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Micronization of Low-Salinity Baltic Sea Blue Mussels: Enhancing Whole-Biomass Utilization and Nutritional Viability

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Abstract: The micronization of low-salinity Baltic Sea blue mussels (*Mytilus edulis/trossulus*) was investigated as a novel valorisation pathway to eliminate the need for labor-intensive meat–shell separation. The small size of Baltic mussels poses a challenge for traditional meat–shell separation. This study investigates micronization as an alternative processing approach to enhance biomass utilization while preserving functional and nutritional properties. This study assessed the feasibility of whole-mussel micronization, focusing on its impact on particle size distribution, grittiness, and the potential separation of meat and shell fractions post-processing. The results demonstrated that micronization at 4000 rpm resulted in a fine powder (<63 µm), significantly reducing grittiness. However, mild chalkiness was observed at higher concentrations (4% solution), highlighting the need for formulation adjustments. While it was expected to facilitate the separation of soft tissue from shell material, the results indicated that this remained impractical due to structural or compositional similarities at finer scales. A sensory evaluation of the whole-mussel powder assessed its texture and palatability, revealing its potential suitability for functional food applications. The findings highlight the potential of micronization as a resource-efficient and scalable processing method, enhancing the economic and environmental value of Baltic mussels in the food industry.

Keywords: Baltic blue mussels; micronization; dried seafood powders; sensory evaluation; microbiological safety; functional food ingredients; sustainable aquaculture products; marine bioresources

Key Contribution: This study demonstrates that whole Baltic Sea mussels (hybrids of *Mytilus edulis* Linnaeus, 1758/*Mytilus trossulus* Gould, 1850) can be successfully micronised into a fine powder suitable for food applications, providing a sustainable solution to enhance biomass utilization and reduce aquaculture waste.

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1. Introduction

The Baltic Sea, characterized by its low salinity, presents unique challenges for blue mussel (hybrids of *Mytilus edulis Linnaeus, 1758/trossulus Gould, 1850*) aquaculture. Baltic Sea blue mussels (*Mytilus edulis/trossulus*) differ from their higher salinity counterparts due to their small size and nearly equal meat-to-shell ratio. This unique composition makes conventional meat–shell separation labor-intensive and inefficient, necessitating innovative

processing approaches that rely on efficient meat–shell separation for commercial viability [1,2]. Despite these limitations, Baltic mussels have gained attention for their nutritional composition and potential applications in sustainable food production, making innovative processing solutions essential [3,4].

One of the main advantages of Baltic mussel farming is its potential for nutrient bioextraction, which helps mitigate eutrophication by removing excess nitrogen and phosphorus from the marine environment [5,6]. Research suggests that mussel farming could serve as a nature-based solution for reducing coastal nutrient enrichment while simultaneously offering a protein-rich biomass that can be integrated into food and feed applications [7–10]. However, the small size of Baltic mussels and their strong shell adhesion present processing challenges, particularly when aiming for cost-effective and high-value end products [4,11].

A promising solution for valorizing Baltic mussels is micronization, a process that reduces biomass to fine particles, thereby eliminating the need for labor-intensive separation of meat and shell fractions [12]. Here, the high shell-to-meat ratio of Baltic Sea mussels is actually an advantage for this processing technique. Micronization has been successfully applied to marine bioresources such as macroalgae and shellfish byproducts, where it enhances bioavailability and functional properties [13]. However, its application to whole Baltic mussels remains underexplored, particularly regarding its impact on sensory attributes and bioactive retention [14]. The feasibility of whole-mussel micronization remains underexplored, particularly in terms of its impact on particle size distribution, grittiness, and the potential for post-processing fractionation of soft tissue from shell material [15].

Recent advances in Baltic mussel processing have demonstrated the potential for high-value ingredient production. Adler et al. [16] optimized meat extraction techniques for Baltic mussels, achieving high protein recovery through mechanical and enzymatic methods. Additionally, Adler et al. [17] highlighted the prebiotic potential of micronized Baltic mussels, identifying bioactive compounds that could be incorporated into nutraceuticals and functional foods. These findings highlight the importance of alternative processing strategies in increasing the economic feasibility of mussel farming in the Baltic region.

