the principle of ionotropic gelation, in which calcium ions interact with alginate carboxyl groups to create crosslinked gel networks. At low alginate concentrations, insufficient carboxyl groups were available to support proper bead formation.

The effect of sodium alginate concentration on bead morphology is presented in Figure 4. Beads produced with higher alginate concentrations exhibited elongated or tail-like shapes. This phenomenon may be attributed to the increased viscosity of concentrated alginate solutions, which caused partial retention of material at the nozzle tip due to surface tension. Gravity and extrusion pressure subsequently pulled the droplet downward, forming beads with extended tails. Conversely, beads produced at lower alginate concentrations displayed surface shrinkage, likely resulting from inadequate polymer density at the outer layer of the gel matrix.

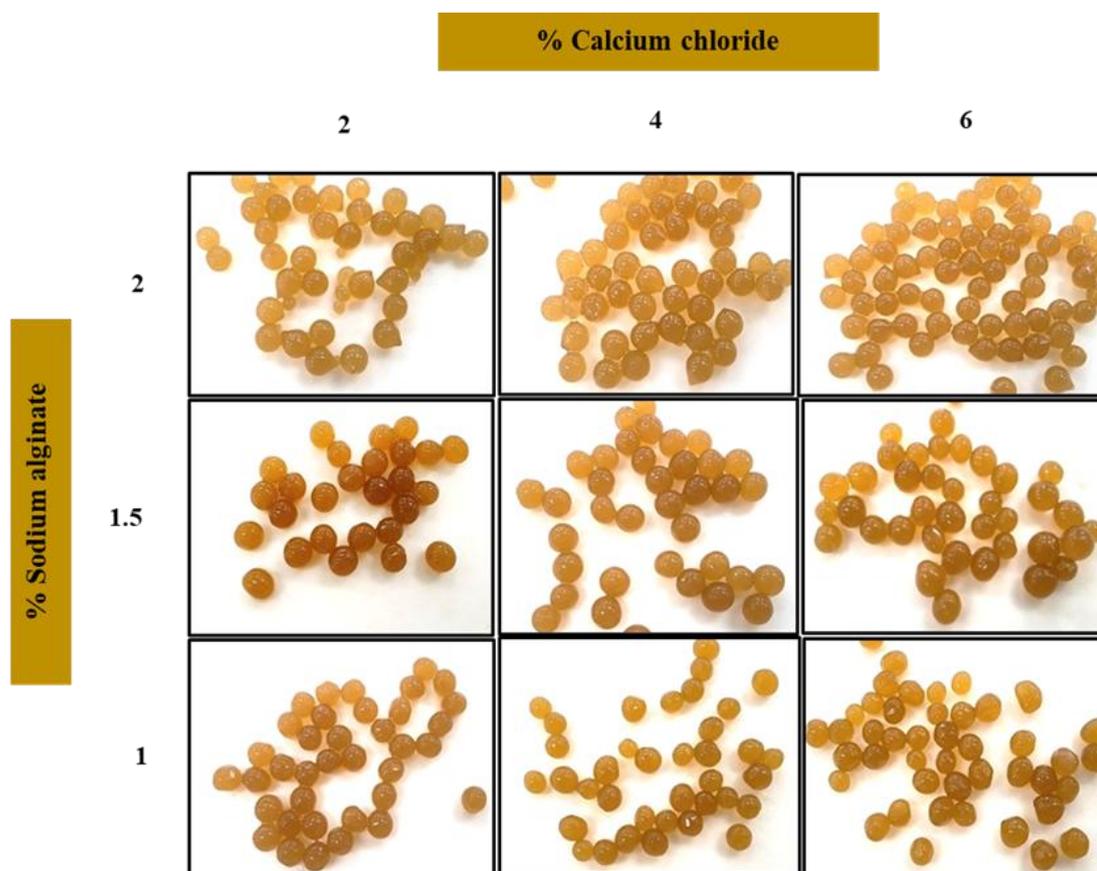


Figure 4. Physical characteristics of longan phenolic beads.

