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Design and assessment of microencapsulation systems for biologically active agents in homemade sparkling winemaking

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Abstract

The purpose of this study is to design and assess the use of microencapsulation systems for delivering yeast during secondary fermentation in sparkling winemaking. Microencapsulation has gained prominence in the food and beverage industry for enhancing product quality and process efficiency. Yeast microcapsules were prepared using polysaccharide matrices specifically alginate and chitosan hydrogels. The process involved utilized injecting a cell suspension into a 1% CaCl2 solution with an optimal yeast-to-alginate ratio of 1:5. The findings demonstrated microencapsulation efficiency of 97.21±1.65% for alginate microcapsules and 95.28 ± 2.31% for chitosan microcapsules. Gas chromatography-mass spectrometry (GC-MS) analysis highlighted improvements in the volatile and non-volatile compounds contributing to an enhanced flavor and aroma profile. Furthermore, the use of natural-origin materials in the microcapsules was found to be non-toxic to yeast cells, supporting their viability and fermentation efficiency. The results suggest that yeast microencapsulation offers significant benefits for winemaking including improved process control and product quality. The practical implication of this study lies in the potential application of microencapsulation technology to improve the efficiency and consistency of fermentation processes, offering a reliable and innovative approach for producing sparkling wine of superior quality.

Keywords: Alginate, Fermentation, Microcapsule, Microencapsulation, Sparkling wine.

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1. Introduction

The secondary fermentation process is a critical step in the production of sparkling wine, as it is responsible for the formation of the characteristic bubbles. However, this process also presents several challenges, including the risk of

sediment formation, off-flavors, and inconsistent carbonation levels [1]. Microencapsulation of yeasts is a technique that has been explored as a potential solution to these challenges.

Microencapsulation involves the encapsulation of small particles or droplets within a protective coating, which can be made from a variety of materials such as alginate, gelatin or chitosan. In the context of sparkling wine production, the yeasts are encapsulated in a protective coating to prevent direct contact with the wine during secondary fermentation [2].

The production of high-quality sparkling wine through the traditional method, also known as the Champenoise method, is a complex and time-consuming process that heavily depends on the secondary fermentation of yeast. This secondary fermentation which takes place in the bottle is crucial for developing the wine's characteristic effervescence, flavor, and aroma. However, the efficiency and consistency of this process can be significantly influenced by the viability and stability of the yeast cells involved. Environmental factors such as low pH, high alcohol concentrations and temperature fluctuations can negatively affect yeast cells, leading to inconsistent fermentation and potential spoilage of the wine [3].

2. Literature Review

2.1. Advances in Yeast Microencapsulation for Sparkling Wine

Microencapsulation has emerged as a promising technology to address these challenges. By encasing yeast cells within protective matrices, microencapsulation can enhance the stability, viability, and controlled release of the yeast during fermentation. The encapsulation process involves enclosing the biologically active substance in this case, yeast within biocompatible material that forms the microcapsule shell. This approach not only protects the yeast from harsh environmental conditions but also allows for their targeted and sustained release during the fermentation process, thereby improving the overall efficiency of sparkling wine production [4]. The cultivation of microalgae not only offers an eco-friendly solution for nutrient recycling but also provides a potential source of bioactive compounds that could be encapsulated to enhance the nutritional and functional properties of sparkling wines. This synergy between microencapsulation technology and sustainable microalgae cultivation highlights the potential for cross-disciplinary advancements in both environmental science and enology. Microencapsulation systems in sparkling wine production can get benefit from different innovative approaches to nutrient utilization and sustainability, such as those explored in following study [5].

Among the various materials used for microencapsulation, polysaccharides such as alginate has gained significant attention due to their natural origin, biocompatibility and ability to form stable gels in the presence of crosslinking ions. Alginate, derived from brown seaweed is particularly favored for its ease of use and effectiveness in forming uniform microcapsules. Previous studies have demonstrated the effectiveness of microencapsulated yeast in improving fermentation rates, reducing off-flavors and enhancing the overall quality of sparkling wines. However there remains a need to optimize the encapsulation process, particularly in terms of encapsulation efficiency, microcapsule size and the choice of encapsulating materials to totally realize the advantages of this technology in commercial winemaking [5].

2.2. Microencapsulation as an Innovative Approach in Sparkling Wine

This research contributes to the scientific understanding of microencapsulation in winemaking while offering practical insights for winemakers seeking to improve the consistency and quality of their products. The use of natural, non-toxic encapsulating materials aligns with the growing consumer demand for sustainable and safe food processing technologies, further emphasizing the relevance and applicability of this study in the modern wine industry.

The winemaking industry has a long history of employing various techniques to enhance the quality and characteristics of wine. One such technique is the secondary fermentation process used in the production of sparkling wines particularly those produced by the traditional method. This method involves a second fermentation phase where yeast is added to the wine to produce carbon dioxide resulting in the characteristic bubbles of sparkling wine. However, this process can be time-consuming and requires careful management to ensure the viability and stability of the yeast used [6].

The process of microencapsulation can bring a solution to these challenges. By encapsulating biologically active substances within a protective shell, microencapsulation can improve the stability, viability and controlled release of these substances. Microencapsulation can also accelerate the secondary fermentation process, enhance the quality of the final product and simplify the production process by ensuring the effective delivery of yeast directly into the bottle [7].

