RESEARCH PAPER

Development of multi-component functional Beverage pearls with improved texture and stability

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Abstract

The research paper is based on the development of multi-component functional beverage pearls that have improved texture, stability, and bioactive retention properties. The research paper discusses the development of a beverage base using a selection of functional ingredients, sweeteners, and stabilizers, followed by the formation of pearls using suitable hydrocolloids like sodium alginate, gelatine, pectin, and carrageenan. The formation of pearls is done using ionic gelation and extrusion methods, and the parameters are optimized in the process. The beverage pearls are then tested and evaluated based on their physicochemical, mechanical, and sensory properties. The results of the research paper showed improvement in the gel strength of the pearls up to 150 g/cm², and the percentage of encapsulation is as high as 88%. The stability study showed that the optimized formulations have bioactive retention properties of more than 78% after 45 days of storage, and the results are quite promising in terms of minimal leakage and texture retention. The study showed that the beverage pearls have a high acceptability rate among consumers, and the results are quite promising in the development of beverage pearls, which have the potential to be produced on a large scale in the food industry.

Keywords: *Functional beverage pearls, Nanoencapsulation, Hydrocolloids, Gel strength, Bioactive stability, Encapsulation efficiency, Texture optimization, Sensory evaluation.*

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1. Introduction

Functional beverages have been quite popular in recent times due to their health-enhancing capabilities, which go beyond basic nutrition. They are usually formulated with bioactive ingredients such as vitamins, minerals, antioxidants, and plant extracts, offering health benefits such as immunity, gut health, and energy, among others [1]. People are looking for ways to consume bioactive ingredients in an enjoyable manner, which has given rise to innovation in product forms such as gel, beads, and pearls, which can effectively carry functional ingredients. Beverage pearls, also referred to as gel beads or specified ingredients, are small balls made from liquids or semi-liquid ingredients [2]. These ingredients are normally processed using methods such as ionic gelation and enzymatic gelation [3]. The beverage pearls provide a distinctive experience for the consumer, who gets to experience taste, texture, and visual appeal. This makes them quite popular in today's consumer market. Furthermore, beverage pearls provide a platform for using multiple bioactive ingredients in a single format while protecting them from degradation [4].

However, despite the advantages of such products, the development of multi-component beverage pearls is faced with challenges, especially concerning texture and stability. The texture of the pearls must remain intact during storage and consumption [5]. At the same time, it is important that they remain tight and prevent the leakage of bioactive ingredients. The interaction of bioactive components and pH levels can have negative effects on the gel matrix texture. For instance, to enhance the texture and stability of beverage pearls, there is a need to choose hydrocolloids, gelling agents, and stabilizers [6]. The use of a blend of natural polymers, including alginate, pectin, and gelatin, is one of the options to develop a strong gel structure with high potential for carrying multiple compounds. In addition, there is a need to consider processing conditions, including crosslinking time, ionic strength, and storage conditions, to enhance stability and the controlled release of bioactive compounds [7].

The development of multi-component functional beverage pearls with improved texture and stability is a significant aspect in the food and nutraceutical industry. The product provides a convenient delivery of bioactive ingredients in a new and enjoyable experience [8]. The research aims to formulate beverage pearls with multi-functional ingredients and assess their structure, physicochemical properties, and sensory characteristics, and explore ways to improve the stability and texture of the product, thus contributing to the next generation of functional foods that meet the requirements of the consumer.

1.1 Objectives

- To develop multi-component functional beverage pearls using suitable bioactive ingredients such as vitamins, antioxidants, and plant extracts.
- To select and optimize hydrocolloids (alginate, gelatin, pectin, carrageenan) for improving gel strength, texture, and structural stability.
- To evaluate the effect of encapsulation parameters such as calcium concentration, pH, viscosity, and crosslinking time on pearl formation.
- To analyze the physicochemical, mechanical, and sensory properties of the developed beverage pearls for quality assessment.
- To assess storage stability, bioactive retention, and overall performance for potential large-scale functional food applications.

2. Literature review

Some of the recent literatures related to this study are discussed as follows,

Hao et al. (2025) propose the use of nanoencapsulation as an efficient means of maintaining the sensitive nutrients of the functional foods and enhancing their absorption. The small-sized carriers (liposomes, lipid nanoparticles and biopolymer nanoparticles) protect bioactive compounds against heat, light, oxidation, and pH variations, thereby increasing their stability, controlled release as well as overall efficacy in both foods and beverages.

Quintero-Quiroz et al. (2026) have provided the advantages of hydrodynamic cavitation (HC) in conservation of nutrients in fruit and vegetable purees. They found that using HC to preserve the vitamin C and antioxidants was much higher than using thermal processing, but might have an effect on the texture. This technique uses less thermal energy, which maximises nutrient retention and enhances food surpluses to be used in a sustainable manner.

Damini and Mahendran (2026) have provided the functional applications of plant-based proteins in the contemporary food systems. Legume, cereals, seeds, and pseudo- cereal proteins are emulsifiers, gelators, foamers and water-holders. The further improvement of their processing methods makes them ideal in use as fat replacers, stabilizers, edible films, or bioactive carriers in dairy alternatives, meat analogues, and functional beverages.

Machado et al. (2025) have noted the versatility of soft gels, including hydrogel, organogels, aerogels, and bigels. Modification of texture, provision of nutrients, fats replacement and shelf-life extension are done using soft gels. Their tunable characteristics enable them to be used in frying, 3D printing and nano-enabled foods besides the fact that they have been used in 3D printing but cost, scalability, and consumer acceptance are major issues to commercialization.

Nanoorganogels to encapsulate bioactive compounds in food have been proposed as an efficient solution by Saravana Raj et al. (2025) to enhance stability, bioavailability, and shelf life. These are cross-linked 3D network-based gels which may be fluid-filled or solid. Although studies are few, the nanoorganogels have high functionality in food and nutraceutical applications.

The proposed design by Su and He (2024) includes anti-smudge, anti-icing, and anti-corrosion, among other features on transparent and durable coating. These coatings retain their properties despite abrasion during mechanical operations, their peeling or during exposure to severe pH conditions, which proves them to be applicable in industrial and everyday life.

Tian et al. (2025) have shown that Pickering emulsions with whey protein isolate and chitosan are stable. These emulsions are both size and mechanically stable than conventional emulsions, and are more resistant to destruction in foods, such as reduced fat mayonnaise. The management of droplet interaction and volume ratio are important in improving the shelf life and product quality.