The particle size and encapsulation conditions of the beads are summarized in Table 1. The mean bead diameter ranged from 2.34 to 3.86 mm, with all formulations exhibiting relatively narrow particle size distributions. Variations in calcium chloride concentration had minimal influence on bead size, whereas sodium alginate concentration exerted a pronounced effect. Specifically, higher alginate concentrations yielded larger and mechanically more robust beads, attributable to the increased viscosity of the alginate solution. As previously reported by Ouwerx, Velings, Mestdagh, and Axelos (1998), elevated viscosity delays droplet detachment during extrusion, thereby promoting the formation of larger beads. This observation aligns with the principles of shear-driven dripping and  $\text{Ca}^{2+}$ -mediated “egg-box” crosslinking mechanisms (Cao, Wang, Zhang, & Liu, 2020; Davarci, Turan, & Ozdemir, 2017; Del Gaudio, Russo, Rosaria Conte, & Colombo, 2005). Within the tested range of  $\text{CaCl}_2$  concentrations, surface gelation occurred rapidly, and further increases in bath concentration resulted in only marginal changes in bead diameter. In contrast, increasing alginate concentration enhanced the density of the ionic network, effectively reducing pore size and limiting the diffusion of phenolic compounds into the gelling medium. This phenomenon contributed to improved encapsulation efficiency (Colin, Roussel, Dufour, & Dupont, 2024; Davarci et al., 2017). These findings underscore the critical role of solution viscosity in modulating particle size and enhancing the structural integrity and retention of bioactive compounds within the beads. The encapsulation efficiency of total phenolic compounds ranged from 51.05% to 66.95%, with a general trend of increasing efficiency at higher sodium alginate concentrations. In contrast, calcium chloride concentration exhibited a negligible impact on encapsulation efficiency. The optimal encapsulation condition was achieved using 1.5% (w/v) sodium alginate, consistent with previous findings on phenolic compound encapsulation from *Clitoria ternatea* petal extract (Pasukamonset, Kwon, & Adisakwattana, 2016).

**Table 1.** Effects of sodium alginate and calcium chloride concentrations on bead properties and encapsulation efficiency obtained by extrusion.

Treatment	Concentrate of sodium alginate (%w/v)	Concentrate of CaCl <sub>2</sub> (%w/v)	Beads diameter (mm)	Encapsulation efficiency (%)	Total phenolic compound (mg GAE g <sup>-1</sup> beads)	Antioxidant activity (%)
1	1	2	3.86	51.05 ± 0.38 <sup>f</sup>	2.944 ± 0.03 <sup>b</sup>	28.52 ± 0.15 <sup>g</sup>
2	1	4	3.83	55.09 ± 0.57 <sup>e</sup>	3.176 ± 0.12 <sup>g</sup>	32.84 ± 0.11 <sup>f</sup>
3	1	6	2.75	60.53 ± 0.10 <sup>c</sup>	3.551 ± 0.05 <sup>e</sup>	46.49 ± 0.30 <sup>c</sup>
4	1.5	2	3.44	58.48 ± 0.80 <sup>d</sup>	3.459 ± 0.18 <sup>e</sup>	40.28 ± 0.64 <sup>e</sup>
5	1.5	4	3.51	66.95 ± 0.45 <sup>a</sup>	3.845 ± 0.11 <sup>a</sup>	55.06 ± 0.89 <sup>a</sup>
6	1.5	6	2.47	63.41 ± 0.50 <sup>b</sup>	3.698 ± 0.08 <sup>b</sup>	53.83 ± 0.86 <sup>b</sup>
7	2	2	3.22	52.63 ± 0.31 <sup>f</sup>	2.811 ± 0.15 <sup>i</sup>	28.16 ± 0.25 <sup>g</sup>
8	2	4	3.27	58.45 ± 0.77 <sup>d</sup>	3.506 ± 0.27 <sup>d</sup>	45.92 ± 0.72 <sup>d</sup>
9	2	6	2.34	54.28 ± 0.61 <sup>e</sup>	3.221 ± 0.12 <sup>f</sup>	32.31 ± 0.21 <sup>f</sup>

**Note:** Different superscript letters within a column denote significant differences at  $p \leq 0.05$  (Duncan's multiple range test).

