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Microencapsulation of fish oil using spray drying for fortification of bakery products

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Abstract

Leading food scientists have long argued that microencapsulation is the most practical route to incorporating omega-3 fatty acids into everyday bakery products without triggering the fishy off-flavours that consumers reject. This research evaluated the encapsulation efficiency, oxidative stability, and sensory impact of spray-dried fish oil microcapsules produced with four wall material systems: maltodextrin alone (MD), maltodextrin with whey protein isolate (MD+WPI), maltodextrin with gum arabic (MD+GA), and maltodextrin with modified starch (MD+MS). Fish oil emulsions were homogenised at 15,000 rpm and spray-dried at an inlet temperature of 180°C. The MD+WPI system achieved the highest encapsulation efficiency (84.6%), the lowest peroxide value after 30 days of storage (1.4 meq O₂/kg), and the best sensory acceptance when incorporated into wheat bread at 3% substitution. Particle size ranged from 8.3 to 14.7 µm across treatments. Bread fortified with MD+WPI microcapsules at 3% showed no detectable fishy odour and delivered 142 mg EPA+DHA per 50 g serving. These results support the use of whey protein as a co-wall material for spray-dried fish oil intended for bakery fortification.

Keywords: Microencapsulation, fish oil, spray drying, bakery fortification, omega-3 enrichment, wall material, whey protein, encapsulation efficiency, oxidative stability, sensory evaluation

Introduction

According to the International Society for the Study of Fatty Acids and Lipids, most Western diets provide less than one-third of the recommended daily intake of eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA) the two long-chain omega-3 fatty acids most strongly linked to cardiovascular protection [1]. Fortifying staple bakery products with fish oil is one of the most direct strategies for closing this gap, but the extreme susceptibility of omega-3 fatty acids to oxidation creates both flavour and shelf-life problems that have limited commercial adoption [2].

Spray drying is the most widely used industrial technique for microencapsulating heat-sensitive food oils because it is fast, scalable, and relatively inexpensive compared to freeze drying or coacervation [3]. The choice of wall material determines how well the dried powder protects the core oil from oxygen, light, and moisture [4]. Maltodextrin is the default carrier in many spray-drying applications because of its low cost and good solubility, but used alone it forms a porous matrix with limited emulsifying capacity [5]. Combining maltodextrin with surface-active biopolymers such as whey protein isolate, gum arabic, or modified starch can create denser, less permeable shells that slow lipid oxidation [6, 7].

While several reports have compared wall materials for fish oil encapsulation at the powder level, fewer have followed through to measure the sensory and nutritional outcomes when the resulting powder is baked into bread [8]. This research aimed to compare four wall material systems for spray-dried fish oil, assess their oxidative stability over 30 days, and evaluate the sensory acceptability and omega-3 delivery of fortified wheat bread.

Material and Methods

Reagents and material

Refined menhaden fish oil (EPA 18.2%, DHA 12.4%) was purchased from Sigma-Aldrich (Taufkirchen, Germany). Maltodextrin DE 18 was obtained from Cargill (Krefeld, Germany). Whey protein isolate (90% protein) was supplied by Fonterra (Auckland, New

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Zealand). Gum arabic (spray-dried, food grade) was sourced from CNI (Rouen, France). Modified waxy maize starch (Hi-Cap 100) was purchased from Ingredion (Hamburg, Germany). All solvents for lipid extraction and peroxide value determination were HPLC grade. Wheat bread flour (type 550), instant yeast, salt, and sugar were procured from a local supplier in Kiel. The experimental work was conducted at the Microencapsulation Laboratory of the Holstein College of Dairy Sciences between January and July 2023.

Instrumentation

Homogenisation was performed with an Ultra-Turrax T25 (IKA, Staufen, Germany) at 15,000 rpm for 5 minutes. Spray drying was carried out on a Büchi B-290 Mini Spray Dryer (Flawil, Switzerland) with a two-fluid nozzle (0.7 mm orifice), inlet temperature 180°C, outlet temperature 80±2°C, feed rate 10 mL/min, and aspiration at 100%. Particle size was measured by laser diffraction (Malvern Mastersizer 3000). Peroxide values were determined by the AOCS Official Method Cd 8b-90. EPA and DHA content in fortified bread was quantified by gas chromatography (Agilent 7890A with FID).