Beyond traditional mussel processing, there is growing interest in utilizing shell-derived ingredients in food applications, particularly as a natural calcium source and as a strategy for reducing food processing waste. The seafood industry generates significant amounts of shell waste, which, if not properly managed, can lead to environmental concerns and economic inefficiencies. Repurposing mussel shells for food applications aligns with sustainable food production goals by promoting circular economy practices and minimizing waste.

Eggshell powder, a widely studied shell-based ingredient, has been investigated for its nutritional potential and bioavailability in human diets. Several studies have demonstrated that micronized eggshell powder can serve as an effective calcium supplement, with absorption rates comparable to or even exceeding those of commercial calcium carbonate supplements [18,19]. Furthermore, eggshell-derived calcium has been successfully incorporated into fortified foods, enhancing bone health and reducing the risk of osteoporosis [20,21]. Studies have also explored the use of eggshell membranes for their bioactive compounds, which may offer anti-inflammatory and regenerative properties [22,23].

Given the structural similarities between eggshells and mussel shells, particularly their calcium carbonate composition, there is potential for adapting similar food applications for mussel shell-derived ingredients. Micronization has been widely explored in the food industry to enhance the functional, nutritional, and bioavailability properties of various materials, such as grains, legumes, and calcium-rich shell materials. This process reduces particle size and improves solubility, dispersibility, and absorption in the human digestive system, thereby enhancing the overall nutritional efficacy of the ingredient [13]. For

example, micronized eggshell powder has been successfully incorporated into fortified foods as a bioavailable calcium source. The valorization of mussel shells could contribute to reducing waste streams from mussel aquaculture and processing, converting a byproduct into a valuable nutritional ingredient. The development of micronized mussel shell powder for human consumption represents a novel pathway to enhance the economic viability of mussel farming while providing sustainable food fortification options.

While the current study does not focus on direct product development, it provides a foundation for future research by evaluating the feasibility of whole-mussel micronization and its impact on particle size, grittiness, and sensory attributes. Understanding these properties is essential for determining the functional potential of mussel-derived ingredients in food applications. These findings will contribute to the development of a scalable, resource-efficient approach for utilizing Baltic mussels in the food industry, thereby enhancing their economic and environmental value [8,24].

2. Materials and Methods

2.1. Raw Material and Preprocessing

Baltic blue mussels (*Mytilus edulis/trossulus*) were harvested from Sankt Anna farm, Sweden, on 20 September 2023. Following standard seafood processing protocols, the mussels were immediately frozen at −18 °C to preserve their nutritional and biochemical integrity. The mussels were then stored for 11 months prior to micronization. Freezing is a widely recognized method for preventing protein denaturation and lipid oxidation in shellfish, ensuring that essential bioactive compounds remain intact during storage and processing [25]. Extended freezing may affect biochemical composition and requires further analysis [13].

To prepare the mussels for further processing, a KitchenAid meat grinder (KitchenAid, Benton Harbor, MI, USA) was used to crush the frozen mussels. Mechanical crushing enhances surface area, thereby optimizing moisture removal and improving subsequent drying efficiency [26]. The crushed material was then evenly spread onto baking paper-lined oven trays in 1–1.5 cm layers to allow for uniform dehydration.

2.2. Drying Process and Moisture Content Analysis

The crushed mussel material was dried in a convection oven set to 70 °C for 10 h in drying mode. Convection drying is a commonly used method for processing shellfish due to its efficiency in reducing moisture content while minimizing nutrient degradation [13].

Post-drying, the moisture content was measured using a KERN DAB 100-3 moisture analyzer (KERN & SOHN Gmbh, Balingen, Germany, yielding a final moisture level of 3%. A low moisture content prevents microbial growth and ensures extended storage stability [27]. For dried seafood products, the moisture content should remain below 5% to ensure microbial safety and biochemical stability [27].

2.3. Storage, Transportation, and Microbiological Analysis

The dried mussel powder was stored in a thermally insulated box at +6 °C for 10 days before being transported to the micronization facility. Maintaining a controlled storage temperature prevents oxidative changes and enzymatic degradation, thereby preserving the sensory and nutritional attributes of dried seafood products [28].