The optimized encapsulation conditions using alginate with natural polymers are summarized in Table 2. Adding gelatin, gum Arabic, or pectin at a 1:0.5 (v/v) ratio decreased porosity and increased viscosity, which in turn improved bead stability through synergistic interactions in the alginate network (Mohamed, Mustafa, Fitrianto, & Manap, 2017). Among all blends, alginate + gum Arabic produced the highest encapsulation efficiency ( $74.86\% \pm 0.17$ ). Gum Arabic acts as an emulsifier, helping disperse the extract evenly during bead formation, and in the CaCl<sub>2</sub> bath, it limits bead aggregation by moderating electrostatic interactions among alginate carboxyl groups. It also helps retain water within the bead, supporting moisture stability and protecting the encapsulated compounds (Annisa et al., 2022).

Beyond these effects, gum Arabic strengthens the ionic gel via hydrogen bonding and electrostatic interactions with alginate and calcium, creating a denser, more cohesive matrix. The tighter network reduces pore size and diffusion losses to the gelling medium, raising encapsulation efficiency and slowing release (Colin et al., 2024). Gum Arabic also improves bead resilience under acidic conditions and moderate thermal stress, which is advantageous for gastrointestinal delivery and food processing. Overall, these results highlight gum Arabic as an effective co-polymer with alginate for enhancing stability and delivery efficiency of bioactive compounds. Similarly, Lima-Tenório et al. (2024) reported that gum Arabic hydrogels enhanced the viability and controlled release of plant growth-promoting bacteria, suggesting broader applications in sustainable agriculture. These findings are consistent with our results, reinforcing gum Arabic's role in improving encapsulation efficiency and bead integrity.

### 3.2. Stability to pH of Longan Beads

The release of phenolic compounds from longan beads was evaluated at pH 2, 5, and 8 over a 2-hour period (Figure 5). Under acidic conditions (pH 2), only limited release of phenolic compounds was observed. This behavior is attributed to the reduced solubility of alginate at low pH, where excess protons convert alginate into insoluble alginic acid and diminish electrostatic repulsion among negatively charged chains (González-Rodríguez, Holgado, Sanchez-Lafuente, Rabasco, & Fini, 2002). As a result, the diffusion of phenolics through the bead matrix was restricted, leading to slower release rates.

In contrast, at alkaline pH (pH 8), a markedly higher release of phenolic compounds occurs. Deprotonation of alginic acid at elevated pH enhances fluid uptake into the beads, causing swelling and facilitating compound release (Ghosal & Ray, 2011). This observation aligns with Woo et al. (2007), who reported that alginate exhibits strong gelling properties under acidic conditions but becomes structurally weaker in alkaline environments due to ion exchange between calcium and sodium ions.

