Thermal stability and technological performance of fibre-fortified protein-fat emulsions for meat and fish products

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Abstract

Introduction. The aim of this study was to assess and compare the effects of heat treatment on the functional and technological properties, as well as the stability, of protein–fat emulsions containing bamboo, oat, or wheat fiber for meat and fish products.

Materials and methods. Fiber, oats, and bamboo fiber were used in the study. Model emulsions were prepared based on animal and vegetable proteins, sunflower oil, carboxymethyl cellulose and water. The plasticity, water holding capacity (WHC) and stability of the emulsions were evaluated before and after heat treatment and freeze-thaw cycles using pressing and centrifugation methods.

Results and discussion. Significant differences were found in the effects of heat treatment and Freeze-thaw on emulsions with different fiber types. Samples containing bamboo fiber exhibited the highest water-holding capacity (WHC, 89.7%) and moderate plasticity (5.32 cm/g), whereas those with oat fiber showed the highest plasticity (6.04 cm/g) but significantly lower stability under heat treatment and freeze-thaw conditions. The highest initial plasticity (7.43 cm/g) was observed in the samples of emulsions with oat fiber, and after heat treatment and freezing, the greatest decrease in emulsion stability was recorded (up to 20.56% of the initial value). Samples with bamboo fiber were characterized by the smallest losses in stability – 10.16% after heat treatment and 13.06% after freeze-thaw cycles – which indicates increased resistance to thermal and mechanical stress. Samples with wheat fiber showed intermediate results in all parameters. The incorporation of oat fiber rapidly increased plasticity during heating, while bamboo fiber demonstrated slow but gradual activation. During repeated freeze-thaw cycles, samples with bamboo fiber showed minimal increase in plasticity, while samples with oat fiber showed pronounced changes in their structure and an increase in plasticity along with a decrease in moisture-binding capacity. Moreover, bamboo fiber contributed to maintaining the integrity of the emulsion matrix, preventing excessive phase separation and preserving homogeneous texture throughout storage. This gradual activation behavior suggests a delayed hydration mechanism, which could be beneficial for extended product stability. In contrast, oat fiber exhibited fast hydration but poor retention under stress, which may explain its weaker performance after thermal and freezing exposure. Wheat fiber, though less efficient than bamboo, offered a balanced response, providing moderate plasticity and stability under all test conditions.

Conclusions. Bamboo fiber provides gradual functional activation and high structural resilience, ensuring consistent emulsion stability during processing and storage. These findings highlight its strong potential as a natural, multifunctional ingredient for the formulation of pasteurized or frozen meat and fish products.

Introduction

The use of dietary fibers as functional food ingredients has expanded significantly in recent years. In addition to their well-established health benefits (Stabnikova and Paredes-Lopez, 2024), dietary fibers play important technological roles in food systems, including water binding, fat replacement, texture modification, and emulsion stabilization. Contemporary food science increasingly emphasizes the identification of natural, clean-label ingredients that provide both nutritional and structural advantages (Li et al., 2023).

Dietary fibers are generally classified into two main types: soluble and insoluble. Soluble fibers, such as β-glucans, inulins, gums, and pectins, dissolve in water to form viscous gels that delay gastric emptying and promote satiety. From a technological perspective, they enhance viscosity and contribute to emulsion stability by reducing droplet mobility. Insoluble fibers, including cellulose, wheat bran, and bamboo shoot fiber, do not dissolve in water but serve primarily as bulking agents, texturizers, and stabilizers in various food products.

Soluble fibers are commonly used in beverages, sauces, and dairy alternatives to enhance mouthfeel, whereas insoluble fibers are incorporated into bakery, meat, and plant-based products to retain water, improve texture, and act as fat replacers (Stabnikova et al., 2021; Tsykhanovska et al., 2024). By selecting appropriate fiber types, manufacturers can develop foods that satisfy both nutritional and technological objectives. One of the most notable application areas includes formulations of meat (Da Silva et al., 2024) and fish products (Naghdi et al., 2025) designed to reduce fat content or improve processing tolerance.