Rout et al. (2025) have suggested that protein microgels are suitable carriers of lipophilic bioactive substances. These tiny particles (0.5- 5 μm) entrap water and safeguard delicate nutrients whilst controlled release, enhancing bioavailability. The application of their use is conducive to the creation of sustainable and protein-rich, functional plant-based foods.

Table 1: Comparison of Emerging Technologies and Ingredients for Functional Food and Beverage Applications

Technology	Application	Key Benefits	Author (s) & Year
Nanoencapsulation	Protect nutrients and improve	Shields bioactives from heat, light,	Hao et al. (2025) [9]

	bioavailability	oxidation, and pH; controlled release	
Hydrodynamic Cavitation (HC)	Preserve vitamins and bioactives in fruit/vegetable purees	Higher vitamin C and antioxidant retention; non-thermal method	Quintero-Quiroz et al. (2026) [10]
Plant-Based Proteins	Functional ingredient for emulsification, gelation, fat replacement	Emulsification, gelation, foaming, water-holding; edible films and bioactive carriers	Damini & Mahendran (2026) [11]
Soft Gels (Hydrogel, Organogel, Aerogel, Bigel)	Texture modification, nutrient delivery, fat replacement	Tunable properties, extended shelf life, versatile applications	Machado et al. (2025) [12]
Nanoorganogels	Encapsulation of food bioactives	Improved stability, bioavailability, and shelf life	Saravana Raj et al. (2025) [13]
Multi-Functional Coatings	Transparent protective surface with multiple functions	Anti-smudge, anti-icing, anti-corrosion, durable under stress	Su & He (2024) [14]
Pickering Emulsions (WPI-Chitosan)	Stable emulsions in reduced-fat foods	Maintains droplet size, mechanical stability; improved shelf life	Tian et al. (2025) [15]
Protein Microgels	Carrier for lipophilic bioactive	Protects nutrients, controlled release, enhanced bioavailability	Rout et al. (2025) [16]

2.1 Research gap

Even though considerable progress has been made in the nanoencapsulation technology, soft gels, plant-based proteins, and emulsions, some research gaps still exist in the development of multi-component functional beverage pearls. Most of the research work carried out in the field has been centered on the encapsulation of a single component or isolated systems, and the interaction effects of various bioactive, hydrocolloids, and processing parameters have not been adequately studied, particularly in relation to the storage conditions. Besides, the challenges faced in the development of multi-component systems in terms of texture, structure, and controlled delivery have not been adequately addressed in most research work. The application of these advanced delivery systems in a cost-effective and consumer-friendly manner is still a new area that needs further exploration. The application of non-thermal processing techniques in the development of encapsulation systems is still a new area that needs further exploration in relation to the enhancement of the nutritional and sensory value of the beverage pearls.

3. Methodology

The methodology of this study focuses on the systematic development and evaluation of multi-component functional beverage pearls with improved texture and stability. Initially, suitable bioactive ingredients, sweeteners, and stabilizers were selected to prepare a uniform base beverage. Appropriate hydrocolloids such as sodium alginate, gelatine, pectin, and carrageenan were chosen for encapsulation. Pearl formation was carried out using ionic gelation and extrusion techniques under controlled conditions of pH, viscosity, calcium concentration, and crosslinking time. The developed pearls were then characterized for physicochemical, mechanical, and sensory properties, followed by storage stability analysis to assess bioactive retention and overall performance.

3.1 Selection of Functional Ingredients

The selection of functional ingredients is a vital first step in the formulation of multi-component functional beverage pearls, as this affects the nutritional value and the stability of the final product. Functional ingredients are usually vitamins, minerals, antioxidants, and bioactive compounds from plants, which have the potential to provide various health benefits, depending on the ingredient in question. The selection of these ingredients should be in line with the intended function of the final product, whether the function is energy enhancement, improvement of digestive health, or the prevention of diseases.

In addition to the selection of the ingredients, the compatibility of the ingredients in the multi-component system is a critical aspect that should be considered in the formulation of the beverage pearls [17]. The interaction of bioactive ingredients is a critical aspect in the formulation of the beverage pearls, as this affects their effectiveness in the final product. Vitamins are sensitive to light, heat, and oxygen, and this affects their stability in the final product. Probiotics are sensitive to environmental factors and should be maintained in controlled environments. Similarly, polyphenols and plant extracts may interact with certain ingredients in the product, thus affecting their availability and stability in the final product.

Another significant factor is the stability of these ingredients during processing and storage. Variables like temperature, pH, moisture levels, and oxygen activity may cause degradation of these ingredients. For instance, vitamin C is highly susceptible to oxidation, while probiotics are sensitive to high temperatures. To address this problem, techniques like encapsulation and stabilization are used, along with selecting compatible carriers for these ingredients [19]. Another significant factor is the sensory effect of functional ingredients. Some ingredients may possess undesirable taste, odor, and color properties, which may influence consumer perception. Hence, it is significant to maintain a balance between functionality and sensory appeal while selecting ingredients for formulation. Selecting ingredients that are compatible in both nutritional and sensory value makes them more attractive and desirable. Thus, it is significant to select and assess functional ingredients, their interactions, and their stability, which are significant in developing efficient and stable beverage pearls. Table 2 shows the Selection Criteria and Characteristics of Functional Ingredients.

Table 2: Selection Criteria and Characteristics of Functional Ingredients [18]

Functional Ingredient Type	**Examples**	**Health Benefits**	**Key Stability Issues**	**Considerations in Formulation**
Vitamins	Vitamin C, Vitamin D, B-complex	Immunity, metabolism, antioxidant activity	Sensitive to heat, light, oxidation	Require encapsulation or antioxidants for protection
Minerals	Calcium, Iron, Zinc	Bone health, oxygen transport, immunity	May interact with other compounds, cause precipitation	pH control and chelation required
Antioxidants	Polyphenols, flavonoids, carotenoids	Reduce oxidative stress, anti-aging	Degrade under light, oxygen, and heat	Use protective carriers or encapsulation
Probiotics	Lactobacillus, Bifidobacterium	Gut health, digestion	Sensitive to temperature, pH, oxygen	Require mild processing and protective matrices
Plant Extracts	Green tea extract, turmeric, aloe vera	Anti-inflammatory, antioxidant, therapeutic	May affect taste, stability, and color	Flavor masking and compatibility testing needed

3.2 Choice of Gelling Agents and Hydrocolloids

The selection of proper gelling agents and hydrocolloids is a critical parameter in the formulation of multi-component functional beverage pearls, as it directly affects the structural integrity and texture of the final product. Hydrocolloids are polymers that are capable of binding water and forming three-dimensional networks that are able to entrap liquids and other bioactive compounds. Gelling agents such as sodium alginate, pectin, gelatin, and carrageenan are generally preferred for their safety and ease of gel formation and for their ability to produce desirable textures ranging from soft and elastic to firm and brittle [2].