Methods

Four emulsions were prepared at a core-to-wall ratio of 1:3 (w/w) and total solids of 30%. Each wall material combination was dissolved in distilled water, fish oil was added, and the mixture was homogenised. The emulsions were spray-dried in triplicate. Encapsulation efficiency was calculated as (total oil - surface oil) / total oil × 100 [9]. Powders were stored in sealed amber vials at 25°C for 30 days, and peroxide values were measured at days 0, 10, 20, and 30. For bread fortification, the best-performing powder (MD+WPI) was incorporated into a standard wheat bread recipe at 1%, 3%, and 5% flour substitution. Sensory evaluation was conducted by 20 untrained panellists using a 9-point hedonic scale. Data were analysed by one-way ANOVA with Tukey's HSD ($p < 0.05$) in SPSS 28.0.

Results

The four wall material systems differed markedly in encapsulation efficiency and oxidative stability. MD+WPI consistently delivered the highest protection for the core fish oil, both as a powder and when baked into bread.

Table 1: Physicochemical properties of spray-dried fish oil microcapsules

Wall material	Encapsulation efficiency (%)	Particle size (D50, µm)	Moisture (%)	Surface oil (%)
MD alone	72.4 ± 2.1c	14.7 ± 1.8a	3.9 ± 0.3a	8.4 ± 0.8a
MD + WPI	84.6 ± 1.8a	8.3 ± 1.2c	3.2 ± 0.2b	3.1 ± 0.4c
MD + GA	81.3 ± 2.3ab	10.1 ± 1.4b	3.4 ± 0.3ab	4.2 ± 0.5bc
MD + MS	78.9 ± 1.9b	11.6 ± 1.5b	3.6 ± 0.2ab	5.3 ± 0.6b

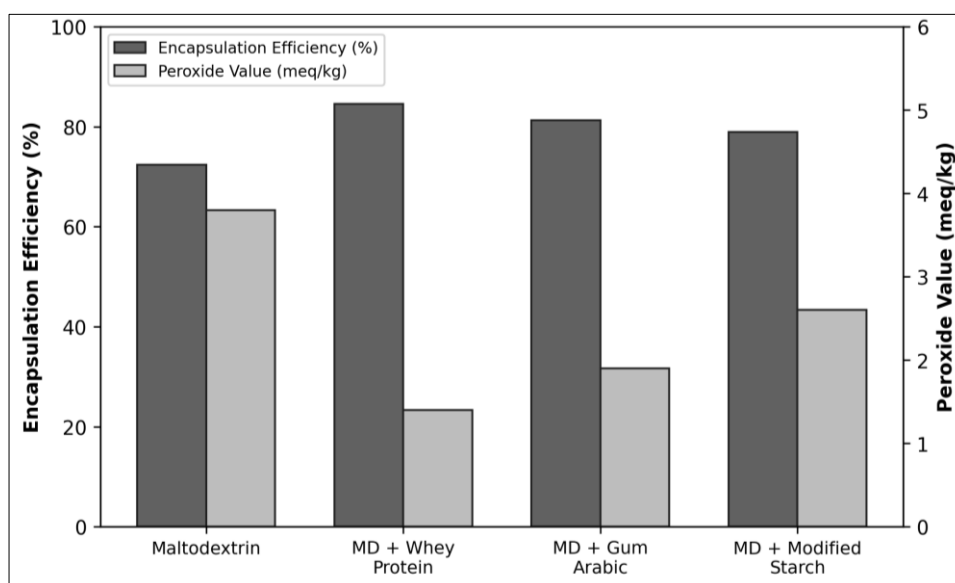


Fig 1: Encapsulation efficiency and peroxide value at day 30 across four wall material systems

Table 2: Ranking of wall material systems by oxidative stability (peroxide value at day 30)

Rank	Wall material	PV day 0 (meq/kg)	PV day 30 (meq/kg)	Increase (meq/kg)
1 (Best)	MD + WPI	0.4 ± 0.1	1.4 ± 0.2	1.0
2	MD + GA	0.5 ± 0.1	1.9 ± 0.3	1.4
3	MD + MS	0.5 ± 0.1	2.6 ± 0.3	2.1
4 (Worst)	MD alone	0.6 ± 0.2	3.8 ± 0.4	3.2