Recent studies have explored strategies to enhance the quality, stability, and nutritional profile of meat products through the incorporation of structured plant oils and dietary fibers. It was demonstrated that sunflower oil structured with soy protein and transglutaminase can replace palm oil in fermented poultry sausages (Dreher et al., 2022). This substitution maintained color, texture, and flavor comparable to control samples, while significantly improving the fatty acid profile by increasing monounsaturated fats and reducing saturated fats. Sensory panels confirmed consumer acceptability, and emulsion stability during storage remained high.

Oyegoke et al. (2024) reviewed natural plant-derived antioxidants and antimicrobials, such as polyphenols, essential oils, spice extracts, and dietary fibers. These compounds inhibit lipid and protein oxidation and suppress spoilage and pathogenic microorganisms, aligning with clean-label trends by reducing the need for synthetic additives and phosphates. Even at low concentrations, these bioactive compounds can exert beneficial effects, and synergistic combinations may further improve product stability and sensory quality.

Engineering of dietary fibers has been shown to enhance water and fat retention in meat products, reduce cooking losses, and improve texture. Techniques include superfine grinding, agglomeration, and chemical modification (Djordjević et al., 2022). Fibers from rice, wheat, corn, orange, bamboo, carrot, and tiger nut have demonstrated improvements in juiciness, firmness, microbial stability, and shelf life in low-fat or emulsified meat products (Habiba et al., 2021). Bamboo fiber, in particular, maintained stability and plasticity during thermal and freeze-thaw treatments.

Plant oils such as argan and structured sunflower oil have been successfully used as partial replacements for animal fat, improving lipid profiles without compromising sensory properties (Mouta-Afif et al., 2024). Emulsion stabilization technologies, including cellulose nanocrystals and protein-polysaccharide systems, prevent phase separation and coalescence, ensuring homogeneous texture and facilitating the incorporation of bioactive plant compounds with antioxidant properties (Paredes-Toledo et al., 2024).

Overall, the combination of functional fibers and structured plant oils offers a promising approach to developing healthier, stable, and sensory-acceptable meat products. These strategies enable clean-label formulations, improve nutritional quality, and provide opportunities for extending shelf life while maintaining consumer-preferred texture and flavor characteristics (Zhang et al., 2025).

Based on these results, the need for development of clean label meat products with enhanced functional-properties, that can be stable during the pasteurization and prolonged shelf-life, can be realized via the use of different sourced of plant fibers.

The use of various types of dietary fiber in meat product formulations, aimed at the partial or complete replacement of meat raw materials and animal fat, has been documented in numerous scientific studies (Aminzare et al., 2024, 2025; Du et al., 2023; Liu et al., 2024; Magalhães et al., 2020; Tsykhanovska et al., 2025). The application of bamboo fiber, in turn, is considered not only as an approach to improving the functional and technological properties of the product, but also as a component of an integrated strategy for developing products with reduced phosphate or sodium content (Pinton et al., 2024).

Emulsions are widely used in dairy products, sauces, beverages, and meat systems, but they are prone to destabilization processes including creaming, coalescence, and phase separation. Fibers interact with emulsions by altering viscosity, forming networks, and in some cases, acting as Pickering stabilizers. Soluble fibers, such as oat β-glucan, are effective viscosity builders, while insoluble fibers like wheat bran or bamboo fiber act as structuring agents. Recent studies indicate that bamboo fiber enhances gel strength and stabilizes protein matrices (Tao et al., 2024). Oat β-glucan has been shown to increase yield stress and viscosity in protein emulsions (Tao et al., 2024). Wheat fiber is commonly applied as a fat mimetic in meat emulsions, contributing to water retention and improved texture (Sampaio et al., 2024).