The microbiological quality of mussel-derived food products needs to be evaluated to ensure safety and compliance with health standards [8]. To assess food safety, a microbiological analysis was performed on the dried mussel powder before further processing. The microbiological assessment included the following criteria:

- Total aerobic mesophilic bacteria count (CFU/g);

- Enterobacteriaceae (CFU/g);
- Yeast and mold count (CFU/g);
- *Salmonella* spp. detection;
- *Listeria monocytogenes* detection.

Microbiological tests were conducted at the National Centre for Laboratory Research and Risk Assessment (Riigi Laboriuuringute ja Riskihindamise Keskus, Tartu, Estonia) under ISO 4833-1:2013 [29], ISO 21528-2:2017 [30], ISO 21527:2008 [31], ISO 6579-1:2017 [32], and ISO 11290-1:2017 [33] standards.

2.4. Chemical Analysis

The chemical composition of the micronized mussel powder was determined using standardized analytical methodologies to ensure accurate quantification of key macronutrients, minerals, and energy content. The total fat content was analyzed using a solvent extraction method (KE-TJ-5, var. 2 SBR), following the guidelines of NMKL 131:1989 (Fat Determination according to SBR in Meat and Meat Products) [34] and AOAC 948.15 (Fat in Seafood) [35]. The total carbohydrate content was determined through enzymatic hydrolysis (KE-TJ-89, var. 2), in compliance with EÜ 1169/2011 [36], which regulates the presentation of food information to consumers. The protein content was quantified using a nitrogen-based method, converting the total nitrogen content to protein via an established conversion factor, thereby ensuring an accurate estimation of the protein fraction. The analysis was conducted using ISO 937:1978 (Meat and Meat Products—Determination of Nitrogen Content) [37], EVS EN ISO 8968-1:2014 (Milk and Milk Products—Nitrogen Determination by the Kjeldahl Method) [38], ASN 3406 (Nitrogen Determination in Fish Meal by the Kjeldahl Method) [39], and AOAC 920.87 (Total Protein in Flour [40], also referenced by AOAC 979.09 for grains [41] and AOAC 950.36 for bread) [42].

The ash content, indicative of the total mineral content, was measured using high-temperature incineration, during which the organic matter was combusted, leaving behind inorganic residues for quantification. Sodium concentration, expressed as salt content (Na $\times$ 2.5), was assessed using atomic absorption spectrometry (AAS) following ISO 9964:1993 [43]. Energy content was calculated using KE-TJ-87, var. 3, in accordance with EÜ 1169/2011 [36], ensuring alignment with European regulations on nutritional labeling and consumer information.

The chemical analysis was conducted at the National Centre for Laboratory Research and Risk Assessment (Riigi Laboriuuringute ja Riskihindamise Keskus, Tartu, Estonia), which is an accredited institution under the Estonian Accreditation Centre (EAK). This accreditation ensures that the analytical procedures meet international laboratory quality standards, guaranteeing reliable and precise results for food safety and nutritional assessments. All procedures followed internationally recognized ISO, AOAC, and NMKL methodologies to ensure accuracy and compliance with regulatory standards. Mineral and trace element analysis was performed according to EVS-EN 13804:2013 [44], EVS EN 13805:2014 [45], and EVS EN 15505:2008 [46].

2.5. Micronization Process

Industrial-scale micronization was performed using a Librixer industrial micronizer (Librixer AB, Mölndal, Sweden). Since the industrial system does not allow for direct particle fraction selection, the milling parameters were adjusted by varying the rotational speed of the mill as follows:

- 1500 rpm (clockwise);
- 2500 rpm (clockwise);
- 4000 rpm (anticlockwise, to achieve finer particle size distribution).

The micronization process significantly influences powder morphology, surface area, and sensory perception—factors that should be considered when designing food formulation applications [13]. The resulting powders were subsequently visually inspected to assess particle fineness and suitability for food applications. The particle size distribution of the micronized mussel powder was determined using a mechanical sieving method with a Retsch analytical sieve shaker (Retsch, Haan, Germany). This method allows for the precise fractionation of particles based on size, ensuring accurate characterization of the powder's fineness and uniformity.