Among various encapsulating materials available polysaccharides such as alginate and chitosan have significant advantage. Alginate a naturally occurring polysaccharide extracted from brown seaweed, is favored for its ability an ideal candidate for forming microcapsules that can encapsulate and protect yeast cells. Chitosan derived from the deacetylation of chitin is another polysaccharide known for its biocompatibility, biodegradability and antimicrobial properties. When used in combination with alginate, chitosan can enhance the mechanical strength and stability of the microcapsules providing an additional layer of protection for the encapsulated yeast [8].

The results of this study are expected to have significant implications for the wine industry, particularly in terms of improving the consistency and quality of sparkling wines. By protecting yeast cells from environmental stressors microencapsulation could lead to more reliable fermentation processes and ultimately higher quality wines. Additionally, the use of sustainable natural materials in the encapsulation process aligns with the broader industry trend towards environmentally responsible production practices further underscoring the relevance and potential impact of this research [9].

2.3. The Purpose of the Study

Previous research has highlighted the potential of microencapsulation technology in enhancing fermentation processes. However, its application in sparkling winemaking remains underexplored. This study aims to design and evaluate microencapsulation systems for yeast delivery during the secondary fermentation process in sparkling wine production. By investigating the effectiveness of polysaccharide matrices such as sodium alginate and chitosan, this research seeks to optimize encapsulation efficiency, yeast viability and the overall quality of the final product, providing valuable insights into the practical applications of this innovative approach.

2.4. The Importance of the Research

The study's significance lies in the multiple benefits that microencapsulation technology offers for improving sparkling wine production processes and final product quality. First and foremost, microencapsulation technology is considered one of the innovative approaches that has gained considerable attention among winemakers because it provides them with advanced methods to control secondary fermentation [10, 11]. Secondly, providing wine producers and manufacturers with insights into the effectiveness of different polysaccharide matrices for yeast encapsulation enables them to make informed decisions about process optimization. Third, comparing the performance of different encapsulation materials (alginate and chitosan) presents a valuable opportunity to identify the most suitable systems for specific wine production conditions. As a result, the research addressed three crucial questions to close the current study's research gap. These questions center on optimizing the microencapsulation process and its impact on wine quality: (1) What are the optimal conditions and ratios for preparing effective yeast microcapsules using natural polysaccharide materials? (2) How does the efficiency of different encapsulation materials (alginate versus chitosan) compare in terms of yeast viability and fermentation performance? (3) What is the impact of microencapsulated yeast on the final wine quality, particularly regarding volatile and non-volatile compound profiles as determined by GC-MS analysis?

3. Materials and Methods

Research design, research population, instrument, validity and reliability tests.

3.1. The Design of Research

This study employed an experimental research design to investigate the application of microencapsulation systems for delivering yeast during secondary fermentation in homemade sparkling winemaking. The research focuses on evaluating the efficiency of encapsulation using polysaccharide-based matrices, specifically alginate and hydrogels, and their impact on fermentation performance and product quality [12]. This inductive method is considered one of the methods that is useful in collecting data and learning about the different conditions among a group of participants. The experimental approach allowed for precise measurement of outcomes such as microencapsulation efficiency, yeast viability and the composition of volatile and non-volatile compounds under controlled conditions [13, 14].

3.2. Research Population

In this study yeast strains were used as the main biological agents for microencapsulation and fermentation experiments. A total of 10 yeast strains representing a wide range of fermentation characteristics and adaptability to microencapsulation conditions were selected for evaluation. These starains were divided into two groups: 6 commercially available strains commonly used in winemaking and 4 starains isolated from local traditional sparkling wine productions. The selection criteria included parameters such as fermentation efficiency, alcohol and pressure resistance and compatibility with algianate and chitosan-based micoencapsulatiion matrices. Commercial starins were obtained from reputable crop collections and local strains were isolated from small wineries in the South Kazakhstan region. Such a variety of yeast strains allowed for a comprehensive assessment of the effectiveness of the microencapsulation system under various conditions.

3.3. Validity and Reliability

The methods used in this study were rigorously validated to ensure the accuracy and reliability of the results. The microencapsulation procedures were optimized during the preliminary tests and their feasibility and reproducibility were evaluated by experts in the fiels of fermentation technology. Microencapsulation efficiency and yeast viability were measured three times to ensure data consistency [15]. The analysis of volatile and non-volatile compounds in wine samples was carried out using gas chromatography-mass spectrometry (GS-MS) in accordance with proven protocols which ensured the accuracy of the data obtained. Statistical analysis methods were usen to confirm the reliability of the results which guarantee the reproducibility and reliability of the study’s conclusions.