Among these gelling agents, sodium alginate is most commonly used for pearl formation because it is capable of forming stable and strong gels in the presence of calcium ions. Pectin, specifically low-methoxyl pectin, is also capable of forming gels in the presence of divalent ions and is used for producing softer textures. Gelatin is used for producing thermo-reversible gels with desirable elastic and smooth textures. Carrageenan, specifically kappa-carrageenan, is used for producing strong and rigid gels for enhancing the texture and strength. The selection of hydrocolloids should also take into account their compatibility with other functional ingredients. Bioactive compounds may react with hydrocolloids, which could affect gel network formation and stability [5]. For instance, high acidity may reduce gel strength, and salt and protein presence may influence crosslinking. Hence, it is critical to understand the physicochemical interactions between hydrocolloids and other bioactive compounds to avoid problems such as syneresis, phase separation, and leakage of active ingredients.

Besides selecting each hydrocolloid individually, blending two or more hydrocolloids is another successful approach to enhance mechanical strength and texture properties. Blending two hydrocolloids, such as alginate-gelatine or carrageenan-pectin, may result in synergistic interactions, thus producing stronger and more elastic gel networks and better mechanical strength. Furthermore, blending hydrocolloids helps control texture properties, making them neither too hard nor too weak for consumer perception [7]. Moreover, processing parameters such as pH, temperature, ionic strength, and crosslinking time are critical factors in influencing the properties of the resulting gel. Optimal processing parameters guarantee reproducibility in bead formation, particle size, and stability upon storage. In summary, the choice and combination of hydrocolloids are critical in ensuring the development of beverage pearls with enhanced texture, mechanical properties, and stability.

Table 3: Effect of Different Hydrocolloids on Gel Strength and Texture Properties [17]

Hydrocolloid	**Concentration (%)**	**Gel Strength (g/cm²)**	**Hardness (N)**	**Elasticity (%)**	**Syneresis (%)**
Sodium Alginate	1.5	120 ± 5	3.2 ± 0.2	85 ± 3	2.1 ± 0.3
Pectin	2	95 ± 4	2.5 ± 0.1	78 ± 2	3.5 ± 0.4
Gelatin	3	80 ± 3	2.0 ± 0.2	90 ± 4	4.2 ± 0.5
Carrageenan	1.5	135 ± 6	3.8 ± 0.3	70 ± 3	1.8 ± 0.2

From Table 3, it can be seen that carrageenan had the highest gel strength (135 g/cm²) and hardness (3.8 N). Gelatin had the highest elasticity (90%) and thus contributed to its soft and flexible texture. On the other hand, gelatin had high syneresis. Sodium alginate had good gel strength and low syneresis, thus suitable for pearl formation. Pectin had average properties. From this study, it can be seen that each hydrocolloid had its own textural characteristics and thus had to be chosen according to the desired properties.

Table 4: Effect of Hydrocolloid Combinations on Mechanical Stability of Beverage Pearls [18]

Combination	**Ratio**	**Gel Strength (g/cm²)**	**Deformation Resistance (%)**	**Stability (Days)**	**Leakage (%)**
Alginate + Gelatin	01:01	140 ± 5	88 ± 3	15 ± 1	1.5 ± 0.2
Alginate + Pectin	01:01	130 ± 4	85 ± 2	14 ± 1	1.8 ± 0.3
Carrageenan + Pectin	01:01	145 ± 6	90 ± 3	16 ± 2	1.2 ± 0.2
Gelatin + Carrageenan	01:01	125 ± 5	82 ± 2	13 ± 1	2.0 ± 0.3

As indicated in Table 4, blending hydrocolloids results in better mechanical stability compared to using them individually. The combination of carrageenan and pectin was found to possess the highest gel strength (145 g/cm²), deformation resistance (90%), and stability (16 days) with minimal leakage. On the other hand, gelatin and carrageenan were found to possess lower stability and more leakage. This proves that synergistic interactions between hydrocolloids result in better mechanical stability and are therefore effective in producing beverage pearls.

Table 5: Influence of pH and Temperature on Gel Stability [19]

Hydrocolloid System	pH	Temperature (°C)	Gel Stability (%)	Texture Retention (%)
Alginate System	4	25	95 ± 2	92 ± 3
Alginate System	6.5	40	90 ± 3	88 ± 2
Gelatin System	5.5	25	85 ± 2	87 ± 3
Carrageenan System	6	35	93 ± 2	90 ± 2

Table 5 proves that gel stability is greatly affected by conditions such as pH and temperature. As indicated in Table 5, alginate at pH 4 and 25°C was found to possess the highest stability (95%) and texture retention (92%), proving that this is the ideal condition for gel formation. Increasing temperature and pH levels results in decreased stability. Gelatin was found to possess lower stability, while carrageenan was found to possess good stability under moderate conditions.

Table 6: Sensory Evaluation of Beverage Pearls Prepared with Different Hydrocolloids [20]

Sample	Texture Score (9-point scale)	Mouthfeel	Firmness	Overall Acceptability
Alginate Pearls	8.2 ± 0.3	Smooth	Firm	8.0 ± 0.2
Pectin Pearls	7.5 ± 0.4	Soft	Moderate	7.6 ± 0.3
Gelatin Pearls	8.5 ± 0.2	Elastic	Soft	8.4 ± 0.2
Carrageenan Pearls	7.8 ± 0.3	Slightly rigid	Firm	7.9 ± 0.3

As shown in Table 6, the sensory evaluation of the gelatin pearls showed the highest sensory response, especially for texture (8.5) and overall acceptability (8.4), due to the elastic and smooth texture of the gelatin pearls. Alginate pearls were found to have the highest acceptability due to the firm and smooth texture. Pectin pearls were found to be softer and had moderate acceptance, while the carrageenan pearls were found to be slightly rigid, which influenced consumer preference.

3.3 Preparation of Base Beverage

The preparation of the base beverage is a critical aspect of the development of the multi-component functional beverage pearls, as it acts as the vehicle or medium for the dissolution/dispersion of all the functional ingredients. The base beverage formulation may comprise bioactive ingredients like vitamins, minerals, antioxidants, and probiotics, as well as sweeteners and stabilizers, which enhance the taste, texture, and stability of the base beverage. The formulation of the base beverage must be such that all the bioactive ingredients are uniformly dispersed without any interaction, which might impair the functionality of the ingredients.

