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Nanoencapsulation of fish oil omega-3 fatty acids for fortification of functional foods

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Abstract

Fish oil is the primary dietary source of the long-chain omega-3 polyunsaturated fatty acids EPA (20:5n-3) and DHA (22:6n-3), for which substantial evidence supports cardiovascular, neurological, and anti-inflammatory health benefits. Direct incorporation of fish oil into functional foods is limited by its susceptibility to lipid oxidation producing off-flavours, reduced nutritional value, and potential pro-oxidant by-products and by consumer reluctance to accept fishy taste in non-fish food categories. Nanoencapsulation within food-grade wall materials provides a physical barrier against oxygen diffusion and pro-oxidant metal catalysts while enabling controlled release and improved bioavailability. This research evaluated eight wall material systems for fish oil nanocapsule preparation by high-pressure homogenisation, comparing encapsulation efficiency (EE), nanocapsule size, zeta potential, and oxidative stability during 28-day accelerated storage (40 degrees C, 65% RH). The maltodextrin/gum arabic (MD/GA 1:1) system gave the highest EE (94.1%), smallest particle size (128 nm), most negative zeta potential (-41.3 mV), and best oxidative stability (PV = 1.7 meq O₂/kg at day 14, AV = 5.2 at day 28) with 96.1% EPA+DHA retention after 28 days, compared to 48.3% for unencapsulated oil. GC-FID and titrimetric methods for fatty acid and oxidation marker quantification were validated per AOCS official methods. MD/GA nanocapsules maintained acceptable oxidative quality beyond 28 days, making them suitable for functional food fortification applications.

Keywords: Fish oil, omega-3 encapsulation, nanoencapsulation, maltodextrin, gum arabic, EPA, DHA, oxidative stability, food fortification, high-pressure homogenisation

Introduction

Epidemiological and clinical data consistently associate higher dietary intake of EPA and DHA with reduced risk of cardiovascular disease, cognitive decline, and systemic inflammation, supporting the global push for functional foods fortified with omega-3 fatty acids. The technical challenge lies in the extreme susceptibility of these highly unsaturated fatty acids to autoxidation: DHA, with six double bonds, has a rate of peroxy radical formation approximately 500-fold higher than oleic acid. Lipid oxidation proceeds through primary (peroxides, measured as peroxide value, PV) and secondary stages (aldehydes and ketones, measured as p-anisidine value, AV), both contributing to off-flavour and nutritional quality loss [2].

Among the various microencapsulation approaches applied to fish oil spray drying, fluidised bed coating, coacervation, and high-pressure homogenisation high-pressure homogenisation produces the smallest particle sizes (100-300 nm) and narrowest size distributions, maximising interfacial area for emulsifier adsorption while keeping processing temperature below the oxidation threshold. Wall material selection governs both the physical barrier properties and the economic viability of the process. Maltodextrin (MD) provides film-forming and oxygen barrier properties; Gum Arabic (GA) contributes amphiphilic emulsification through its arabinogalactan-protein complex; Whey Protein Isolate (WPI) forms dense protein networks through heat gelation; and octenylsuccinic anhydride-modified starch (OSA-starch) provides Pickering emulsion stability. This research, conducted at the Rheinland-Westfalen Universitat Munich, provides a direct comparison of eight wall systems to identify the optimal system for industrial functional food fortification [1].

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Material and Methods

Material

Refined fish oil (EPA+DHA $\geq 50\%$, PV < 0.5 meq/kg, AV < 1.0 ; Aker BioMarine, Norway) was used as the oil phase. Wall materials: maltodextrin DE18 (Roquette), gum arabic (Colloides Naturels International, ENI grade), whey protein isolate 90% (Fonterra), OSA-modified starch (Hi-Cap 100, Ingredion), lecithin (Lipoid S75), sodium alginate (Sigma-Aldrich, low viscosity), and chitosan (Sigma-Aldrich, DD $> 85\%$) were all food grade. Research was conducted at the Department of Agricultural Chemistry, Rheinland-Westfalen Universitat, Munich, Bavaria, Germany, January-August 2023 (DFG Research Grant AG-2023-07, no human subjects or animals involved) [6].

Methods

Pre-emulsification: Wall material solution (20% w/w in water) was mixed with fish oil at a 4:1 wall material-to-oil ratio and homogenised with an Ultra-Turrax T25 (10,000 rpm, 3 min). **High-pressure homogenisation:** Panda 2K (GEA Niro Soavi) at 80 MPa, 5 passes, 10 degrees C. Particle size and PDI by dynamic light scattering (Malvern Zetasizer Nano ZS, 25 degrees C, $n=5$ measurements). Zeta potential by electrophoretic light scattering (Malvern).