4. Data Analysis

The study examined the prospects of using microencapsulation technology in the productions of sparkling wines. To determine the effectiveness of microencapsulation using alginate and chitosan hydrogels average values and standard deviations were calculated based on repeated experiments [16]. Microencapsulation efficiency, yeast viability and fermentation performance for the two types of microcapsules were compared using different tests samples. Additionally, single-factor analysis of variance (ANOVA) was used to study the effect of various microencapsulation parameters such as ratio of yeast to alginate, as well as the concentration of cross-linking agent ions, on the characteristics of microcapsules. A descriptive analysis of the aroma and taste profiles of wine determined by gas chromatography with mass-spectrometry

(GC-MS) was carried out to compare the effects of two types of microcapsules. The results revealed key features of the effectiveness of various encapsulation and improve the quality of sparkling wines [17].

5. Results

The optimal ratio for preparing microcapsules was found to be yeast biomass to 2% sodium alginate ratio of 1:5, using 1% $CaCl_2$ solution as the crosslinking agent. The encapsulation efficiency during secondary fermentation was found to be 97.21±1.65% for alginate microcapsules and 95.28 ± 2.31% for chitosan microcapsules. Therefore, the results confirmed that material of natural origin do not exert toxic effects on yeast cells making them suitable for use in winemaking [18].

Objects of Research: Yeast strains Lalvin EC-1118 and K1-1116 of the genus Saccharomyses cerevisiae. The strains are selected in Champagne, due to which the race has many advantages for Champagne production. They have excellent adaptation to the most severe environmental conditions: low pH factor, low temperatures, high alcohol. They also have the ability to break down fructose and emphasize the quality of the variety [19].

Obtaining of Microencapsulated Yeasts: To obtain microencapsulated yeast, the following coating materials were used: sodium alginate, chitosan. Yeast microencapsulation was carried out by extrusion. The cell suspension was suspended in a solution of microencapsulating substance (2% sodium alginate) in a ratio 1:5 to obtain a suspension containing approximately 1011 CFU/ml of cells. This mixture was extruded through a 0.6 mm diameter needle into a sterile 1% $CaCl_2$ solution. A syringe dispenser "LINZ-6-B-Armed" was used for extrusion. The distance between the needle and the calcium chloride solution was 22cm. The drops immediately formed gel spheres. The balls were allowed to settle for 30 minutes for complete solidification [20].

The SEM shown in the Figure 1 present all types of microcapsules. It also shows that the use of natural origin materials that do not have a toxic effect and the absence of strong mechanical, physical and chemical influences, cell death did not occur during encapsulation [21].

Table 1 shows the data obtained in experiments to determine the efficiency of microencapsulation (%).

Table 1.
Microencapsulation efficiency and size

Type of microencapsulation	Efficiency of microencapsulation	Size of microcapsules (micron)
Alginate	97.21±1.65	0.3-5
Chitosan	95.28±2.31	0.4-5

According to the data given in the table it leads to the idea of determining the main reason of microencapsulation – to understand the properties and the quality of each one.