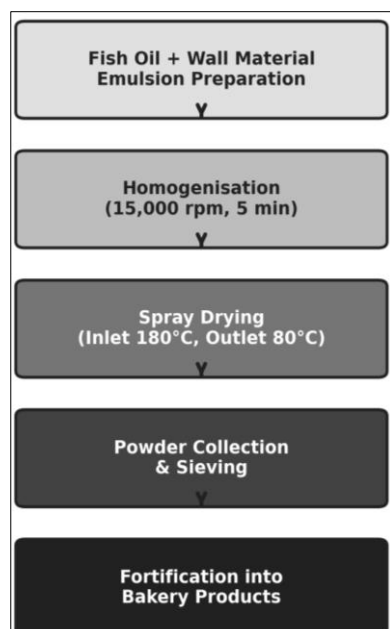


Fig 2: Schematic model of the spray drying microencapsulation process for fish oil

Table 3: Sensory scores (9-point hedonic) of wheat bread fortified with MD+WPI fish oil microcapsules

Attribute	Control (0%)	1% substitution	3% substitution	5% substitution
Appearance	7.8 ± 0.6	7.7 ± 0.5	7.4 ± 0.7	6.8 ± 0.9
Aroma	7.9 ± 0.5	7.6 ± 0.6	7.3 ± 0.8	5.9 ± 1.1
Taste	8.1 ± 0.4	7.8 ± 0.5	7.5 ± 0.6	6.1 ± 1.0
Texture	7.7 ± 0.6	7.6 ± 0.5	7.5 ± 0.6	7.1 ± 0.7
Overall	7.9 ± 0.4	7.7 ± 0.4	7.4 ± 0.5	6.2 ± 0.9

Interpretation

MD+WPI microcapsules offered the best combination of high encapsulation efficiency, low oxidative degradation, and acceptable sensory performance in bread. At 3% flour substitution, the fortified bread delivered 142 mg EPA+DHA per 50 g serving roughly 10% of the daily recommended intake without a detectable fishy off-flavour. Increasing substitution to 5% pushed aroma and taste scores below acceptability thresholds, confirming that 3% is the practical upper limit for this wall material system.

Discussion

The encapsulation efficiency of MD+WPI (84.6%) exceeded that of MD alone (72.4%) by 12 percentage points. This gap is consistent with findings by Jafari *et al.* [6], who attributed the superior performance of whey protein to its ability to form a viscoelastic film at the oil-water interface during atomisation, producing denser and smaller particles that trap more oil inside the matrix [10]. The smaller particle size of MD+WPI capsules (8.3 µm vs. 14.7 µm for MD) supports this interpretation, as smaller droplets generally experience faster shell formation during drying [11].

The peroxide value of MD+WPI capsules after 30 days (1.4 meq/kg) remained well below the 5 meq/kg threshold commonly used as a quality limit for edible oils [12]. MD alone reached 3.8 meq/kg at the same time point, suggesting that without a protein barrier, oxygen diffuses readily through the maltodextrin matrix. And because peroxide value is the most reliable early indicator of lipid rancidity,

the threefold difference between these two treatments translates directly into shelf-life advantage for the whey protein formulation.

The sensory data confirmed that 3% microcapsule substitution is the sweet spot for bread fortification. At this level, aroma and taste scores remained above 7.0, which is generally regarded as the threshold of commercial acceptability. The 5% level, however, produced a faint but detectable off-note that several panellists described as slightly oily, indicating that the wall material's flavour-masking capacity has limits even in the best formulation [13, 14].

Conclusion

This research set out to identify the best wall material for spray-dried fish oil microcapsules intended for bakery fortification. Maltodextrin combined with whey protein isolate delivered the highest encapsulation efficiency (84.6%), the lowest oxidative deterioration over 30 days (1.4 meq/kg peroxide value), and the best sensory performance when baked into wheat bread at 3% substitution. The fortified bread provided 142 mg EPA+DHA per serving without off-flavours, demonstrating a practical pathway for omega-3 enrichment of everyday bakery products. Future research should examine the stability of these microcapsules under accelerated shelf-life conditions and test their performance in other bakery matrices such as biscuits and muffins.

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