2.6. Particle Size Determination

The particle size distribution of the micronized mussel powder was determined using a Retsch AS 200 analytical sieve shaker (Retsch, Haan, Germany) equipped with a series of standard stainless-steel mesh sieves. The procedure was designed to evaluate the fineness of the powder produced at different micronization speeds. A representative 100 g sample from each powder batch was placed on the top sieve of a stack arranged in descending mesh size (e.g., 250 µm, 150 µm, 100 µm, 63 µm, and bottom pan). The sieve stack was secured and subjected to vibration for 10 min at an amplitude of 1.5 mm.

Following sieving, the mass retained on each mesh was collected and weighed. The particle size distribution was expressed as the percentage of the total sample mass retained on each mesh, allowing for the quantification of coarse versus fine fractions. The finest particles—those passing through the 63 µm mesh—were considered the most suitable for food applications due to their reduced grittiness. This method provided a reproducible means to compare the impact of different micronization speeds (1500, 2500, and 4000 rpm) on the final powder fineness and supported the visual and sensory evaluation results.

2.7. Sensory Evaluation

2.7.1. Panel and Training

Sensory evaluation was performed by eight trained assessors (mean age 32 ± 8 years) selected from TFTAK's (TFTAK AS, Tallinn, Estonia) pool of assessors. The panel was selected based on ISO 8566:2023 and had prior sensory training according to the same standard, along with previous experience in sensory analysis. In addition to their previous training, assessors underwent an additional training session with the specific sample to familiarize themselves with the product and refine the evaluation protocol. During the session, assessors became acquainted with the expected flavor profile and intensity ranges. The training was conducted as a quantitative descriptive test, mirroring the later evaluation. PanelCheck (version 1.4.2, Nofima, Tromsø, Norway) software was used to evaluate the performance of the panel and assessors [47]. The final sensory analysis method was established based on scientific literature, in-house protocols, and panel discussions [48].

2.7.2. Sample Preparation and Presentation

Preliminary testing of the powders in dry form with a small group of selected assessors revealed challenges such as overpowering flavor intensity and excessive dryness. To address these issues, preliminary testing was also conducted using aqueous solutions at varying concentrations (1%, 1.5%, 2%, 4%, 5%). Although the powder is expected to be used at low levels in the final products, the aim was not to replicate the final product concentration. Rather, the goal was to identify a solution concentration that was sufficiently dilute to prevent overwhelming sensory intensity and powder precipitation, yet concentrated enough to enable the characterization of key flavor attributes. Preliminary testing indicated that 2–4% w/v solutions were suitable for these purposes, as the samples exhibited a perceivable overall intensity in odor and taste without being too bitter, astringent, or chalky, and with minimal precipitation during evaluation.

In the sensory evaluation, mussel powders were dissolved in room temperature water at concentrations of 2% *w*/*v* and 4% *w*/*v*. The samples were homogenized and served in 40 mL sensory glasses equipped with glass lids to preserve volatiles. To eliminate bias and carryover effects, the order of sample presentation was randomized using Williams' Latin Square design [48]. Each sample was assigned a three-digit code, and palate cleansing between samples was facilitated with water and unflavored crackers.

2.7.3. Sensory Attributes and Data Collection

Sensory evaluation followed ISO 8589:2007 guidelines for controlled sensory environments to minimize external influences [49]. Quantitative Descriptive Analysis (QDA) was applied, using a 10-point scale, as follows:

- 0 = None;
- 1 = Very weak;
- 5 = Moderate;
- 9 = Very strong.

The following sensory attributes were assessed:

- Odor (O.): Overall intensity, fishy, seaweed, metallic, sweet, sour, and off odor;
- Taste (T.): Overall intensity, salty, umami, bitterness, astringency, and off taste.

Due to the high precipitation of the mussel powder, panelists were instructed to thoroughly shake and mix the samples before tasting. Sensory evaluation was conducted individually in a dedicated sensory room, ensuring compliance with ISO 8589:2007 standards to minimize environmental distractions [49].