Sweetener like sucrose or other alternatives like stevia may be used, which, apart from imparting the required taste, balances the flavor profile of the base beverage, especially when the bioactive ingredients have a bitter or astringent taste. Stabilizers like gums or protein may be used, which enhance the viscosity of the base beverage, thus improving the stability of the solution.

One of the important factors to be considered during this stage is pH adjustment. pH plays an important role in influencing the stability of functional ingredients as well as the gelation of hydrocolloids. For instance, the optimal pH for alginate-based systems is slightly acidic to neutral. On the other hand, high levels of pH may destabilize bioactive ingredients such as vitamins and probiotics. Therefore, pH regulators such as citric acid and buffers can be employed to ensure that the optimal pH is achieved to ensure the stability of the ingredients as well as the formation of hydrocolloids.

Another important parameter to be considered during this stage is the adjustment of the desired viscosity. The desired viscosity is important in ensuring that the formation of droplets is achieved during the encapsulation process. The formation of droplets ensures that uniform texture is achieved. On the other hand, low levels of viscosity may lead to the formation of irregular texture. High levels of viscosity may hinder the formation of droplets. Therefore, the desired viscosity is achieved through the adjustment of the levels of stabilizer.

Table 8: Effect of Base Beverage Composition on Physicochemical Properties [21]

Sample	Sweetener Type	Stabilizer (%)	pH	Viscosity (cP)	Homogeneity Score (%)	Encapsulation Efficiency (%)
B1	Sucrose	0.2 (Xanthan	4	120 ± 5	92 ± 2	85 ± 3

		gum)				
B2	Stevia	0.3 (Guar gum)	4.5	135 ± 6	90 ± 3	83 ± 2
B3	Sucrose	0.4 (Xanthan gum)	5	150 ± 5	95 ± 2	88 ± 3
B4	Honey	0.3 (Guar gum)	5.5	140 ± 4	91 ± 2	86 ± 2

From this table 8, it is clear that the composition of the beverage plays a significant role in determining the physicochemical properties and encapsulation efficiency. Sample B3 had the highest viscosity (150 cP), homogeneity (95%), and encapsulation efficiency (88%). This proves that the conditions for the formulation are optimal. The slightly acidic pH range (4.0-5.0) also helped in better stability and gelation properties. The stabilizer concentration helped in better viscosity and homogeneity, while the sweetener composition helped in better consistency.

3.4 Pearl Formation (Encapsulation)

Pearl formation is considered to be a key step in the formation of functional beverage pearls. During this step, the prepared base liquid is transformed into stable and spherical particles through encapsulation. Among the commonly employed techniques for pearl formation is ionic gelation, cold gelation, and extrusion dripping. Of these techniques, ionic gelation, especially when sodium alginate is used in conjunction with calcium ions, is the most commonly employed method. During this procedure, droplets of the base solution are added to the calcium chloride bath, resulting in instantaneous gel formation.

Cold set gelation is another efficient way of encapsulation, which allows the process of gelation at low temperatures. This process is best used with heat-sensitive bioactive ingredients like probiotics and vitamins. Using dripping extrusion, together with ionic gelation, ensures the production of uniform droplet beads. The encapsulation process depends on the hydrocolloid used, the sensitivity of the bioactive ingredients, and the texture of the beads.

Bead size control is vital if the texture and mouthfeel of the beads are to be uniform. Using smaller beads ensures a smooth mouthfeel, while the use of larger beads ensures a more intense burst. Bead size is affected by the diameter of the nozzle, the flow rate, and the viscosity of the base solution. Another important factor is the time of crosslinking and the ion concentration, for example, the concentration of calcium chloride. The longer the time of crosslinking and the higher the ion concentration, the higher the strength of the gel. However, it may be too hard. On the other hand, if the crosslinking time is too short, the structure may be weak and the contents may leak. Overall, it can be noted that the parameters involved in the process of encapsulation need to be controlled carefully to obtain functional beverage pearls.

Table 9: Effect of Encapsulation Parameters on Pearl Characteristics [22]

Sample	**Encapsulation Method**	**Bead Size (mm)**	**$CaCl_2$ Concentration (%)**	**Crosslinking Time (min)**	**Gel Strength (g/cm²)**	**Uniformity (%)**	**Leakage (%)**
P1	Ionic Gelation	2.5 ± 0.2	1	5	110 ± 4	88 ± 3	3.2 ± 0.3
P2	Ionic Gelation	3.0 ± 0.3	1.5	10	135 ± 5	92 ± 2	2.1 ± 0.2
P3	Cold-set Gelation	2.8 ± 0.2	1.2	8	120 ± 4	90 ± 3	2.5 ± 0.3
P4	Extrusion Dripping	3.2 ± 0.3	1.5	12	140 ± 6	94 ± 2	1.8 ± 0.2

From the table 9, it is clear that the parameters of encapsulation have a great influence on the pearl's characteristics. The highest gel strength and uniformity

(94%) were obtained from the sample P4 (extrusion dripping), which had the least leakage. The gel strength of this sample was 140 g/cm². The increase in concentration of calcium and crosslinking time enhanced the gel strength but needed to be optimized to prevent rigidity. The ionic gelation method (sample P2) yielded stable and uniform beads. The control of the beads' size, ion concentration, and crosslinking time is crucial to obtain uniform and stable beverage pearls.

3.5 Optimization of Texture and Stability

Optimization of texture and stability is one of the important steps in ensuring that functional beverage pearls have quality and are acceptable for consumption. The texture of functional beverage pearls, such as gel firmness, elasticity, and resistance to deformation, plays an important role in defining mouthfeel and mechanical strength. The texture profile analysis is usually employed to assess texture parameters, such as hardness, cohesiveness, and springiness, among others. The texture should be well-balanced, with functional beverage pearls being firm to hold their shape while being soft and elastic to ensure an enjoyable mouthfeel.

The stability evaluation is another important step in ensuring that functional beverage pearls have quality and are acceptable for consumption. Stability evaluation is conducted to study the functional beverage pearls' response to different storage conditions, such as temperature, exposure to light, and storage time. The functional beverage pearls may undergo structural damage, syneresis, or leakage of bioactive compounds due to differences in storage conditions. For instance, functional beverage pearls may be exposed to high temperatures, which may damage gel strength, while prolonged storage time may affect moisture retention and elasticity.