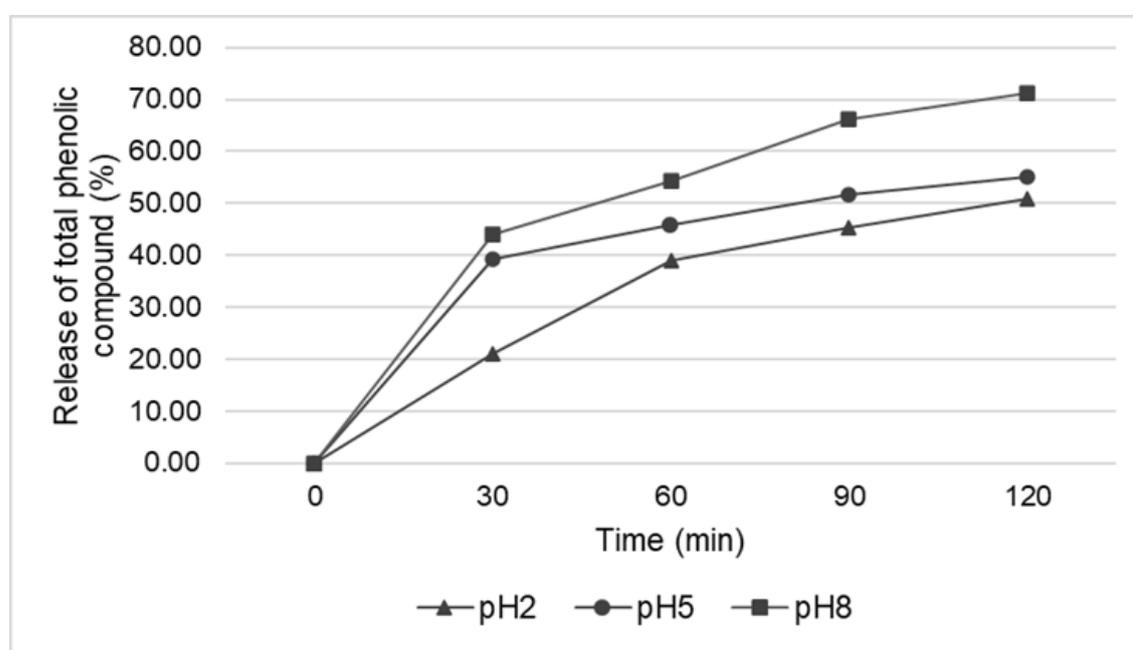
Recent studies further support these findings Lima-Tenório et al. (2024) reported that alginate-based hydrogels maintained structural integrity and delayed the release of bioactives in low-pH environments, reinforcing the stability of such systems under gastric conditions. However, contradictory results have been reported in systems using

modified alginate or alternative crosslinking agents. For instance, Zobot et al. (2022) observed that certain alginate formulations exhibited premature release of polyphenols even under acidic conditions, likely due to weaker gel networks or insufficient crosslinking. These discrepancies highlight the importance of formulation-specific parameters, including polymer concentration, crosslinking ion type, and bead architecture.

**Table 2.** Effects of combined sodium alginate with natural polymers on bead properties and encapsulation efficiency.

Sample	Bead diameter (mm)	Encapsulation efficiency (%)	Hardness (N)	Springiness	Cohesiveness
SA	3.54	65.54 ± 0.048 <sup>d</sup>	4.210 ± 0.244 <sup>c</sup>	0.927 ± 0.020 <sup>b</sup>	0.446 ± 0.064 <sup>c</sup>
SA + Gelatin	3.32	69.69 ± 0.225 <sup>c</sup>	5.654 ± 0.217 <sup>b</sup>	0.935 ± 0.024 <sup>a</sup>	0.453 ± 0.031 <sup>b</sup>
SA + Gum Arabic	3.25	74.86 ± 0.171 <sup>a</sup>	7.125 ± 0.167 <sup>a</sup>	0.601 ± 0.019 <sup>d</sup>	0.525 ± 0.026 <sup>a</sup>
SA + Pectin	3.29	71.35 ± 0.187 <sup>b</sup>	5.267 ± 0.136 <sup>b</sup>	0.893 ± 0.167 <sup>c</sup>	0.414 ± 0.129 <sup>d</sup>

**Note:** Different superscript letters (a-d) within a column indicate significant differences at  $p \leq 0.05$  (Duncan's multiple range test). SA = sodium alginate. Blends were prepared at a 1:0.5 (v/v) ratio.



**Figure 5.** Release profile of total phenolic compound from the longan beads (Sodium Alginate + Gum Arabic) in pH 2, pH5, and pH8.

### 3.3. Assay of Sterilization Effect

The antimicrobial efficacy of gamma irradiation on longan beads was evaluated at doses of 2.5, 5.0, 7.5, and 10.0 kGy (As shown in Table 3). Microbial counts were assessed using 3M Petrifilm™ plates. Prior to irradiation, the total aerobic bacterial population was  $3.3 \times 10^2$  CFU/g. After treatment with 2.5 and 5.0 kGy, the viable counts decreased to  $2.8 \times 10^0$  and  $8.0 \times 10^{-1}$  CFU/mg, respectively. Complete microbial inactivation was achieved at 7.5 kGy, where no detectable colonies of bacteria or molds were observed. Non-irradiated samples contained mold populations of  $2.5 \times 10^2$  CFU/mg, which were also eliminated following exposure to 7.5 kGy. According to Codex guidelines (Yoon, 2011), the maximum recommended dose for food irradiation is 10 kGy, unless higher levels are justified by specific technological requirements. The results of this study demonstrate that an irradiation dose of 7.5 kGy is sufficient to ensure microbial safety of longan beads while remaining within international regulatory limits.