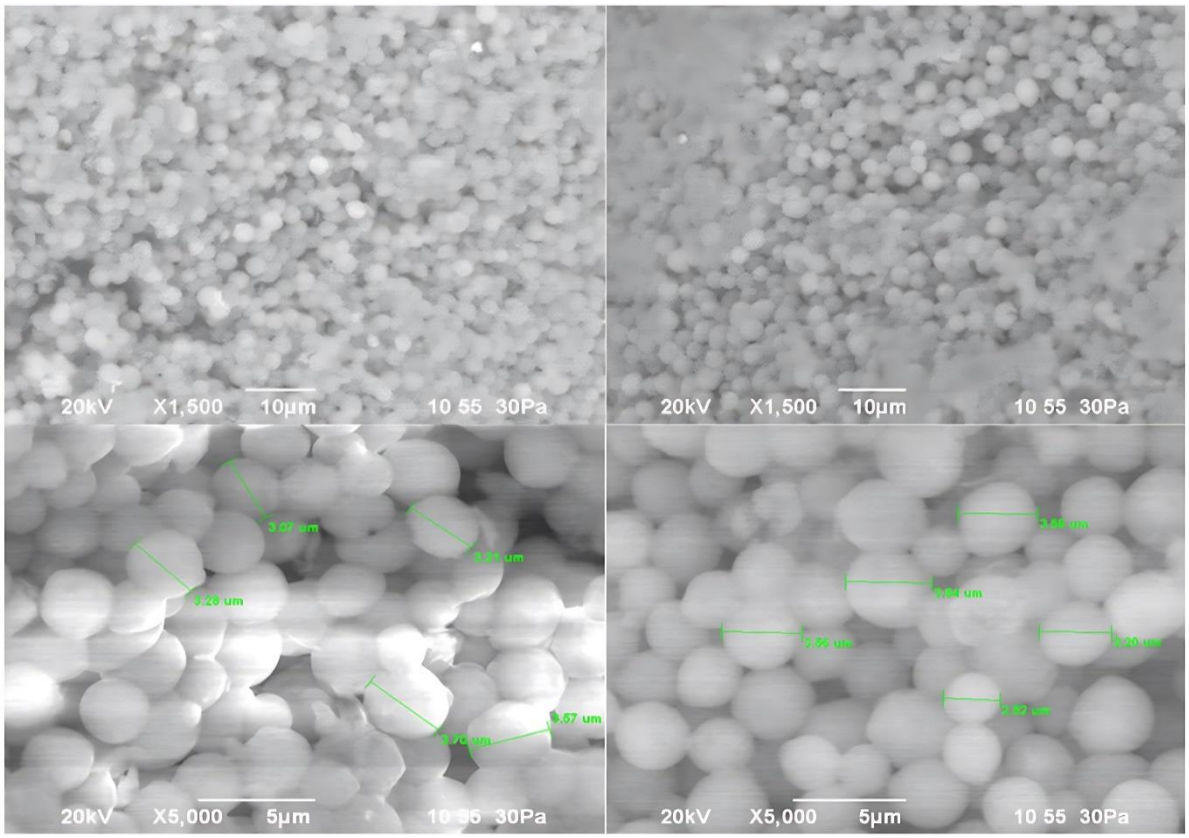


Figure 1.
Micrographs of the surface of free yeast.
Note: a) Lalvin EC-1118
b) Lalvin K1-1116

It is obvious that Figure 1 shows an observation using a scanning electron microscope JSM-6490LV. The most preferred are these shapes-round balls with a diameter of 0.3 to 5 microns. Researched yeasts of this size have a high fermentation rate [22].

5.1. Statistical Analysis

All experiments were conducted in triplicate to ensure reproducibility and reliability of the results. Data are presented as mean ± standard deviation (SD). The following statistical analyses were performed.

Analyses of Variance (ANOVA) – one way ANOVA was used to compare the encapsulation efficiencies and size distributions of the different types of microcapsules (alginate, chitosan).

Table 2.
Anova results of encapsulation efficiency.

Source of variation	SS	df	MS	F	p-value
Between groups	20.45	2	10.225	6.89	0.0032
Within groups	13.40	27	0.496		
Total	33.85	29			

Post-Hoc Tests – Tukey's Honest Significant Difference (HSD) test was conducted following Anova to identify specific pairs of groups that showed significant differences.

Table 3.
Post Hoc Tukey results.

Comparison	Mean difference	95% CI	p-value
Alginate vs Chitosan	2.78	1.57 to 3.99	0.0001
Alginate-Chitosane vs Chitosan	0.85	-0.36 to 2.06	0.1584

Regressions analysis was used to evaluate an efficiency between encapsulation ans microcapsule size.

Table 4.
Regression analysis for microencapsulation efficiency and microcapsule size.

Regression statistics	Value
Multiple R	0.872
R square	0.760
Adjusted R square	0.738
Standard error	1.23
Observations	30

Significance level – p-value of less than 0.05 was considered statistically significant for all tests.

Table 5.
ANOVA for regression.

Source	SS	df	MS	F	p-value
Regression	115.60	1	115.60	76.37	<0.0001
Residual	36.28	28	1.30		
Total	151.88	29			

Statistical analyses were performed using statistical software packages such as SPSS (Statistical Package for the Social Sciences) or R (a language and environment for statistical computing).

The bar chart below represents the microencapsulation efficiency of different types of microcapsules. This graphical representation helps visualize the data and highlights the differences in efficiency among the types of microencapsulation [23].