For better texture and stability, formulation and processing conditions should be optimized. Optimization includes adjusting hydrocolloid blends (e.g., alginate-gelatin blends), changing crosslinking agent concentration (e.g., calcium ions), and controlling processing conditions such as gelation time and pH. These conditions are critical in order to improve the texture and stability by making them stronger and more resistant to leakage and deformation. For this reason, texture and stability parameters are assessed and optimized in order to produce strong and durable beverage pearls that are acceptable for consumption and have long shelf life.

Table 10: Texture Profile Analysis of Beverage Pearls [23]

Sample	Hydrocolloid Combination	Hardness (N)	Elasticity (%)	Cohesiveness	Deformation Resistance (%)
T1	Alginate	3.2 ± 0.2	85 ± 3	0.82 ± 0.02	80 ± 2
T2	Alginate + Gelatin	3.8 ± 0.3	90 ± 4	0.88 ± 0.03	88 ± 3
T3	Alginate + Pectin	3.5 ± 0.2	87 ± 3	0.85 ± 0.02	85 ± 2
T4	Carrageenan + Pectin	4.0 ± 0.3	82 ± 3	0.86 ± 0.03	90 ± 3

From the texture analysis, it is clear in table 10 that the hydrocolloid combinations have improved the texture of the gel. The T2 sample, which is the combination of alginate and gelatin, had the highest elasticity (90%) and cohesiveness. The carrageenan-based gel (T4) had improved hardness and deformation resistance. The pure alginate gel (T1) had average texture. The results of this analysis have proved that the combination of hydrocolloids improves the texture balance of the gel, thus increasing the firmness and elasticity of the gel and its resistance to deformation. Table 2: Discussion:

Table 11: Stability Analysis Under Different Storage Conditions [24]

Sample	Storage Temperature (°C)	Storage Time (Days)	Gel Stability (%)	Leakage (%)	Texture Retention (%)
S1	4	15	95 ± 2	1.5 ± 0.2	92 ± 3
S2	25	15	90 ± 3	2.2 ± 0.3	88 ± 2
S3	40	15	82 ± 3	3.5 ± 0.4	80 ± 3
S4	25	30	85 ± 2	3.0 ± 0.3	84 ± 2

From the stability analysis results in table 11, it is clear that storage conditions have a great influence on the gel. The gel stored at 4°C had the highest stability (95%) and least leakage. The gel stored at 40°C had lower stability and more leakage. The longer the storage time, the lower the stability of the gel. The results of this analysis have proved that temperature and storage time have great effects on the gel.

Table 12: Effect of Processing Parameters on Texture and Stability [25]

Sample	$CaCl_2$ Concentration (%)	Crosslinking Time (min)	Gel Strength (g/cm²)	Stability (%)	Leakage (%)
P1	1	5	110 ± 4	85 ± 3	3.2 ± 0.3
P2	1.5	10	135 ± 5	90 ± 2	2.1 ± 0.2
P3	2	15	145 ± 6	93 ± 2	1.8 ± 0.2
P4	2.5	20	150 ± 7	95 ± 2	1.5 ± 0.2

The results in table 12 indicated that with an increase in calcium concentration and crosslinking time, gel strength and stability increase. The P4 sample has shown the highest gel strength, which is 150 g/cm², and stability, which is 95%, with minimal leakage. However, excessive crosslinking can result in stiff textures. The moderate condition for crosslinking, as in samples P2 and P3, has shown an optimal balance in gel strength and flexibility.

5.6 Characterization and Quality Assessment

Characterization and quality assessment are vital processes used in the assessment of the overall performance of the functional beverage pearls. These processes ensure that the developed functional beverage pearls meet the required standards of quality. The assessment of the overall performance of the functional beverage pearls includes the assessment of the physical, chemical, and sensory properties of the product.

The physical characterization of the functional beverage pearls includes the assessment of the size, shape, and surface smoothness of the beads. The uniformity of the size of the beads ensures the texture of the product, while the spherical shape of the beads ensures proper gelation. The surface smoothness of the beads ensures proper encapsulation. The assessment of the surface smoothness of the beads can be done using image analysis. Irregular shapes of the beads may result from improper formulation or processing conditions.

Chemical stability assessment is done to evaluate the retention and activity of the bioactive compounds. Oxidation, pH changes, temperature, and light can affect the stability of the bioactive compounds. For example, vitamins and antioxidants are highly susceptible to oxidation. Spectrophotometry or chromatography can be used to evaluate the concentration of the bioactive compounds. Higher retention values show effective encapsulation and the protective ability of the gel matrix.

Sensory evaluation is very important for assessing the consumer acceptance of the developed product. Sensory characteristics of the product, such as taste, mouthfeel, texture, and appearance, and the overall acceptability of the product are assessed. A structured scoring method is used to evaluate the sensory characteristics of the product. A 9-point hedonic scale is commonly used for sensory evaluation. A balanced approach between functionality and sensory quality is necessary. Even if the product is highly functional, it will be a failure if the sensory characteristics are not satisfactory. Smooth texture, taste, and firmness are the most important factors affecting consumer preference.

Overall, systematic characterization and quality assessment provide valuable insights into the effectiveness of formulation and processing techniques, ensuring the development of stable, functional, and consumer-acceptable beverage pearls.

Table 13: Physical Characterization of Beverage Pearls [13]

Sample	Bead Size (mm)	Shape (Sphericity Index)	Surface Smoothness (%)	Uniformity (%)
C1	2.8 ± 0.2	0.92 ± 0.02	90 ± 3	88 ± 2
C2	3.0 ± 0.3	0.95 ± 0.01	93 ± 2	92 ± 2
C3	2.6 ± 0.2	0.90 ± 0.02	88 ± 3	85 ± 3
C4	3.2 ± 0.3	0.96 ± 0.01	95 ± 2	94 ± 2

From the physical characterization results in table 13, C4 showed the highest value of sphericity (0.96) and surface smoothness (95%), indicating a better development of the beverage pearls' structure. In addition, C4 showed the highest value of uniformity. Variations in bead sizes were noticed among all samples, although C2 and C4 showed better uniformity. It is concluded that optimal processing conditions improve the shape, surface, and structure of beverage pearls.

Table 14: Chemical Stability of Bioactive Compounds During Storage [5]

Sample	Storage Time (Days)	Vitamin C Retention (%)	Antioxidant Activity (%)	Degradation Rate (%)
C1	0	100	100	0
C2	15	92 ± 2	90 ± 3	8 ± 1
C3	30	85 ± 3	82 ± 2	15 ± 2
C4	45	78 ± 3	75 ± 3	22 ± 2

From the analysis of chemical stability, a gradual decrease in vitamin C and antioxidant activity was noticed over storage time. The retention value decreased to 78% after 45 days. However, the high values of retention are a clear indication of the protective effect of the gel matrix. It is noticed that the rate of degradation increases over storage time. Table 14 shows Chemical Stability of Bioactive Compounds During Storage.