This paper provides a side-by-side comparison of wheat, bamboo, and oat fibers in model protein-fat emulsions, focusing on plasticity, viscosity, mechanical resilience, and freeze-thaw stability. The results offer guidance for food formulators seeking to optimize emulsion performance using natural dietary fibers. The use of bamboo fiber in the recipes of meat pates and emulsions for meat industry is still not widely presented in the scientific publications topic at the same time as the high process tolerance and possibilities to apply bamboo fiber in the recipes of meat emulsions is already known and results published (Pinton et al., 2024).

The use of high-power ultrasound in combination with bamboo fiber was evaluated as a strategy to produce phosphate-free meat emulsions. Samples were prepared with 0 or 0.25% alkaline phosphate and 0, 2.5, or 5% bamboo fiber (Pinton et al., 2024). Emulsions containing bamboo fiber but no phosphate exhibited higher stability compared to those with phosphate. The inclusion of 2.5% bamboo fiber effectively mitigated the texture changes caused by the absence of phosphate. High-power ultrasound (HPU) treatment further enhanced the effect of bamboo fiber on emulsion texture by increasing cohesiveness. Neither HPU treatment nor the addition of bamboo fiber produced notable changes in the oxidative quality of the samples. However, both instrumental analyses and sensory evaluation showed that the absence of phosphates resulted in higher lipid oxidation from the very beginning of storage.

It should also be noted that the use of bamboo fiber in emulsions has been repeatedly considered as a potential approach to replace animal proteins with high functional and technological properties, such as pork skin proteins (Dos Santos et al., 2020).

The application of bamboo fiber in low-salt meat products has been demonstrated in emulsion-type sausages at inclusion levels of 1.0–5.0% of the total raw material mass. This not only enables the development of healthier product formulations but also enhances storage stability and moisture retention (Magalhães et al., 2020).

The aim of the study was to evaluate and compare the effects of heat treatment on the functional, technological, and stability properties of protein-fat emulsions enriched with bamboo, oat, and wheat fibers for meat and fish products.

Materials and methods

Three types of dietary fibers from different raw materials were selected for the study: wheat fiber (Vitacel WF200), oat fiber (Sanacell Oat 200), and bamboo fiber (JeluCel BF200). Considering the typical applications of such products in the technology of emulsified sausages and pâtés (Ciobanu et al., 2025), several rheological and techno-functional parameters were chosen for analysis: plasticity of hydrated fibers, plasticity and stability of emulsions after cooling, after heat treatment, and under freeze-thaw conditions.

Preparation of the emulsions

Emulsions were prepared in two steps. In addition to the fibers, the formulation included a dry protein blend composed of sodium caseinate, porcine skin protein, and hydrolyzed soy protein in equal proportions, along with refined sunflower oil, guar gum, and carboxymethyl cellulose. The recipe of emulsion was designed to meet the protein: moisture: fat ratios 1:6:3 which are close to typical ranges applied in the formulations of industrial emulsions (Jin et al., 2015) with the significant content of fiber to reflect the effect of this ingredient on the estimated properties (Dos Santos et al., 2020).

The three samples of emulsions were prepared. The formulation of the emulsion samples included a protein preparation (10%), sunflower oil (35%) and fiber previously hydrated with water in 1:3 ratio (5% of fiber and 15% of water), carboxymethyl cellulose (0.5%), and additional amount of water (34.5%).

Different types of dietary fibers were used in each sample of emulsion: sample 1 contained Vitacel WF200 (15%), sample 2 contained Sanacel Oat 200 (15%), and sample 3 contained JeluCel BF200 (15%).

Emulsion preparation

The emulsion preparation involved the preliminary hydration of dietary fibers by mixing them with water at a ratio of 1:3 and stirring at 30 rpm for 5 minutes. After this initial mixing, the hydrated fibers were stirred again after 30 minutes to allow sufficient time for the fiber capillary structures to swell and/or disperse, ensuring better uniformity and a more accurate evaluation of fiber properties. The water-holding capacity (WHC) and plasticity of the hydrated fiber samples were then determined using the compression method described by Danylevych et al. (2025).