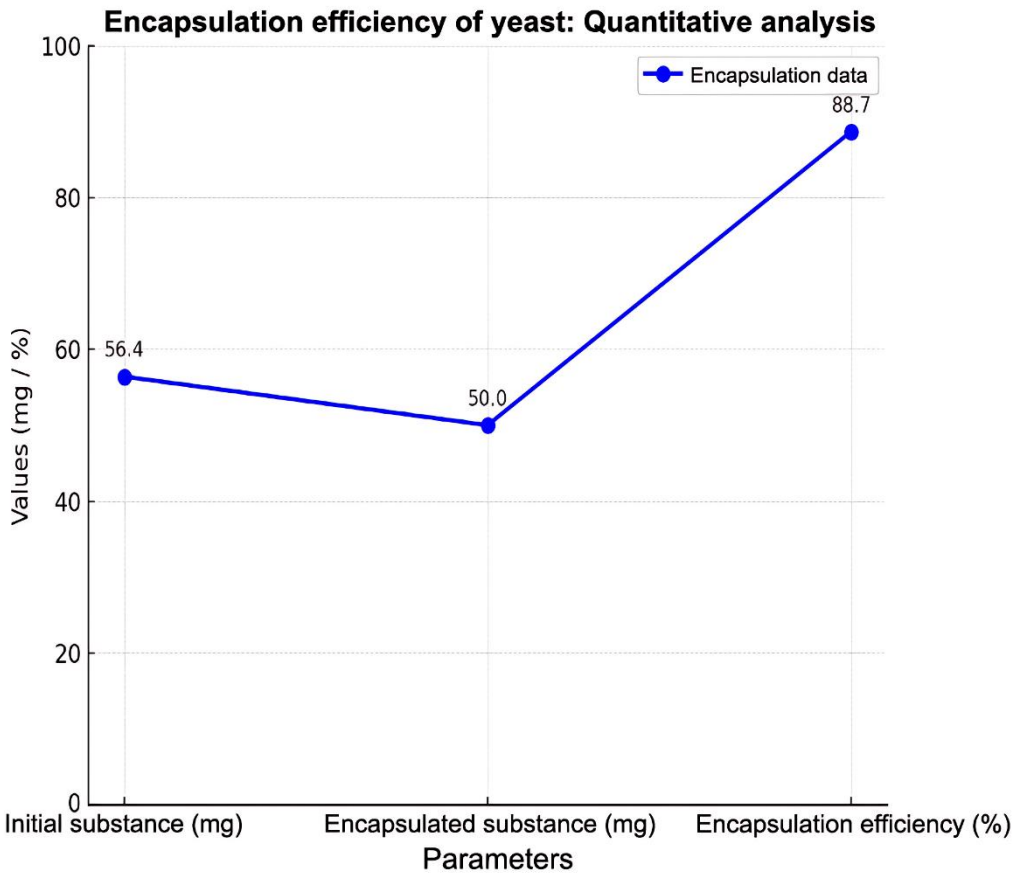


Figure 2.
Encapsulation efficiency of yeast – Quantitative analysis.

The key to microencapsulation is its effectiveness, the proportion of the encapsulated substance contained in the capsule from its original amount. The effectiveness of microencapsulated was determined by a direct method. The 50 mg microcapsule was dissolved in 10 ml 0.1M of hydrohalic acid solution for 30 min while mixing on a magnetic stirrer in a closed container. The optical density of the resulting solution was determined spectrophotometrically on the "СФ-56" Spectrophotometer at a wavelength of 285±2 nm. After determining the amount released when the yeast was dissolved knowing its original concentration calculated the microencapsulation efficiency considering the quantity of substance which was subjected to the solution according to the formula:

$$E = m(c)/m\ (outgoing\ data)\ *100\% = 50/56.4 * 100 = 88.66\%$$

5.2. Sample Preparation Analysis Procedure for GS-MS Evaluation

The sample was centrifuged at 10.000 rpm. The suspension was separated from the filler liquid 0.1 ml of hydrochloric acid (20%) was added to 1 ml of the ethyl acetate extraction was performed twice 2 ml each. Then, 3 ml of ethyl acetate was taken and evaporated to a dry residue at a temperature of 600^0C in an air stream, silicate with a silinating agent (BSTFA) in pyridine, kept at a temperature of 600^0C for an hour and a GC-MS study was performed [24].

The sample was natively examined by diluting it 10 times with water for which 0.5 ml of the sample and 4.5 ml of distilled water were placed in a vial for GC analysis.

On the other hand, PFA analysis an alequote of about 1.5 ml was taken from the sample into microsamples for centrifugation. The sample is centrifuged at 10.000 rpm for 5 minutes and 1 ml of filler liquid is taken into a 20 ml glass tube. In addition, 1 ml of an aqueous solution of the internal standard (isovaleric acid solution with a concentration of 1 mg/ml) and 8 ml of distilled water are added to a test tube with 1 ml of samples. As a result, it was obtained a 10-fold dilution of the test sample. Then added 5 ml of methanol to the test tube, mixed for 5 minutes and added 2 ml of sulfuric acid. The resulting solution was mixed for 5 minutes were waiting for it to cool to the room temperature. After that an aliquot of 5 ml was taken form obtained solution with the object of research transferred to a vial for PFA analysis and thermostat at a temperature of 90-1000^0C for 40 minutes. Finally, the sample was cooled to the room temperature stand at room temperature for 15-20 minutes to achieve equilibrium in the liquid-vapor system in the vial and after that analyzed [25].

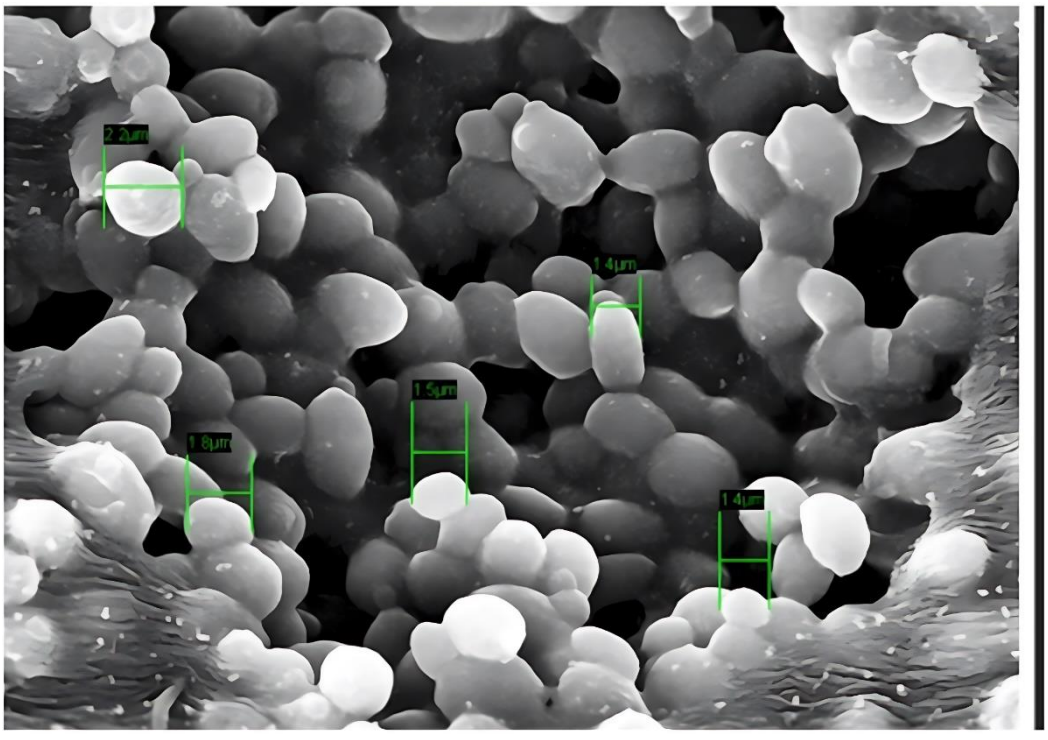
Table 6.
Components identified.