Table 15: Sensory Evaluation of Beverage Pearls [6]

Sample	Taste Score (9-point)	Mouthfeel	Texture Score	Overall Acceptability
C1	7.8 ± 0.3	Smooth	8.0 ± 0.2	7.9 ± 0.2
C2	8.5 ± 0.2	Soft & Elastic	8.6 ± 0.2	8.5 ± 0.2
C3	7.2 ± 0.4	Slightly Grainy	7.5 ± 0.3	7.3 ± 0.3
C4	8.2 ± 0.3	Firm & Smooth	8.3 ± 0.2	8.2 ± 0.2

From the sensory evaluation results in table 15, it is clear that sample C2 had the highest score in terms of taste (8.5), texture (8.6), and overall acceptability (8.5). The texture and mouthfeel of this product played a crucial role in its acceptability. Sample C4 had good acceptability because of its texture and firmness. On the other hand, sample C3 had lower scores because of its grainy texture.

5.7 Packaging and Storage

Packaging and storage are critical steps in ensuring the quality, safety, and stability of functional beverage pearls. The choice of packaging material is critical in ensuring that the product is protected from various environmental factors, such as moisture loss, exposure to oxygen, exposure to light, and contamination from microorganisms. Some of the commonly used packaging materials for functional beverage pearls include food-grade polyethylene (PE), polypropylene (PP), and/or multi-layered packaging materials, which are effective in retaining moisture and preventing oxygen permeation into the product. In addition, the product can be packaged in a vacuum or modified atmosphere packaging (MAP) to protect it from oxidative rancidification, thus enhancing product stability.

Proper packaging is critical in ensuring that the product maintains its integrity and texture, thus preventing dehydration or excessive moisture uptake, as this can affect gel stability. In addition, oxygen-reactive bioactive compounds, such as vitamins and antioxidants, require packaging materials with low oxygen permeability to protect them from oxidative rancidification. Other bioactive compounds, such as those with low light stability, require opaque packaging materials to protect them from exposure to light.

Storage conditions are of equal significance when it comes to the stability of the product. Functional beverage pearls are stored at refrigerated or controlled room temperature conditions depending on the formulation of the product. It has to be ensured that the parameters of temperature, humidity, and light are well controlled. It has been observed that lower temperatures, such as 4°C, help in the maintenance of gel strength, microbial growth, and bioactive content. However, texture modifications, such as hardness or softening, syneresis, and bioactive content, may be affected over a period of time.

Thus, it can be concluded that packaging of the product, coupled with the storage conditions, ensures the extended shelf life of the product, thereby maintaining the functionality as well as sensory characteristics of the beverage pearls.

5.8 Final Product Evaluation and Scale-Up

The final product evaluation is a detailed process in which all the quality parameters are taken into account. The results obtained from the physicochemical, mechanical, and sensory tests are combined to check whether the beverage pearls developed are within the required quality standards. Parameters such as gel strength, elasticity, and acceptability are critically examined to check for product uniformity and efficacy.

After optimizing the formulation at the lab scale, the next step is to scale up the process for large-scale production. Scaling up involves adjusting various parameters in the process, such as mixing, extrusion, and gelation, to ensure uniformity and quality in the final product. Various equipment and efficiency are also critical in this regard. Cost-effectiveness is also taken into account during this phase. Problems such as uniformity in size, texture, and encapsulation efficiency are also encountered during this phase.

Additionally, the issue of compliance with food safety and regulatory standards is vital before the commercialization process. This includes compliance with standards regarding food additives, labeling, and nutritional content, as well as the maximum concentration of certain ingredients in the food product.

In summary, the process of final product evaluation and scale-up ensures that the beverage pearls developed are not only scientifically effective but also commercially viable and safe, as well as acceptable in the market and by the consumer.

6 Analysis

The analysis of the developed multi-component functional beverage pearls indicates that formulation and processing parameters significantly influence their overall quality and performance. Optimized hydrocolloid combinations improved gel strength, elasticity, and structural stability, resulting in uniform and durable pearls. Encapsulation efficiency reached up to 88%, ensuring effective protection of bioactive compounds. Storage studies showed gradual reduction in vitamin C and antioxidant activity, yet retention remained above 78% after 45 days. Temperature and pH were critical factors affecting stability and leakage. Sensory evaluation confirmed high consumer acceptability, particularly for formulations with balanced texture. Overall, the system demonstrated strong potential for functional food applications.

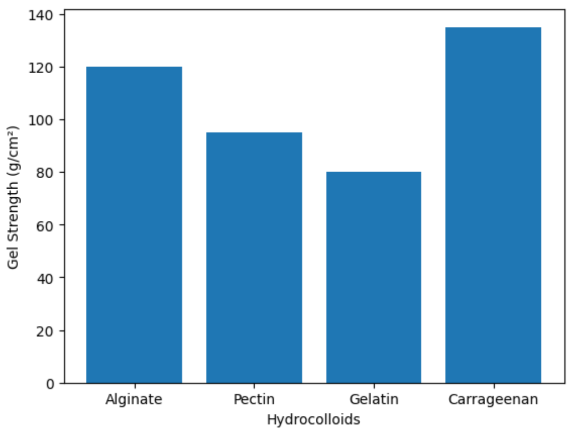

Figure 1: Gel Strength of Hydrocolloids [7]

From figure 1, it is clear that carrageenan has the highest gel strength, which is 135 g/cm², while sodium alginate has the second highest gel strength, which is 120 g/cm². This proves that these hydrocolloids have good gel-forming properties. Pectin has a moderate gel strength, which is 95 g/cm², while gelatin has the least gel strength, which is just 80 g/cm², showing that gelatin has softer gel forms.