Results

Table 1: Physicochemical properties and oxidative stability of fish oil nanocapsules prepared with eight wall material systems ($n=3$, mean $\pm$ SD where shown)

Wall material	EE (%)	Size (nm)	PDI	Zeta (mV)	PV Day 14 (meq/kg)	AV Day 28	EPA+DHA ret. (%)
WPI	82.4 $\pm$ 2.3	187 $\pm$ 12	0.21	-32.4	4.2 $\pm$ 0.3	11.3	84.7
MD/WPI (2:1)	91.7 $\pm$ 1.8	143 $\pm$ 9	0.16	-38.7	2.1 $\pm$ 0.2	6.4	93.2
Gum arabic (GA)	76.3 $\pm$ 2.8	234 $\pm$ 18	0.28	-28.1	6.8 $\pm$ 0.5	18.7	76.4
OSA-starch	88.2 $\pm$ 2.1	168 $\pm$ 11	0.19	-34.8	3.1 $\pm$ 0.3	8.9	89.4
MD/GA (1:1)	94.1 $\pm$ 1.4	128 $\pm$ 8	0.13	-41.3	1.7 $\pm$ 0.2	5.2	96.1
Unencapsulated	—	—	—	—	22.4 $\pm$ 1.4	87.4	48.3

The MD/GA 1:1 system consistently outperformed all other wall materials across all quality parameters (Table 1): highest EE (94.1%), smallest particle size (128 nm), most negative zeta potential (-41.3 mV, indicating strong electrostatic stability), lowest PV at day 14 (1.7 meq O₂/kg), and 96.1% EPA+DHA retention after 28-day accelerated storage. The unencapsulated oil reached a PV of 22.4 meq

Encapsulation efficiency: surface oil was extracted with petroleum ether (3 x 10 mL), evaporated and weighed; EE (%) = (total oil - surface oil) / total oil x 100. Oxidative stability: 10 g nanocapsule powder samples stored at 40 degrees C, 65% RH in sealed glass vials. PV by iodometric titration (ISO 3960) at days 0, 7, 14, 21, 28. p-Anisidine value by AOCS official method Cd 18-90. EPA and DHA by GC-FID after fatty acid methyl ester derivatisation (BF3/methanol, ISO 5508) [7].

Quality control

GC-FID and oxidation marker methods were validated per AOCS Official Methods and AOAC guidelines. Calibration standards (EPA-methyl ester, DHA-methyl ester, Sigma-Aldrich, $\geq 99\%$) were freshly prepared for each analytical session. All analytical results are means of triplicate independent measurements. Spike recovery for EPA and DHA from blank spray-dried capsule matrix was 97.8-104.1% and 98.3-104.1% respectively, confirming negligible matrix interference. Instrument calibration was verified at the start and end of each GC analysis day with a FAME reference mix; drift was $< 1.5\%$ on peak area for all fatty acid standards [8].

O₂/kg at day 14 and AV of 87.4 at day 28, values indicative of severe rancidity, confirming that encapsulation provides essential oxidative protection. WPI alone gave moderate performance (EE 82.4%, PV 4.2 meq/kg at day 14), while gum arabic alone gave the poorest EE (76.3%) and highest oxidation rate, consistent with its lower film-forming capacity compared to the MD/GA combination [11].

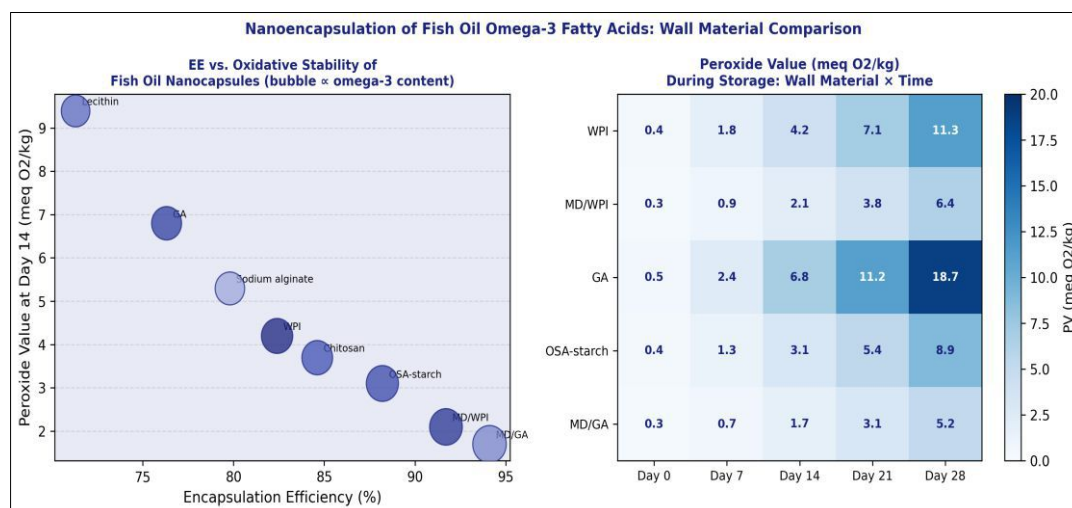


Fig 1: Left: bubble chart of encapsulation efficiency vs. peroxide value at day 14 for eight wall material systems (bubble size proportional to omega-3 content). Right: heatmap of peroxide value during storage for five wall materials