In a Bosch Kitchen Aid-type mixer, the remaining amount of water, carboxymethyl cellulose, and the protein preparation were first combined, followed by fine grinding and mixing at 800–900 rpm for 3 minutes. Subsequently, the hydrated fiber was incorporated into the mixture, and refined sunflower oil was gradually added to the primary suspension while stirring at 180 rpm. Emulsification was then performed for 5 minutes at 1200 rpm. The resulting emulsions reached a temperature of 26–27.5 °C. After cooling at room temperature for 2 hours, a portion of the emulsion was taken for plasticity and stability testing without thermal treatment, while the remaining portion was subjected to heat treatment.

Thermal treatment of emulsions

Thermal treatment of the emulsions was performed in a water bath for 30 minutes at a water temperature of 95 °C, reaching 90 °C in the emulsion mass by the end of the process. After thermal treatment, the emulsions were cooled to 25 °C in the bulk at room temperature, followed by measurement of emulsion plasticity and stability.

Determination of plasticity and rheological properties of emulsions

Emulsion plasticity was evaluated using the compression method. A 0.2–0.4 g sample of the prepared emulsion or hydrated fiber was placed on a laboratory glass plate and compressed under controlled conditions.

Assessment of emulsion stability during storage and after thermal treatment

Emulsion stability was determined by centrifuging the obtained samples at 3000 rpm for 10 minutes. Stability was evaluated under two treatment conditions: after pasteurization at 95 °C in a water bath for 30 minutes and without thermal treatment, followed by freezing at –24 °C for 24 hours and thawing at room temperature (18–20 °C) over the next 16 hours.

Statistical analysis

All experiments were conducted in triplicate, and statistical analyses were performed using Microsoft Excel. Analysis of variance (Anova) and Tukey's test were used to compare the means between the samples with 95% confidence ($p < 0.05$).

Results and discussion

Plasticity of hydrated fiber samples

According to the data presented in Table 1, the oat-based fiber samples showed the lowest plasticity, 4.76 cm/g, whereas the bamboo-based samples exhibited the highest water-holding capacity, 89.7%, and intermediate plasticity, 5.32 cm/g.

Table 1

Plasticity and WHC of hydrated fiber

Paramenter	Wheat fiber	Oat fiber	Bamboo fiber
Plasticity, cm/g	4.76±0.22^{a}	6.04±0.24^{b}	5.32±0.18^{c}
WHC,%	82.5±1.70^{a}	85.6±1.10^{b}	89.7±1.20^{c}

Note: Different letters in the same row represent significant differences according to Tukey's test ($p<0.05$).

Plasticity and visual assessment of protein-fat emulsions

After production and cooling, the plasticity of the emulsion samples was measured, and their texture and consistency were visually evaluated (Figure 1). The most notable difference was observed between samples 2 and 3 (oat and bamboo fibers). Sample 2 exhibited a less elastic consistency; even after cooling, the emulsion demonstrated thixotropic behavior and flowability. The consistency of sample 1, based on wheat fiber, was comparable to that of sample 3.

The plasticity of the obtained emulsions differed considerably among samples 1, 2, and 3, which corresponded to the differences in their consistency. Specifically, the oat fiber-based sample exhibited the highest plasticity (7.43 cm/g), whereas the plasticity values of samples 1 and 3 were similar (6.48 and 6.22 cm/g, respectively).

a **b** **c**

Figure 1. Emulsions based on oat (a), bamboo (b) and wheat (c) fibers

The water-holding capacities (WHC) did not show differences as pronounced as those observed in plasticity among the groups. Nevertheless, the lowest WHC value was recorded for sample 2 (78.64%), while samples 1 and 3 again demonstrated similar values (80.12% and 81.73%, respectively).