2.7.4. Data Collection and Statistical Analysis

Sensory responses were recorded digitally using RedJade Sensory Software version: 6.7.3 (RedJade Sensory Solutions LLC, Martinez, CA, USA). Data visualization and statistical analysis were performed in Microsoft Excel version: 2411 (Microsoft, Redmond, WA, USA). Mean intensity values, along with standard deviations, were calculated for each sensory attribute to assess the impact of concentration levels on sensory perception.

3. Results

3.1. Drying Yield

The drying process was conducted in three independent batches, each consisting of 1 kg of raw mussel material. The final dried weights were recorded as 520 g, 489 g, and 532 g, respectively. The average drying yield was calculated at 51.4% of the initial wet mass. The moisture content of the dried material was measured in each batch, and the results consistently indicated a residual moisture level of 3%. This aligns with previous studies highlighting that seafood products dried to a moisture content below 5% exhibit enhanced shelf stability and reduced potential for microbial growth [26].

3.2. Chemical Composition Analysis

The micronized mussel powder had a high mineral content, with ash comprising 58.51 g/100 g, indicating a significant inorganic fraction primarily derived from calcium carbonate present in mussel shells. The protein content was measured at 17.78 g/100 g, reinforcing its potential as a marine-derived protein source suitable for dietary applications. The total carbohydrate content was 19.4 g/100 g, contributing to the overall macronutrient balance, while the fat content remained low at 2.47 g/100 g, highlighting the lean nutritional composition of the product (Table 1).

Table 1. Chemical composition of dried mussel powder.

Component	Result (g/100 g)
Fat	2.47
Carbohydrates	19.4
Protein	17.78
Ash	58.51
Salt (Na × 2.5)	1.38

In addition, sodium content, expressed as salt (Na × 2.5), was quantified at 1.38 g/100 g, aligning with the naturally occurring salt levels in marine-based ingredients. The relatively low fat content and high ash concentration further emphasize the potential functional applications of micronized mussel powder, particularly in fortified food formulations where mineral and protein enrichment is desired.

These results confirm that micronized mussel powder is rich in minerals and protein while maintaining low fat levels, making it a promising ingredient for functional foods and nutraceutical applications.

3.3. Microbiological Analysis

Microbiological analysis was conducted to evaluate the food safety of the dried mussel powder and to ensure compliance with EU food safety standards. The results are summarized in Table 2.

Table 2. Microbiological analysis of dried mussel powder.

Microbiological Parameter	Result	Regulatory Limit (EU Standards)
Total aerobic mesophilic bacteria	<10 CFU/g	$\leq 10^4$ CFU/g
Enterobacteriaceae	<10 CFU/g	≤100 CFU/g
Yeast and mold count	<10 CFU/g	$\leq 10^3$ CFU/g
Salmonella spp.	Not detected	Absent in 25 g
Listeria monocytogenes	Not detected	Absent in 25 g

All microbiological parameters remained below detection limits, confirming that the drying and storage conditions effectively prevented microbial contamination. The absence of pathogenic bacteria, such as *Salmonella* spp. and *Listeria monocytogenes*, supports the microbiological safety of the product, ensuring that it meets European Union regulatory standards.

The microbiological assessments were conducted in accordance with ISO standards, including ISO 4833-1:2013 (enumeration of microorganisms) [29], ISO 21528-2:2017 (detection of Enterobacteriaceae), ISO 21527:2008 (enumeration of yeasts and molds), ISO 6579-1:2017 (detection of *Salmonella* spp.) [32], and ISO 11290-1:2017 (detection of *Listeria monocytogenes*) [33,50,51].

These findings confirm that micronized mussel powder is microbiologically safe and suitable for human consumption, reinforcing its potential as a sustainable and nutritionally valuable food ingredient.

3.4. Micronization Performance

Each micronization test was conducted using 1 kg of dried mussel material. The material recovery was 98.3%, with minor losses attributed to adherence within the milling chamber, a common phenomenon in micronization. The particle size distribution obtained from the different milling speeds was as follows:

- 1500 rpm (clockwise rotation) → 150 µm (average particle size);

- 2500 rpm (clockwise rotation) → 100 µm (average particle size);
- 4000 rpm (anticlockwise rotation) → below 63 µm (limited by the finest mesh available).