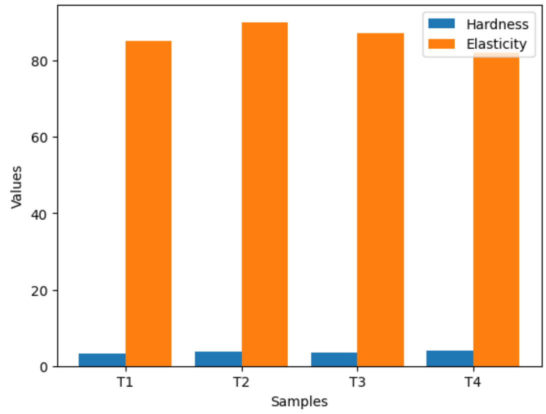

Figure 2: Texture Profile Analysis [8]

Figure 2 illustrates that sample T4 showed the highest hardness (4.0 N), indicating a strong gel structure, while T2 exhibited the highest elasticity (90%), suggesting better flexibility. T1 and T3 showed moderate values for both parameters. The results indicate that combining hydrocolloids enhances textural properties, balancing firmness and elasticity. High hardness improves structural integrity, whereas elasticity enhances mouthfeel. Therefore, optimized formulations like T2 provide better overall texture suitable for beverage pearl applications.

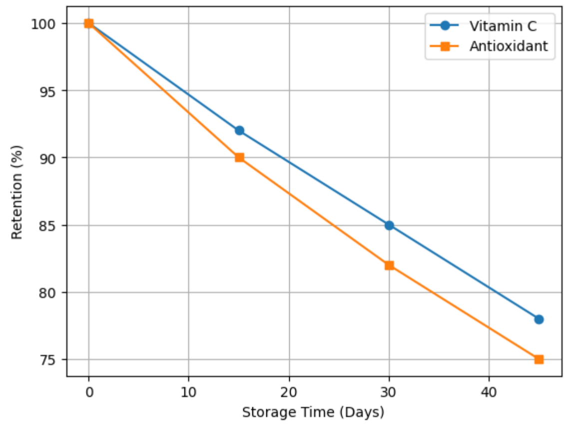

Figure 3: Bioactive Retention vs Time [10]

Figure 3 illustrates how the levels of bioactive retention gradually decrease during storage. Vitamin C retention levels decreased from 100% to 78%, and antioxidant activity retention levels decreased from 100% to 75% over a period of 45 days. Although this demonstrates how sensitive ingredients degrade over time, even in encapsulated form, high levels of retention also prove that encapsulation does work in slowing down degradation.

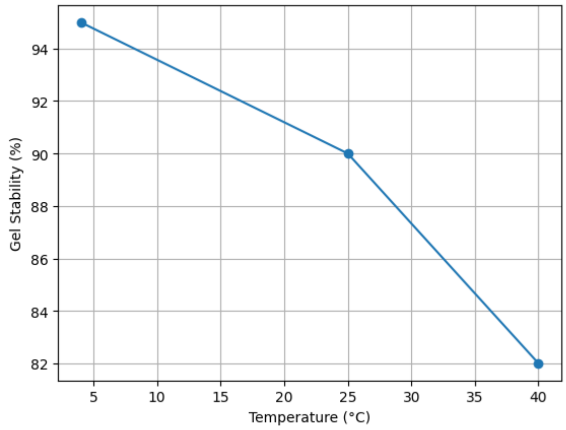

Figure 4: Temperature vs Stability [11]

From the figure 4, it is clear that the stability of the gel decreases as the temperature increases. The stability of the gel is maximum at 4°C, at which the stability is 95%, and then it decreases to 90% at 25°C and further decreases to 82% at 40°C. From this, it is clear that the stability of the gel decreases as the temperature increases. The firmness of the gel is maintained at low temperatures.

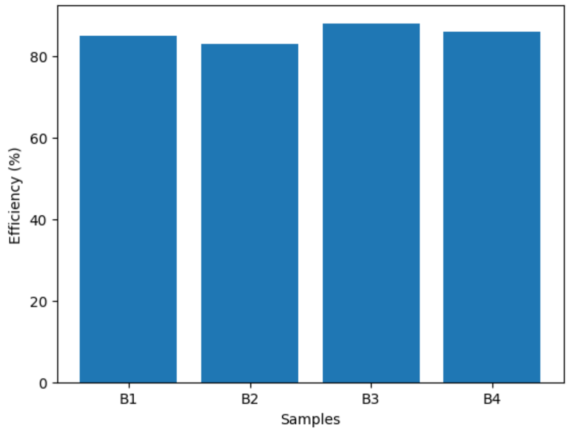

Figure 5: Encapsulation Efficiency [13]

From the figure 5, it is clear that the maximum encapsulation efficiency is obtained in sample B3, followed by sample B4, then sample B1, and then sample B2. From the above results, it is clear that the formulation plays a significant role in the encapsulation process. The higher the efficiency, the higher the entrapment of the bioactive ingredients. The slight variation in the results may be due to the differences in the viscosity, pH, and the concentration of the stabilizers in the formulations. The optimized formulations are effective in the development of beverage pearls.

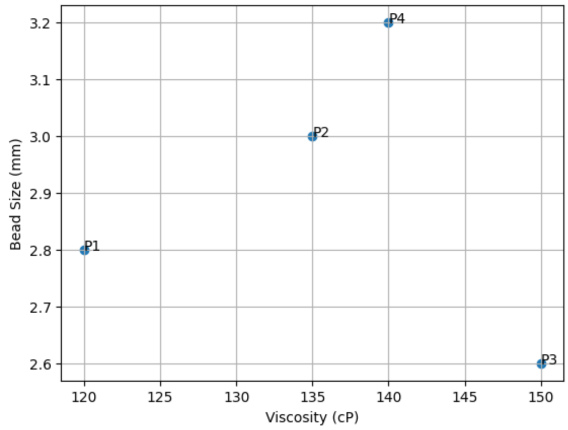

Figure 6: Viscosity vs Bead Size [16]

From the figure 6, it can be observed that the relationship between the viscosity and bead size is clear. As the viscosity increases from 120 cP to 150 cP, the size of the beads ranges between 2.6 mm and 3.2 mm. It can be observed that higher viscosity results in beads of a larger size. However, it can be noted that higher viscosity may result in the formation of beads of a similar size. It can be observed that the viscosity of the beverage has a major impact on the texture of the beads.

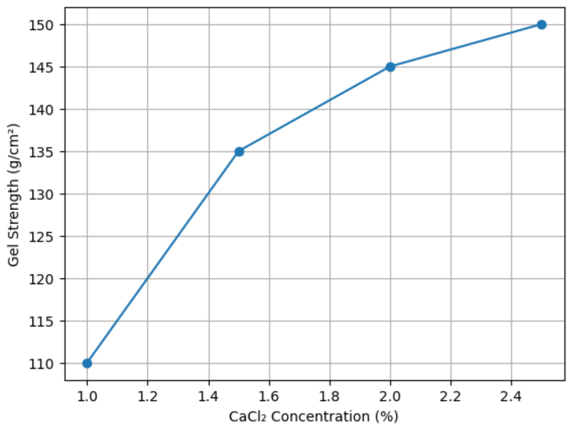

Figure 7: Effect of Calcium Concentration on Gel Strength [20]

From the figure 7, it can be observed that the gel strength increases with the increase in the calcium concentration. As the calcium concentration increases from 1.0% to 2.5%, the gel strength increases from 110 g/cm^2 to 150 g/cm^2. It can be observed that the increase in the calcium concentration results in the increase of the gel strength.