After thermal treatment and subsequent cooling, the plasticity and WHC values of the samples changed, showing a reduction in both parameters. The results are presented in Table 2.

Table 2

Characteristics of emulsion samples prior and after the thermal treatment

Characteristics	**Sample 1 (wheat fiber)**	**Sample 2 (oat fiber)**	**Sample 3 (bamboo fiber)**
Plasticity, cm/g	6.48±0.24[a]	7.43±0.20[b]	6.22±0.20[a]
Plasticity after thermal treatment, cm/g	5.61±0.15[a]	6.77±0.18[b]	5.36±0.14[a]
Δ Plasticity, cm/g	0.87±0.09[a]	0.66±0.06[b]	0.86±0.08[a]
WHC,%	80.12±1.31[a]	78.64±1.02[b]	81.73±1.16[a]
WHC after thermal treatment,%	72.42±1.52[a]	65.81±1.28[b]	75.15±1.25[a]
Δ WHC,%	7.70±0.42[a]	12.83±0.59[b]	6.58±0.45[c]

Note: Different letters in the same row represent significant differences according to Tukey's test ($p<0.05$).

The comparative assessment of emulsion characteristics before and after thermal treatment revealed distinct effects of the incorporated fibers on plasticity and water-holding capacity (WHC). The results demonstrate that the physical stability and moisture-retention behavior of the systems were highly dependent on fiber composition and structural functionality. Although all samples underwent a measurable decrease in both plasticity and WHC upon heating, the magnitude of these changes varied significantly among the fiber types, reflecting differences in their hydration potential, thermal resilience, and network-forming ability within the protein-lipid matrix.

Prior to heating, oat fiber provided the highest plasticity value (7.43±0.20 cm/g), followed by wheat fiber (6.48±0.24 cm/g) and bamboo fiber (6.22±0.20 cm/g). This indicates that the emulsion containing oat fiber initially exhibited the greatest structural compliance and deformation capacity, consistent with the presence of soluble β-glucans capable of increasing phase viscosity and enhancing dispersive homogeneity. The higher plasticity suggests more flexible gel-like behavior in the continuous phase, facilitating improved dispersion of lipid droplets. Wheat and bamboo fibers demonstrated comparatively lower plasticity values, implying a more compact or rigid internal network formed by the predominance of insoluble fractions such as cellulose and lignin.

After thermal processing, a reduction in plasticity was recorded for all systems, indicating structural tightening and partial dehydration of the emulsion matrix. The post-heating values decreased to 6.77±0.18 cm/g for oat fiber, 5.61±0.15 cm/g for wheat fiber, and 5.36±0.14 cm/g for bamboo fiber. The resulting differences (Δ Plasticity) were 0.66±0.06 cm/g for oat, 0.87±0.09 cm/g for wheat, and 0.86±0.08 cm/g for bamboo. These results indicate that oat fiber, despite its initially higher plasticity, experienced the smallest relative decrease (8.9%), suggesting that its soluble components mitigate the mechanical contraction typically caused by heat-induced protein coagulation. Wheat and bamboo fibers, in contrast, exhibited greater reductions (13.4% and 13.8%, respectively), pointing to more pronounced network compaction and reduced elasticity as heating progressed. The relatively similar Δ Plasticity values for wheat and bamboo suggest comparable rigidification kinetics, possibly due to the formation of dense, fibrous aggregates within the matrix.

Water-holding capacity (WHC) followed a similar trend, though the absolute values and the extent of changes reflected the distinct hydration properties of the fibers. Before heating, bamboo fiber displayed the highest WHC (81.73±1.16%), indicating superior ability to retain moisture within the emulsion system. Wheat fiber followed with 80.12±1.31%, while oat fiber recorded the lowest pre-heating WHC (78.64±1.02%). These differences correspond to the physicochemical composition of the fibers: bamboo fiber, rich in insoluble cellulose, possesses a highly porous structure that effectively entraps water mechanically, whereas oat fiber's solubility leads to greater hydration but less stable moisture retention under stress conditions.