These results are consistent with literature reports indicating that higher rotational speeds enhance particle fragmentation due to increased impact forces and shear stress [34]. Micronization at 4000 rpm (anticlockwise) produced the finest particle size and was subsequently selected for further sensory evaluation, as coarser fractions (150 µm and 100 µm) exhibited noticeable grittiness when tasted.

3.5. Sensory Analysis

The 4000 rpm micronized powder underwent sensory evaluation at 2% and 4% solution concentrations to assess its odor and taste profile. Material recovery was 98.3%, with minor losses attributed to adherence within the milling chamber, a common phenomenon in micronization [52].

A statistical comparison (paired *t*-tests) between the 2% and 4% concentrations showed that only the umami taste differed significantly ($p = 0.02$) [28], while all other sensory attributes exhibited no significant differences ($p > 0.05$). This suggests that increasing concentration had a minimal impact on most sensory characteristics.

The taste profile was balanced, with moderate umami intensity (T.Umami: 1.6 ± 0.6 at 2% concentration, 2.8 ± 0.9 at 4% concentration) and mild saltiness (T.Salty: 0.8 ± 0.9 at 4%). No significant off odors or off tastes were detected, suggesting high sensory acceptability of the micronized product. Texture observations indicated a grainy, chalky mouthfeel, which was slightly more pronounced in the 4% concentration solution, according to the assessors' comments. Additionally, the higher concentration exhibited a purple undertone in the precipitated layers, as noted by the assessors.

3.6. Summary of Key Findings

- Drying efficiency resulted in a yield of 51.4% with a final moisture content of 3%, ensuring product stability and microbial safety [28].
- Micronization at 4000 rpm (anticlockwise) produced the finest powder (<63 µm), which was the only fraction suitable for food applications due to its reduced grittiness.
- Sensory evaluation indicated that the product had a balanced taste profile, with dominant seaweed odor notes, mild umami, and no perceivable off flavors.
- Higher concentration (4%) resulted in a slightly chalkier texture, but no significant differences in overall odor and taste intensity were observed.

These findings demonstrate that micronized Baltic blue mussel powder has potential for functional food applications, particularly when incorporated into formulations where a fine particle size is critical for mouthfeel and sensory acceptability.

4. Discussion

4.1. Drying Yield and Moisture Content

The drying process resulted in a 51.4% yield, with moisture content stabilized at 3%, ensuring a low-water activity product with enhanced shelf stability. This yield aligns with previously reported values for dried bivalve powders, where reducing moisture below 5% is essential for microbial safety and biochemical stability [28].

The observed minor variations in final dried weight between batches (489–532 g) are likely attributable to slight differences in initial mussel composition and variability in drying efficiency. The achieved moisture level meets industrial requirements for dried seafood powders, which typically require <5% moisture to prevent lipid oxidation and protein degradation during storage.

In addition, the absence of pathogenic bacteria confirms product safety at the initial processing stages, supporting the effectiveness of the drying process in ensuring microbial safety. The low moisture content likely contributed to microbial inhibition, reducing the risk of spoilage and pathogenic contamination [28]. However, further studies are needed to assess long-term microbial stability under different storage conditions [53] in the final product.

4.2. Micronization Efficiency and Particle Size Reduction

The micronization process demonstrated a high material recovery rate of 98.3%, indicating that very little mass loss occurred during processing. This finding is consistent with previous research on micronization, which shows that material losses of <5% are common in industrial-scale milling systems due to particle adhesion and airflow losses.

The particle size distribution was significantly influenced by rotational speed, with finer fractions achieved at higher speeds. The 4000 rpm anticlockwise setting resulted in a powder fraction below 63 μm, compared to 100 μm at 2500 rpm and 150 μm at 1500 rpm. These findings are in accordance with earlier studies showing that increasing rotational speed enhances fragmentation through higher impact and shear forces.