**Table 3.** Inactivation of microbial population in longan beads by gamma irradiation.

Microorganism (CFU/mg)	Not sterilized	Gamma irradiation			
		2.5 kGy	5 kGy	7.5 kGy	10 kGy
Total aerobic bacteria	$3.3 \times 10^2$	$28 \times 10^{-1}$	$8 \times 10^{-1}$	ND	ND
Yeast/molds	$2.5 \times 10^2$	$30 \times 10^{-1}$	$16 \times 10^{-1}$	ND	ND

Note: \*ND: Not detectable within a detection limit < 1.00 CFU/mg.

### 3.4. Effect of Gamma Irradiation on the Physical and Morphological Characterization of Longan Beads

The morphology of longan beads before and after gamma irradiation was examined using scanning electron microscopy (SEM) at various magnifications (Figure 6). Freeze-dried, non-irradiated beads displayed collapsed and shrunken structures, likely due to sublimation of phenolic compounds and water during the drying process. In contrast, beads irradiated at 2.5–10 kGy exhibited more compact, homogeneous, and spherical shapes compared with unirradiated samples. At doses above 5 kGy, voids within the bead matrix appeared to be filled, resulting in reduced porosity and smoother surfaces.

Closer inspection revealed that non-irradiated beads possessed surface tears, irregular shrinkage, and visible gaps, whereas irradiated beads exhibited intact surfaces without rupture marks. Gamma irradiation influences alginate-based matrices through two competing mechanisms. At low doses ( $\leq 5$  kGy), the formation of free radicals induces cross-linking between polymer chains, thereby reinforcing the gel structure and improving surface integrity (Diehl, 1995; Huq et al., 2012). Conversely, exposure to higher doses ( $\geq 7.5$  kGy) promotes scission of glycosidic bonds, leading to depolymerization, reduced gelling stability, and weakened bead strength (Gul-E-Noor et al., 2009; IAEA, 2015).