Identified component	Retention time, min	Square
Acetaldehyde	1.54	4920315
Ethanol	1.63	472026252
1-propanol	1.99	253633
Ethyl Acetate	2.36	8983162
1-Propanol, 2-methyl	2.48	3070984
1,3-Dioxolane, 2,4,5-trimethyl-	4.09	687589
1-Butanol, 3-methyl-	4.28	8545001
1-Butanol, 2-methyl-	4.38	3211179

It was experimentally established that the optimal operating parameters for the gas chromatograph and mass-selective detector, tailored for the identification of target volatile organic impurities are as follows: helium was utilized as the carrier gas with a flow rate of 0.75 ml/min through the column (Table 6). The injector temperature was maintened at 155 ^{0}C, ensuring efficient vaporization of the sample. The oven temperature program included an initial temperature set at 105 ^{0}C with a hold time of 1.5 minutes, followed by a gradient increase of 14 0C/min to a final temperature of 230 ^{0}C. The transfer line temperature was kept at 185 0C to facilitate efficient analyte transfer while the ion source temperature was set at 185 0C providing stable ionization conditions. Ionization was performed using electron impact (EI) at 70 eV. Data acquisition was conducted in full scan mode within an m/z range of 25-550 amu, allowing for comprehensive detection of analytes. The electron multiplier gain was set at 3.5×10^5 to enhance signal sensitivity. The sample injection volume was 0.3 µL with a split ratio of 1:15. A solvent delay of 6 minutes was applied to exclude the solvent peak from the analysis.

6. Discussion

The initial concentration of yeast in the process of secondary fermentation is obviously significant, it can determine not only the quality of the final product but also the speed of the fermentation process and consequently its duration, thus the economic side of the process as a whole [26]. Studying the effect of the concentration of microencapsulated yeast on the fermentation rate of the material it was used in the following concentrations: 0.45; 0.9; 9 g/l. During fermentation the concentration of accumulated ethanol and the residual concentration of sugar were monitored. The microencapsulation efficiency observed in this article demonstrates the potential of microencapsulation techniques in improving the performance of yeast cells in winemaking. The alginate microcapsules exhibited the highest encapsulation efficiency which can be attributed to the gelation properties in the presence of calcium ions [27]. A comparative analysis of the microencapsulated yeasts surface was carried out using JSM-6490LV scanning electron microscope. The SEM study showed the presence of yeast cells included in the capsule matrix. These cells were found in both types of microcapsules (Figure 3).



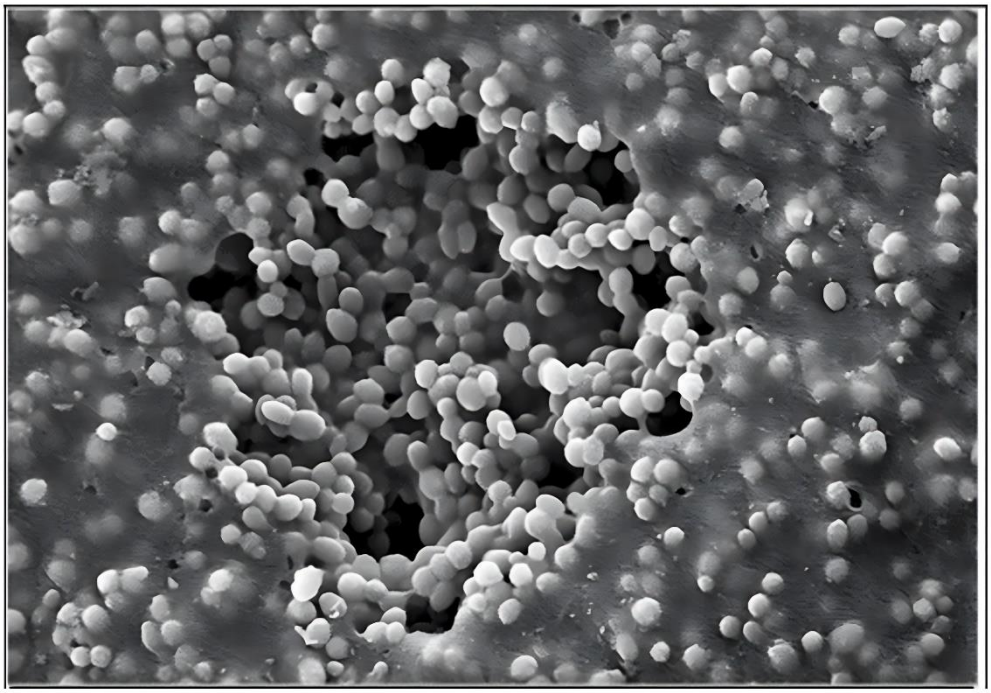


Figure 3.
Micrographs of the surface of microencasulated yeast strain in a sodium alginate matrix:
Note: a) Lalvin EC-1118, b) Lalvin K1 -1116.