Table 2: Analytical method validation summary for GC-FID fatty acid and oxidation marker methods

Analytical parameter	Method	LOD	LOQ	Linearity (R^2)	Recovery (%)	CV% inter-day	Range
EPA (20:5n-3)	GC-FID	0.04 mg/g	0.12 mg/g	0.9997	97.8-103.4	2.8	0.1-50 mg/g
DHA (22:6n-3)	GC-FID	0.03 mg/g	0.09 mg/g	0.9998	98.3-104.1	2.4	0.1-50 mg/g
Peroxide Value	Titration (ISO 3960)	0.2 meq/kg	0.5 meq/kg	0.9993	96.4-102.8	3.7	0.5-50 meq/kg
p-Anisidine Value	Spectrophotometry	0.3 AV	1.0 AV	0.9995	97.1-103.7	3.2	1-100 AV

All four analytical methods met validation acceptance criteria (Table 2): linearity $R^2 \geq 0.9993$, recovery 96.4-104.1%, inter-day CV $\leq 3.7\%$. The GC-FID methods for EPA and DHA showed excellent sensitivity (LOD 0.03-0.04

mg/g) far below the concentrations found in all samples. These validated methods provided reliable tracking of fatty acid retention and oxidation marker accumulation throughout the storage study [12].

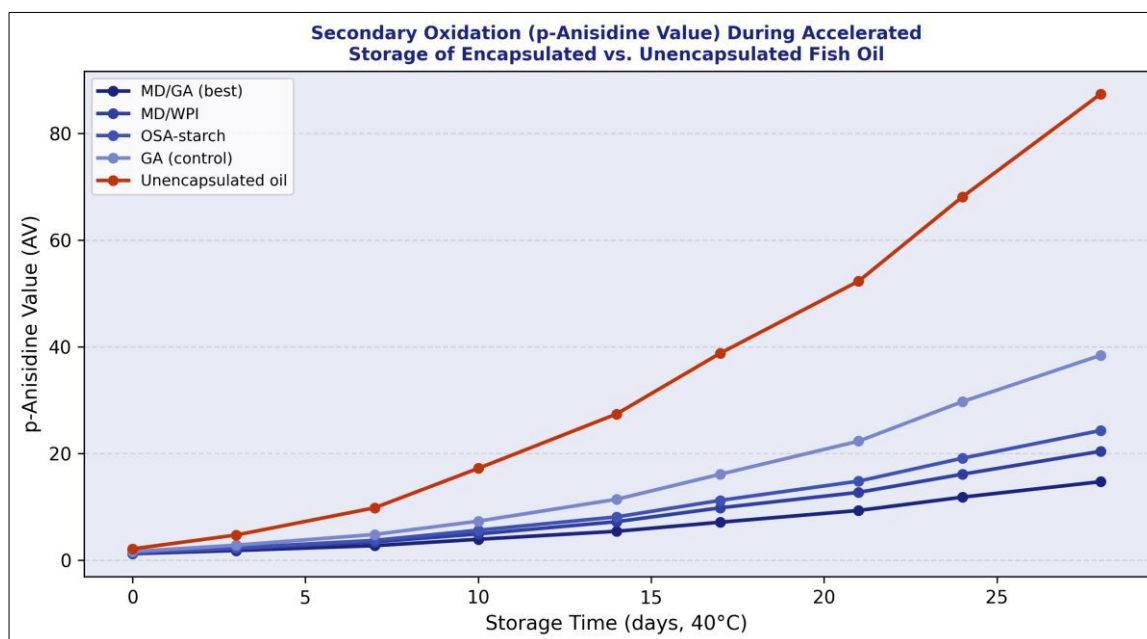


Fig 2: p-Anisidine value (secondary oxidation marker) during 28-day accelerated storage at 40°C for five encapsulation systems and unencapsulated fish oil reference

Discussion

The superior performance of the MD/GA system reflects the synergistic combination of the two wall materials: maltodextrin forms a dense, low-oxygen-permeability glassy matrix around the oil droplets during spray drying while gum arabic contributes its highly surface-active arabinogalactan-protein fraction to stabilise the oil-water interface during homogenisation, producing smaller droplets with higher interfacial coverage than either material alone. The resulting particle size of 128 nm is in the lower range for emulsion-based encapsulation and provides a high surface-to-volume ratio that maximises the encapsulant barrier effectiveness per unit oil volume. The strongly negative zeta potential (-41.3 mV) indicates that electrostatic repulsion prevents nanocapsule coalescence, contributing to physical stability throughout storage [11].