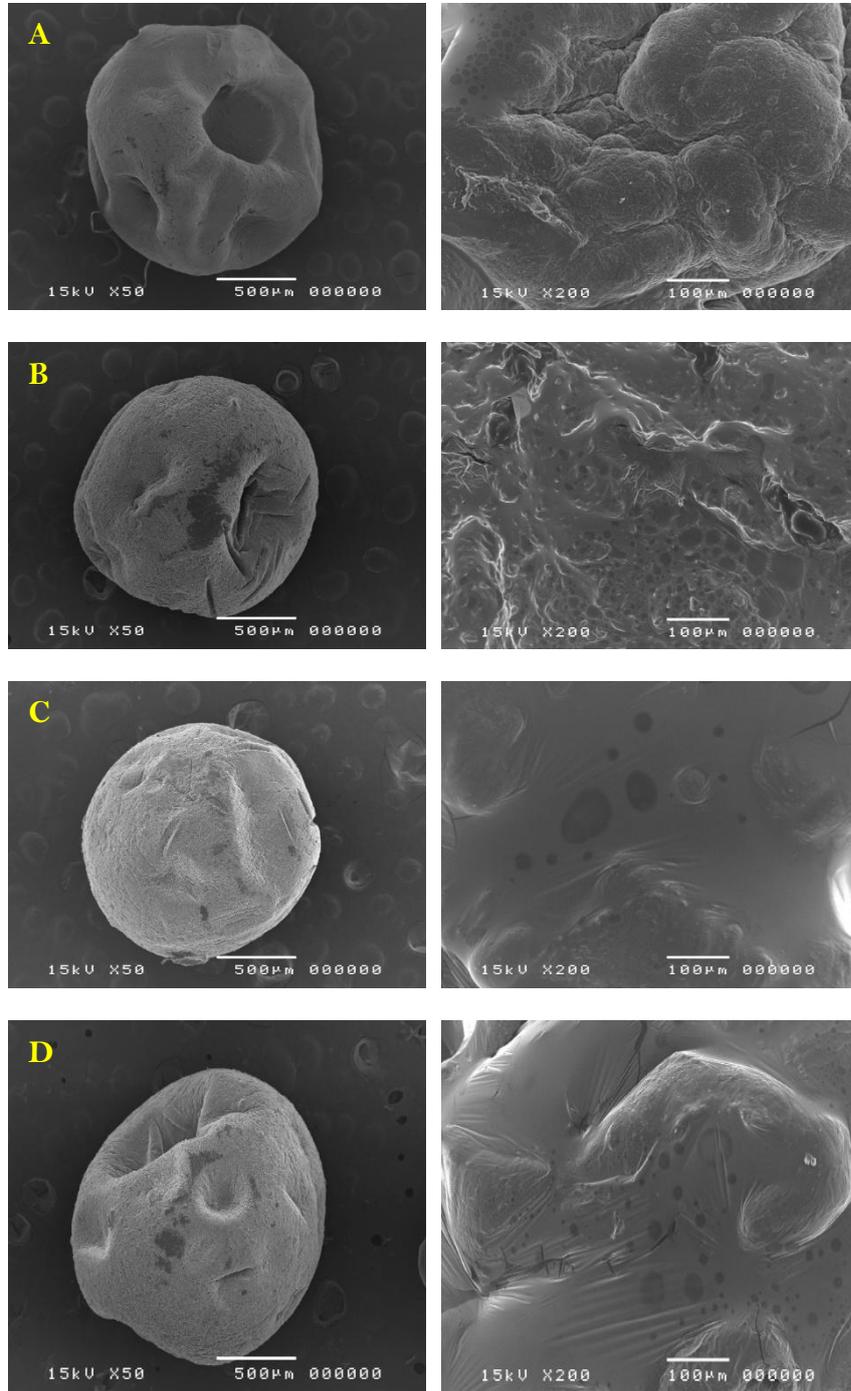
Recent reports are consistent with our observations. Zhang, Li, and Wang (2023) showed that moderate  $\gamma$ -irradiation (3–5 kGy) increased the mechanical strength and surface smoothness of alginate–chitosan beads encapsulating curcumin while retaining antioxidant activity. Likewise, Lee, Park, and Kim (2022) noted greater compactness and lower porosity in polysaccharide hydrogels for probiotic delivery after irradiation. In contrast, several studies document adverse effects at higher doses. Nair et al. (2021) reported that  $>7$  kGy caused pronounced degradation of alginate–pectin networks, yielding brittle beads and reduced encapsulation efficiency, and Naikwadi, Sharma, Bhatt, and Mahanwar (2022) observed impaired release profiles due to excessive polymer breakdown. Such discrepancies likely reflect differences in polymer composition, irradiation parameters, and the physicochemical nature of the encapsulated actives. Overall, our data indicate that moderate doses promote cross-linking, improving compactness and reducing porosity, whereas excessive exposure drives chain scission and weakens the matrix. Optimization is therefore critical to preserve both structural integrity and functional performance and should be tuned to the specific formulation. Mechanical textural parameters were evaluated using Texture Profile Analysis (TPA) compression testing, as presented in Table 4. Longan beads exhibited statistically significant differences in hardness across various treatment conditions ( $p < 0.05$ ). Beads irradiated at 5 kGy demonstrated the highest values for hardness, springiness, and cohesiveness, measured at  $7.426 \pm 0.397$  N,  $0.691 \pm 0.197$ , and  $0.655 \pm 0.014$ , respectively. These enhanced textural attributes suggest improved gel integrity and reduced internal voids, contributing to greater resistance against deformation.