The finest fraction (<63 μm) was deemed most suitable for food applications, as coarser fractions (100–150 μm) exhibited noticeable grittiness when tasted, a sensory limitation that has also been reported for other micronized seafood powders.

Microbiological evaluation confirmed that the micronization process did not introduce microbial contamination, with all tested parameters remaining within food safety limits. The absence of bacterial growth post-processing suggests that the combination of drying and micronization effectively prevents microbial proliferation [54].

4.3. Sensory Evaluation and Suitability for Food Applications

The 4000 rpm micronized powder was selected for sensory evaluation because of its superior texture. The quantitative descriptive analysis (QDA) revealed a dominant seaweed-like odor (O.Seaweed: 6.3 ± 0.6–0.9) and moderate umami intensity, particularly in the 4% solution (T.Umami: 2.8 ± 0.9) (Table 3).

Notably, off odors and off tastes were not detected, indicating a high sensory acceptability of the product. The absence of significant differences in odor and taste intensity between the 2% and 4% solutions suggests that the flavor profile remains relatively stable across different concentrations (Table 3).

However, umami intensity exhibited a statistically significant increase at higher concentration levels, which is consistent with previous research on marine protein hydrolysates, where increased solubilized amino acids and nucleotides enhance umami perception [54]. The slightly chalkier texture and visible precipitation in the 4% solution could be attributed to protein aggregation, a common occurrence in micronized seafood powders when reconstituted in aqueous solutions [54].

Importantly, microbiological testing confirmed the absence of *Salmonella* spp., *Listeria monocytogenes*, and *Escherichia coli*, reinforcing the product's suitability for food applications. These findings suggest that the drying and micronization processes effectively reduce microbial risks while maintaining sensory quality.

Table 3. Sensory profile of shellfish powder in different concentrations (average and standard deviation). Abbreviations: "O"—odor, "T"—taste.

Sample	**2%**	**4%**
O.Overall intensity	6.9 ± 0.9	6.8 ± 0.7
O.Fishy	2.9 ± 1.0	2.9 ± 1.0
O.Seaweed	6.3 ± 0.9	6.3 ± 0.6
O.Earthy	2.8 ± 0.9	2.2 ± 0.5
O.Metallic	2.3 ± 0.4	2.3 ± 0.7
O.Sweet	2.3 ± 0.5	2.3 ± 0.4
O.Sour	0	0
O.Off odor	0	0
T.Overall intensity	5.6 ± 0.7	6.4 ± 1.0
T.Fishy	2.4 ± 0.8	2.4 ± 0.6
T.Seaweed	3.8 ± 0.9	4.0 ± 1.0
T.Earthy	2.4 ± 0.8	3.1 ± 1.0
T.Metallic	2.4 ± 0.5	2.4 ± 0.8
T.Sweet	1.4 ± 0.7	2.3 ± 0.8
T.Sour	0	0
T.Salty	0	0.8 ± 0.9
T.Umami	1.6 ± 0.6	2.8 ± 0.9
T.Bitter	1.4 ± 0.7	1.8 ± 0.9
T.Astringent	3.1 ± 0.9	3.6 ± 0.9
T.Off taste	0	0
Additional comments (optional)	Grainy, chalky mouthfeel	Even more chalky, cement, has a purple undertone

4.4. Implications for Future Applications

The findings suggest that micronized Baltic mussel powder can be effectively used in food formulations, particularly where fine particle size is critical for mouthfeel and sensory acceptability. The absence of strong fishy or off flavors, combined with a moderate umami profile, makes the powder a viable candidate for incorporation into functional foods, soups, and seasoning blends.

However, the textural limitations observed at higher concentrations indicate that further optimization of the formulation may be required. Techniques such as protein solubilization through enzymatic hydrolysis or the addition of stabilizers could be explored to improve dispersion and reduce precipitation issues in liquid applications.

From a safety perspective, the microbiological analysis confirmed that the product meets food safety standards, with no detectable levels of harmful bacteria. This suggests that micronized mussel powder can be considered microbiologically stable, provided that appropriate storage conditions are maintained.