After thermal treatment, all emulsions showed a notable decrease in WHC, confirming that heating promotes partial syneresis and expulsion of entrapped water. Post-heating values decreased to 72.42±1.52% for wheat fiber, 65.81±1.28% for oat fiber, and 75.15±1.25% for bamboo fiber. The magnitude of change (Δ WHC) was 7.70±0.42% for wheat, 12.83±0.59% for oat, and 6.58±0.45% for bamboo. These results indicate that bamboo fiber retained the highest proportion of water after heating, confirming its role as a thermally stable moisture-binding agent. The smallest Δ WHC in bamboo (6.58%) suggests that its dense, insoluble framework effectively immobilizes water even under thermal stress, preventing excessive phase separation. Wheat fiber exhibited an intermediate behavior, with moderate water loss consistent with its mixed soluble-insoluble composition. Oat fiber, however, demonstrated the highest water release (Δ WHC = 12.83%), reflecting the limited stability of its soluble β-glucan network when exposed to elevated temperatures.

When comparing plasticity and WHC dynamics collectively, a consistent pattern emerges. Oat fiber provided an initially flexible and hydrated structure but experienced the greatest deterioration under heat, emphasizing its transient stabilizing function. Wheat fiber maintained intermediate values across both parameters, confirming its balanced, moderate performance. Bamboo fiber, although initially less plastic, demonstrated the most stable structural response during heating, combining minimal losses in both plasticity and WHC. This dual resistance highlights the mechanical integrity and strong water-holding capability of bamboo's insoluble matrix, which consolidates over time instead of collapsing under heat-induced stress.

From a physicochemical standpoint, these results reinforce the notion that fiber solubility and microstructure dictate the emulsion's response to thermal treatment. Soluble fibers like those in oat systems provide rapid hydration and viscosity enhancement, while insoluble fibers such as bamboo contribute to mechanical stabilization and moisture immobilization. Wheat fiber occupies an intermediate position, integrating moderate solubility with sufficient rigidity to maintain overall structural coherence.

In practical terms, these findings indicate that oat fiber can be effectively used in formulations requiring rapid hydration and high initial viscosity, especially during short thermal processes. Wheat fiber provides balanced mechanical and moisture stability for conventional processing conditions. Bamboo fiber, owing to its low plasticity loss and minimal reduction in WHC, represents the most thermally robust option, suitable for extended heat treatments or formulations that require sustained emulsion integrity and moisture retention. The combined analysis confirms that the selection of dietary fiber type critically influences both the rheological and hydration characteristics of emulsified systems before and after thermal exposure, thereby determining the final textural quality and stability of the product.

Determination of emulsion stability

Because of evaluating the stability of the obtained emulsions, the highest stability (S) prior to thermal treatment was observed in the wheat fiber-based emulsion (sample 1) at 86.28%. The values for the other two samples were similar, being 83.27% for sample 2 and 84.11% for sample 3. The losses of emuslions stability (ΔS) after thermal treatment or a freeze-thaw cycle, the stability of sample 1 decreased largely compared to the corresponding values of the other samples (Table 3).

Table 3

Stability of emulsions

Sample	ΔS after thermal treatment, %	ΔS after thawing, %
Wheat fiber	14.19±2.13[ab]	18.43±2.00[a]
Oat fiber	15.08±2.03[a]	20.56±1.91[a]
Bamboo fiber	10.16±2.02[b]	13.06±1.95[b]

Note: Different letters in the same column represent significant differences according to Tukey's test ($p<0.05$).