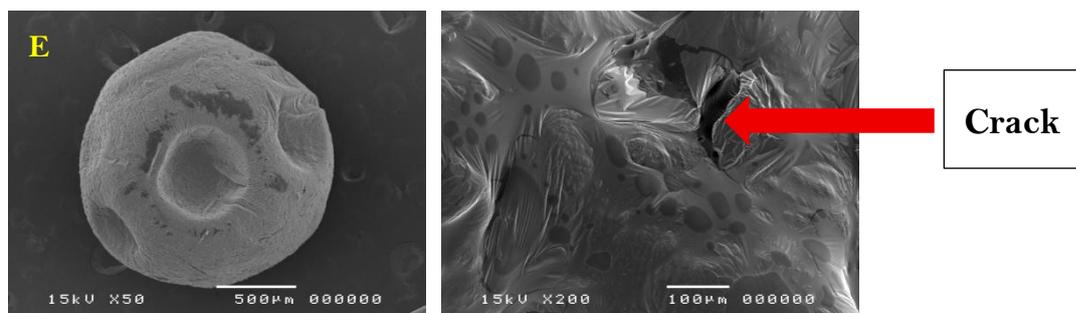
**Table 4.** Mechanical textural parameters of longan beads at different radiation doses.

Radiation doses (kGy)	Hardness (N)	Springiness	Cohesiveness
Un-irradiated	$6.784 \pm 0.163^d$	$0.637 \pm 0.214^{cd}$	$0.575 \pm 0.064^c$
2.5 kGy	$7.246 \pm 0.134^b$	$0.678 \pm 0.245^b$	$0.591 \pm 0.167^b$
5 kGy	$7.426 \pm 0.397^{ab}$	$0.691 \pm 0.197^a$	$0.659 \pm 0.014^a$
7.5 kGy	$7.442 \pm 0.241^a$	$0.648 \pm 0.321^c$	$0.644 \pm 0.089^a$
10 kGy	$7.016 \pm 0.172^c$	$0.633 \pm 0.157^d$	$0.561 \pm 0.052^c$

Note: Different superscript letters (a–d) within a column indicate significant differences at  $p \leq 0.05$  (Duncan's multiple range test).

The observed increase in gel swelling among irradiated beads is consistent with the enhanced mechanical strength at moderate doses. However, when the irradiation dose exceeded 5 kGy, bead expansion became excessive, leading to wall rupture and a decline in structural integrity. This indicates that while moderate gamma irradiation reinforces the bead matrix through polymer cross-linking, higher doses may induce chain scission and compromise mechanical stability.





**Figure 6.** Scanning electron micrographs (SEM) of longan extract beads at low (50×) and high (200×) magnification. (A) Non-irradiated control beads, (B) beads treated with 2.5 kGy, (C) 5 kGy, (D) 7.5 kGy, and (E) 10 kGy. Differences in surface morphology, including smoothness, compactness, and the appearance of cracks or structural disruptions, are shown for comparison.

#### 4. CONCLUSION

This study demonstrated that extrusion using sodium alginate effectively encapsulated phenolic compounds from longan seed extracted into spherical beads with high efficiency. The optimal condition was 1.5% (w/v) alginate, which produced stable beads with superior encapsulation performance. Incorporation of natural polymers, particularly gum Arabic, further improved bead integrity by reducing porosity and enhancing compound retention, resulting in the highest encapsulation efficiency (74.86%). Gamma irradiation influenced both mechanical and microbiological properties of the beads. At 5 kGy, irradiation enhanced textural strength and compactness through cross-linking within the alginate matrix, while 7.5 kGy ensured complete microbial inactivation. Excessive irradiation, however, weakened bead integrity due to polysaccharide chain scission. Overall, these findings highlight that optimized alginate-based encapsulation, combined with polymer blending and moderate gamma irradiation, can improve the stability, mechanical integrity, and bioactive retention of longan beads.

This approach offers promising potential for the development of functional food ingredients and dietary supplements. Practically, it is compatible with simple extrusion and non-thermal, irradiation-assisted terminal sterilization, supporting nutraceutical formulation and shelf-life extension.

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**Competing Interests:** The authors declare that they have no competing interests.

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