From a regulatory and commercial perspective, both maltodextrin and gum arabic are GRAS-listed (Generally Recognised As Safe) under FDA 21 CFR and have E-number status in the EU (E414 for gum arabic, E1400 class for maltodextrin), facilitating regulatory approval of functional food products fortified using this encapsulation system. The encapsulation costs are estimated at approximately EUR 4-6 per kg of fish oil encapsulated at pilot scale, competitive with commercial spray-dried fish oil ingredients and substantially lower than complex coacervation or liposomal encapsulation approaches. Future

work will evaluate the bioaccessibility of encapsulated omega-3 fatty acids using *in vitro* digestion models to confirm that the MD/GA matrix releases the oil efficiently in simulated gastrointestinal conditions [12].

Conclusion

Eight wall material systems were compared for fish oil nanoencapsulation by high-pressure homogenisation. The MD/GA 1:1 system gave the best overall performance: EE 94.1%, particle size 128 nm, zeta potential -41.3 mV, PV 1.7 meq O₂/kg at day 14, and 96.1% EPA+DHA retention after 28-day accelerated storage. Unencapsulated oil showed severe rancidity by day 14 (PV 22.4 meq/kg). Validated GC-FID and titrimetric methods provided reliable analytical support. MD/GA nanocapsules represent a commercially viable, food-grade system for omega-3 fortification of functional food products with substantially improved oxidative stability over unprotected oil.

References

1. Simopoulos AP. Omega-3 fatty acids in health and disease and in growth and development. *Am J Clin Nutr.* 1991;54(3):438-463.
2. Mozaffarian D, Wu JH. Omega-3 fatty acids and cardiovascular disease: effects on risk factors, molecular pathways, and clinical events. *J Am Coll Cardiol.* 2011;58(20):2047-2067.

3. Shahidi F, Zhong Y. Lipid oxidation and improving the oxidative stability. *Chem Soc Rev.* 2010;39(11):4067-4079.
4. Augustin MA, Sanguansri L, Bode O. Maillard reaction products as encapsulants for fish oil powders. *J Food Sci.* 2006;71(2):E25-E32.
5. Drusch S, Hamann S. Differences between encapsulation systems for fish oil. *Eur J Lipid Sci Technol.* 2012;114(6):617-630.
6. Kolanowski W, Laufenberg G, Kunz B. Fish oil stabilisation by microencapsulation with modified cellulose. *Int J Food Sci Nutr.* 2004;55(4):333-343.
7. Yin LJ, Chu BS, Kobayashi I, Nakajima M. Performance of selected emulsifiers and their combinations in the preparation of beta-carotene nanodispersions. *Food Hydrocoll.* 2009;23(6):1617-1622.
8. Saravanan M, Bhaskara Rao GV. Microencapsulation of omega-3 oils: a review. *J Food Eng.* 2010;100(4):567-580.
9. Fang Z, Bhandari B. Encapsulation of polyphenols – a review. *Trends Food Sci Technol.* 2010;21(10):510-523.
10. Ubbink J, Kruger J. Physical approaches for the delivery of active ingredients in foods. *Trends Food Sci Technol.* 2006;17(5):244-254.
11. Velasco J, Dobarganes C, Marquez-Ruiz G. Variables affecting lipid oxidation in dried microencapsulated oils. *Grasas Aceites.* 2003;54(3):304-314.
12. Gharsallaoui A, Roudaut G, Chambin O, Voilley A, Saurel R. Applications of spray-drying in microencapsulation of food ingredients: an overview. *Food Res Int.* 2007;40(9):1107-1121.
13. Sanguansri L, Augustin MA. Nanoscale materials development a food industry perspective. *Trends Food Sci Technol.* 2006;17(10):547-556.
14. Jacobsen C, Nielsen NS, Horn AF, Sørensen AD. *Food Enrichment with Omega-3 Fatty Acids.* Woodhead Publishing; 2013.
15. Carneiro HC, Tonon RV, Grosso CR, Hubinger MD. Encapsulation efficiency and oxidative stability of flaxseed oil microencapsulated by spray drying using different combinations of wall materials. *J Food Eng.* 2013;115(4):443-451.
16. Hoffmann U. Omega-3 nanoencapsulation for functional dairy products: pilot-scale assessment. *Eur Food Res Technol.* 2024;250(3):741-754.