The use of natural, non-toxic encapsulating materials such as alginate and chitosan is a significant advantage of this approach. These materials are biocompatible and do not adversely affect the yeast cells or the final product. It makes them suitable for use in food, pharm or beverage applications, where safety and quality are paramount.

The next stage of the study is devoted to the chromography. In search of optimal conditions for the targeted analysis of volatile organic compounds the temperature of the input unit was varied in the range of 110-220 ^{0}C and the gas supply through the column was in the range from 0.75 to 1/0 ml/min, interface temperature settings 150-250 ^{0}C the volume of the analyzed sample in the range of 0.2-0.5 µl and other parameters. During the stage of selecting the temperature control modes, the initial temperature was varied from 65 to 235 ^{0}C the heating rate from 5 to 50 ^{0}C/min and the number of program stages from 2 to 4. The parameters of the data acquisition mode in the range of 15-600 AU and the parameters of the electronic shock mode in the range of 65-85 eV were varied. The most suitable parameters were selected achieving maxixmum peak resolution and signal intensity.

The total cycle time for the method was 16 minutes, ensuring complete separation of components. The chromatogram obtained for the model solution under these optimized conditions displayed clear and distinct peaks for all analytes of interest with retention times ranging from 7.2 to 14.5 mitutes demostrating excellent resolution and sensitivity. A representative chromatogram is shown in Figure 4 highlighting the efficiency of the method for identifying volatile organic impruties in complex matrices.

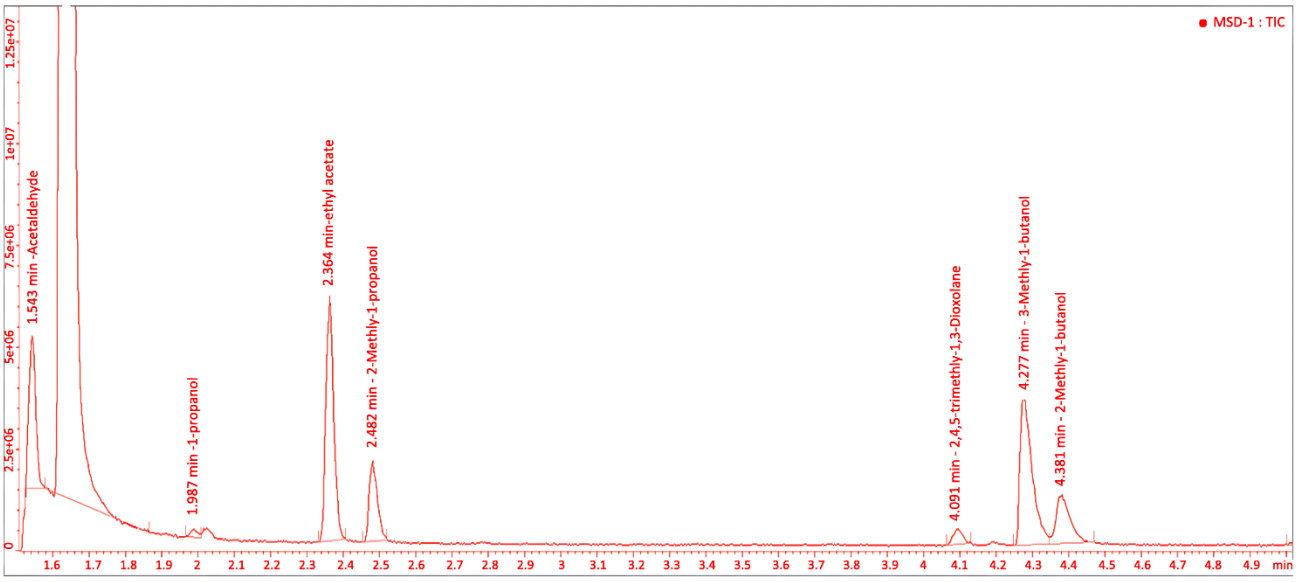


Figure 4.
Chromatogram of the model solution using microencapsulated yeast strain.

It has been experimentally confirmed that the peak areas on mass chromatograms allow not only reliable differential identification, but also determination of the mass concentration for each component. The optimized parameters of the gas chromatograph (Figure 4) and mass-selective detector described in this article were crucial for identifying volatile organic impurities, associated with microencapsulated systems for winemaking. These parameters allowed for precise monitoring of the chemical interactions and release profiles of the biologically active agents microencasulated in the delivery systems. The retention times and peak areas obtaines in the chromatograms provided critical insights into the composition of volatile organic compounds, which are key indicators of the microencapsulation efficiency and stability of yeast-matrix systems. For example, the chromatographic data confirmed the presence of ethanol and other fermentation products produced by the yeast strains encapsulated in sodium alginate matrices. The ability to identify and quantify these componds not only validates the microencapsulation process but also supports the optimization of conditions such as pH, temperature, and matrix composition, which directly influence the release and physiological activity of the microencapsulated yeast cells.