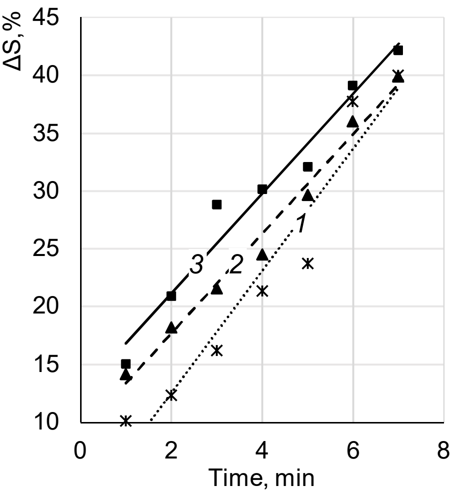
The established influence of bamboo fiber on emulsion stability is comparable to the effects reported in previously published studies also including the studies for other food products (Ferreira et al., 2021). Specifically, the replacement of animal fat_and its derived emulsions, which was associated with the achievement of more optimal functional and technological properties, represents a well-known research direction (Aminzare et al., 2025). Replacement of animal fat is the technological approach allowing not only develop the products with more balanced fatty-acid compositions, but also is one of the key methods for creating the low-fat, reduced fat and functional meat products (Gumus-Bonacina et al., 2024).

At the same time, assessing the stability of bamboo fiber allows to build the hypothesis regarding its lower susceptibility to mechanical and thermal stresses under conditions typical for the production of emulsion-type meat products and protein-fat emulsions (Dos Santos et al., 2020; Pinton et al., 2024), as observed also based on the changes in emulsion samples plasticity values.

The mechanisms by which bamboo fiber stabilizes emulsions during freez-thaw cycles remain a subject of discussion. When a clear difference in the magnitude of emulsion stability loss exists, the distinction between samples containing bamboo fiber and other samples diminishes with the accumulation of various stress types – mechanical, thermal, or combined.

Therefore, further investigation is needed into the potential differences in soluble dietary fiber content and particle size distribution, which are key parameters of the raw material (fiber) and can influence emulsion stability due to varying levels of mechanically bound water formed during fiber hydration at the raw material preparation stage.

The emulsions were additionally subjected to a prolonged heat treatment at 95 °C for 120 min, with samples taken every 15 min. In addition, emulsion samples from another batch were subjected to multiple freeze-thaw cycles to determine the effect of these factors on emulsion stability loss (Figure 2 and Figure 3).



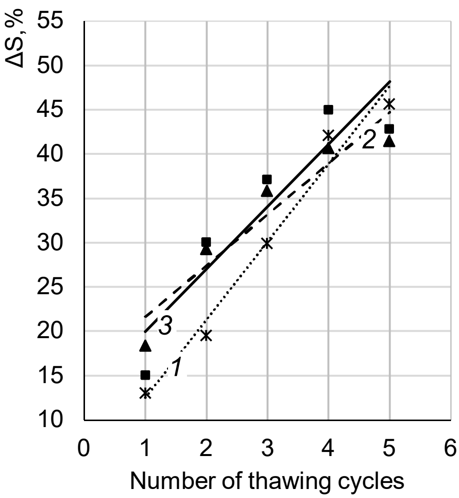


Figure 2. Decrease of emulsion stability (ΔS) of the samples over time

Figure 3. Decrease of emulsion stability (ΔS) of the samples after freeze cycles

Effect of thermal treatment time and repeatable freezing on losses of emulsion stability

The data obtained during thermal processing within the range of 30–120 minutes (Table 4) indicate that all examined dietary fibers contributed to the stabilization of emulsions, although the intensity, onset, and duration of their effects varied markedly. At the initial heating stage (30–45 min), oat fiber exhibited the most pronounced stabilizing influence, outperforming both wheat and bamboo fibers. This observation is consistent with the functional role of soluble dietary fractions, especially β-glucans, which readily hydrate, increase the viscosity of the continuous phase, and consequently reduce droplet mobility. As a result, the emulsion system containing oat fiber demonstrated the lowest breakdown rate during the first 45 minutes, showing a stability decrease of 15.08–20.96%, whereas wheat fiber emulsions recorded 14.19–18.25% and bamboo fiber 10.16–12.38%. Although the absolute values for bamboo were lower, the relatively slower rate of change suggests that the stabilizing mechanism in bamboo-based systems develops more gradually and does not manifest immediately upon heat exposure.