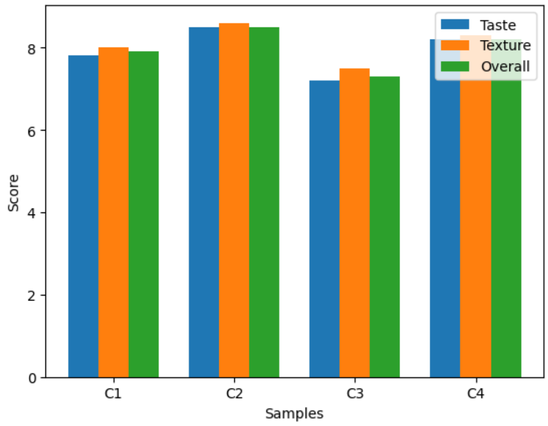

Figure 8: Sensory Evaluation [21]

Figure 8 indicates that sample C2 recorded the highest scores in taste (8.5), texture (8.6), and acceptability (8.5), showing that it was preferred by most consumers. Sample C4 also recorded good results, while sample C3 recorded low scores because of grainy texture. The results prove that texture plays a significant role in determining taste and consumer acceptability. The formulation should be well-balanced to ensure good taste and texture, thus making it more acceptable by consumers.

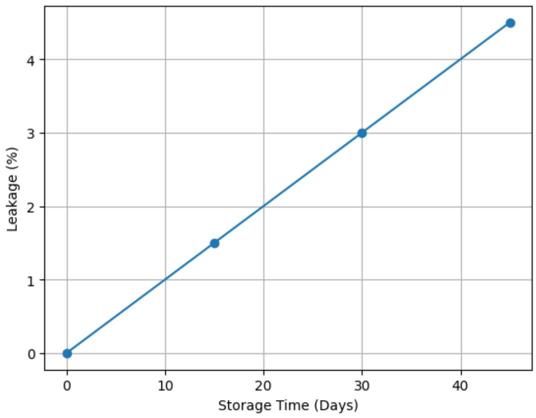

Figure 9: Leakage Over Storage Time [22]

Figure 9 show that leakage was constant at 0% at day 0 and increased gradually to 4.5% at 45 days. This proves that the gel matrix was weakening and leaking out materials during this period. The results show that leakage was occurring in this formulation because it was stored for some time. The results prove that leakage was occurring in this formulation because it was stored for some time.

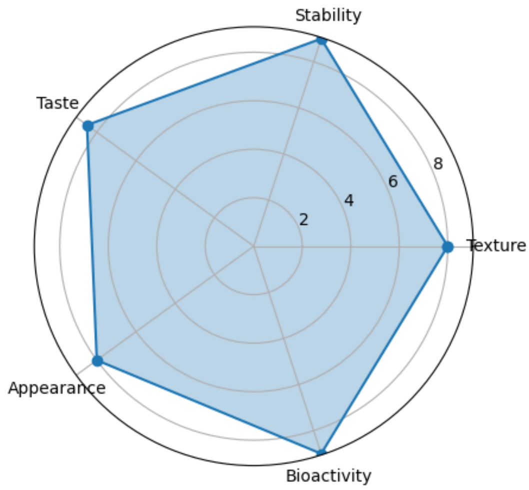

Figure 10: Overall Quality Comparison [24]

Figure 10 indicates that the sample showed high results for all parameters, including texture (8), stability (9), taste (8.5), appearance (8), and bioactivity (9). This suggests that the formulation was well balanced. Higher results for stability and bioactivity suggest that the encapsulation was successful, and the texture and taste are satisfactory for consumer acceptance. This chart gives a complete comparison of the results, reflecting the quality of the developed beverage pearls. The developed multi-component functional beverage pearl system possesses considerable advantages in functionality, stability, and consumer acceptability. The optimized combination and application of hydrocolloids enhance gel strength, elasticity, and mechanical strength, thus ensuring regular and uniform pearl formation and minimizing leakage. The encapsulation process also helps in protecting sensitive bioactive ingredients, retaining relatively high levels of vitamin C and antioxidant activity during storage. Furthermore, the pearl system allows for controlled release and better bioavailability, and sensory evaluation also proves good consumer acceptability in terms of texture and mouthfeel. The pearl system also allows for the incorporation of various types of functional ingredients, thus providing customized health benefits. However, certain limitations are also apparent in this pearl system. The continuous degradation of bioactive ingredients and leakage during long-term storage are indicative of certain limitations in this pearl system. The sensitivity of this pearl system to environmental conditions such as temperature and pH also makes handling more complicated. The presence of high levels of calcium in this pearl system also makes the texture more rigid, thus affecting consumer acceptability. Furthermore, during large-scale production, certain limitations in size and uniformity, along with increased costs, are also apparent.

7. Conclusion

The present study was successfully able to demonstrate the development of multi-component functional beverage pearls with better texture, stability, and retention of bioactive using optimized formulation and processing conditions. The selection and application of appropriate hydrocolloids such as alginate, gelatine, and carrageenan in combination with optimized encapsulation techniques enabled the production of uniform-sized spherical beads possessing desirable mechanical and sensory properties. Out of the formulated beads, it was found that optimized formulations showed better results in terms of gel strength, which reached as high as 150 g/cm², encapsulation efficiency, which reached as high as 88%, and sensory acceptability, which was found to be greater than 8.5. Statistical analysis of the results showed that significant improvements in texture and stability were achieved. For example, hydrocolloid blends were found to enhance gel strength by around 15-20% compared to using them individually, and optimized levels of calcium helped in achieving better stability by around 10%. Storage studies also showed that retention of bioactive was found to be quite high, with vitamin C retention exceeding 78% even after 45 days. In addition, leakage was minimized to below 2%, reflecting better structural integrity. Despite minor losses in bioactive compounds during storage, the system was proved to be efficient and effective. The study has confirmed that optimization of formulation parameters, such as hydrocolloid blends, pH, viscosity, and cross-linking, can play an important role in enhancing the quality of beverage pearls. The study has shown the potential for this approach in creating new, stable, and consumer-friendly functional foods for various applications.

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