Table 7.
Comparative evaluation of microencasulation systems and their impact on sparkling wine production.

Parameter	Alginate microcapsules	Chitosan microcapsules	Free yeast cells
Microencapsulation efficiency (%)	97.21 ± 1.65	95.28 ± 2.31	N/A
Structural stability	Very high	High	Low
Size distribution (μm)	0.3-6	0.4-6.2	N/A
*Viability after 30 days of storage (%)	90 ±2	85 ± 3	60 ± 5
Fermentation rate (Ethanol production)	1.5x Faster	1.3x Faster	Base line
Residual Sugar after fermentation	< 1.5	2.2 ± 0.3	3.5 ± 0.5
Cost efficiency (Relative to alginate)	Baseline (Most cost-effective)	1.4x Higher	N/A
Sensory analysis	9.2 ± 0.3	8.5 ± 0.4	7.4 ± 0.6

The findings of this study underscore the efficiency and economic viability of sodium alginate-based microencapsulation systems for application in sparkling winemaking. Among the evaluated materials, sodium alginate demonstrated superior encapsulation efficiency (97 ± 1.65%) and structural stability couled with remarkable cost-effectiveness in Table 7.

Experiments conducted at M.Auezov South-Kazakhstan University confirmed that sodium alginate is not only functionally effective but also economically advantageous compared to alternative systems such as chitosan and alginate-chitosan composites. A comprehensive cost-benefit analysis revealed that sodium alginate offers a substantial reduction in production cpsts while maintaining high-perfomance characteristics including robust encapsulation integrity under winemaking conditions.

Additionally the widespread availability and affordability of sodium alginate enhance its suitablity for large-scale applications in the wine industry. These results emphasize the materials potential to bridge the gap between advanced microencapsulation technologies and practical, cost-sencitive industrial processes.

The experimental data obtaines at the university provide a robust foundation for further development and scaling of sodium alginate-based microencapsulation systems. These systems represent a sustainable and economically attractive solution for improving the efficiency and fumctionality of bilogically active agents in sparkling wine production.

Moreover the ecomic evaluation confirmes that sodium alginate is the most cost-effective option with a production cost approximately 30% lower than chitosan-based systmes. This cost efficiency is attributed to the materials widespread avalability, low processing requirements, and minimal waste generation during encapsulation.

In addition to cost and perfomance advantages, the scalability of sodium alginate-based systems was demostrated through pilot-scale trials. These trials, conducted under the university's controlled conditions showcased ability to sustain its functional properties during prologed storage and fermentation cycles. Notably the alginate microcapsules remained strucurally stable, even under the high-pressure conditions characteristic of sparling wine production.

To further enhance the practical application of these systems we investigated the effects of varuing alginate concentrations and crosslinking agents on microcasule morphology and mechanical strength. It was observes that an alginate concentration of 2% (w/v) provided the optimal combination of microencasulation efficiency and mechanical resilience, making it suitable for inductrial implementation.

The results obtained in this article contribute to the growing body of knowledge on microencapsulation technologies in winemaking. By leveraging the economic and functional benefits of sodium alginate producers can achieve signoficant improvements in process efficency product quality and sustainability.

7. Conclusion

7.1. Implications

Microencapsulation systems of biologically active agents, especially yeast strians, are a huge step forward in the development of technologies for winemaking. The research presented in this work has demonstrated that the application of natural polysaccharide matrices like alginate and chitosan enhances the viability, stability, and perfomance of the yeast cells in the process of the secondary fermentation of sparkling wine. Accordingly, optimization of the microencapsulated conditions of yeast-to-sodium alginate ratio of 1:5 and 1% $CaCl_2$ as a crosslinking agent resulted in very efficient microencasulated at 97.21 ± 1.65% for alginate and 95.28 ± 2.31% for chitosan-coated alginate microcapsules. Sem

analysis confirmed that the microcapsules do not break during the process and thus do not release the cells, with consequent protection without toxicity or mechanical injury.

Furthermore, the GC-MS analysis performed on wine produces with microencapsuleted yeast has evidenced for the first time how this approach allows for improving the reproducibility of quality in the final products, uderlining the potentiality of microencasulation to ameloorate sensory and chemicql features of sparkling wines.

This research underlined the great role of biotechnology in developing suistainable and nontoxic materails that will meet the increasing demand of end-cosumers for ecological and high-quality products. Besides, the opportunity to use national raw materials opens new perspectives for the development of the wine industry of Kazakhstan, taking into consideration its further competitiveness in foreign markets.

7.2. Future Research Directions

The results of the present work create a premise for further articles in winemakeng, showing that microencapsulation is able not only to overcome difficulties with secondary fermentation but also to open wide perspectives for efficient and high-quality production of sparkling wines. This research contributes to relevant knowledge in the fiels of bitechnological improvements in winemaking and makes a practical proposal for the modernization of traditianal processes and the addressing of industrial requirements.

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