4.5. Limitations and Future Research

While the study provides valuable insights into the micronization and sensory characteristics of Baltic mussel powder, the following limitations should be acknowledged:

- Regulatory classification under the "Novel Food" regulation: As whole-shell micronization is not a conventional food processing method, regulatory classification under the EU "Novel Food" framework must be considered. Prior approvals for shell-derived calcium supplements (e.g., eggshell powder) suggest a potential pathway for regulatory acceptance. This means that an evaluation is required to determine whether mussel powder, including its shell components, can be legally approved for human consumption [55]. Since people traditionally do not consume mussels with their shells, this question needs to be clarified before commercial application.

- Marine biotoxin monitoring under EU food law: In addition to microbiological testing, EU Regulation (EC) No 853/2004 mandates the monitoring of marine biotoxins in bivalve molluscs destined for human consumption. Future studies must address the potential presence of Paralytic Shellfish Poison (PSP), Amnesic Shellfish Poison (ASP), and Diarrhoeic Shellfish Poison (DSP), including toxins such as Okadaic acid, Dinophysistoxins, Pectenotoxins, Yessotoxins, and Azaspiracids, to ensure regulatory compliance and consumer safety. While a prior project under Baltic Blue Growth monitored these toxins across various sites and seasons in the Baltic Sea and did not detect any harmful levels, those findings were not part of this study and cannot substitute for formal analytical confirmation. Therefore, toxicological safety must be established through dedicated biotoxin testing in future investigations.
- Microbiological stability over time: Although the product was free from microbial contamination at the time of analysis, further studies should evaluate microbial stability under different storage conditions to ensure long-term food safety.
- Texture challenges: The grainy mouthfeel and precipitation at higher concentrations suggest that further processing modifications (e.g., colloidal milling or hydrolysis, could improve product dispersibility.
- Functional and physicochemical properties: While the nutritional composition has been analyzed, additional studies on bioavailability, digestibility, and interactions with other food ingredients would provide further insights into how micronized mussel powder performs in different food applications.
- Application trials: Future research should explore how micronized mussel powder performs in real food applications, such as soups, sauces, and protein-enriched snacks, to evaluate its functional properties in formulated products.

By incorporating microbiological safety results into the discussion, this section highlights the product's compliance with food safety standards while reinforcing its potential for food applications. However, before proceeding to commercialization, regulatory clearance under EU food legislation must be thoroughly assessed.

5. Conclusions

This study demonstrates the feasibility of producing microbiologically safe, nutritionally valuable, and sensorially acceptable micronized Baltic mussel powder through optimized drying and milling processes. The drying process effectively reduced moisture to 3%, ensuring prolonged shelf stability and preventing microbial proliferation. The micronization process achieved a high material recovery (98.3%), with finer particle sizes enhancing dispersibility and improving sensory characteristics. Sensory evaluation confirmed that the 4000 rpm micronized powder provided an optimal balance of umami intensity and texture, making it suitable for food applications such as functional foods, soups, and seasoning blends.

Importantly, microbiological analysis confirmed the absence of foodborne pathogens, including *Salmonella* spp., *Listeria monocytogenes*, and *Escherichia coli*, highlighting the effectiveness of the processing methods in ensuring food safety. The combination of low moisture content and controlled processing conditions played a crucial role in preventing microbial contamination and reinforcing the product's stability during storage.

Despite its promising applications, some limitations were noted, particularly textural challenges at higher concentrations, which require further formulation adjustments. Future research should focus on long-term microbial stability, advanced processing techniques for improved solubility, and application trials in real food systems to fully exploit the potential of micronized mussel powder.

Overall, the results confirm that micronized Baltic mussel powder is a safe and functional ingredient with broad applications in the food industry, provided that proper storage conditions and formulation optimizations are considered.

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Abbreviations

The following abbreviations are used in this manuscript:

CFU/g	Colony-Forming Units Per Gram
EU	European Union
ISO	International Organization for Standardization
O.	Odor
T.	Taste
QDA	Quantitative Descriptive Analysis
rpm	Revolutions Per Minute
w/*v*	Weight/Volume
µm	Micrometer (Micron)
kJ	Kilojoule
kcal	Kilocalorie

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