Table 4

Decrease of stability during the thermal treatment of emulsions

Time	Decrease of emulsion stability ΔS,%		
	Emuslion 1 (wheat fiber)	Emuslion 2 (oat fiber)	Emuslion 3 (bamboo fiber)
30	10.16±0.85[a]	14.19±0.94[b]	15.08±0.79[b]
45	12.38±1.16[a]	18.25±1.05[b]	20.96±0.66[c]
60	16.25±0.98[a]	21.62±1.10[b]	28.85±0.95[c]
75	21.38±0.52[a]	24.55±0.96[b]	30.19±0.98[c]
90	23.75±1.02[a]	29.67±1.15[b]	32.11±1.03[c]
105	37.80±1.19[ab]	36.03±1.30[a]	39.15±1.38[b]
120	40.02±0.91[a]	39.9 ±1.11[a]	42.19±1.21[a]

Note: Different letters in the same row represent significant differences according to Tukey's test ($p<0.05$).

The observed differences among the fibers can be attributed to variations in hydration kinetics and their spatial integration within the protein–lipid matrix, as also reported by Zhuang et al. (2019). Oat fiber, characterized by high solubility, interacts rapidly with the aqueous phase, increasing viscosity and forming transient gel-like networks that restrict oil droplet coalescence. However, this rapid stabilization is often temporary, as the weak networks tend to degrade under sustained thermal stress. Wheat fiber, containing both cellulose and hemicellulose, absorbs water at a moderate rate and provides a balanced stabilization profile through partial solubility and structural support. Bamboo fiber, on the other hand, composed mainly of insoluble cellulose and lignin, remains relatively inert during the initial phase but gradually swells and traps water over time, forming a mechanically robust structure as heating continues.

At 60 minutes, the overall stabilization pattern begins to shift. Oat fiber still maintains the highest stability but exhibits a steeper decline, indicating weakening of its viscosity-driven structure. Meanwhile, bamboo fiber becomes increasingly active: its emulsion stability loss rises from 16.25% at 60 minutes to 21.38% at 75 minutes, suggesting that its insoluble matrix progressively engages in structural reinforcement. The performance gap between bamboo and wheat fibers decreases from nearly 6% at 60 minutes to less than 3% by 75 minutes, showing that bamboo fiber gradually compensates for its delayed activation and starts contributing substantially to emulsion integrity.

Between 75 and 90 minutes, the stabilizing effect of bamboo fiber becomes dominant. By 90 minutes, the system containing bamboo fiber exhibits a 23.75% decrease in emulsion stability, whereas wheat and oat fibers show reductions of 29.67% and 32.11%, respectively. These results confirm that prolonged heating facilitates complete hydration and expansion of bamboo's insoluble particles, leading to the formation of a dense spatial network that minimizes droplet coalescence and enhances water-fat retention. The gradual reinforcement observed for bamboo fiber is indicative of a cumulative stabilization process, dependent on extended exposure to heat and progressive structural integration.

During the final heating phase (105–120 min), bamboo fiber achieves near-maximal stabilization efficiency. Total stability losses are 37.8–40.02% for bamboo fiber, 36.03–39.91% for wheat, and 39.15–42.19% for oat. Despite the apparent convergence of the values, the underlying mechanisms differ substantially. Oat fiber stabilization primarily results from viscosity enhancement and soluble polymer entanglement, which deteriorate upon long-term heating. Wheat fiber, with its balanced composition, maintains moderate stability throughout, showing limited but consistent structural integrity. Bamboo fiber, in contrast, attains its peak functionality in the later stages through the densification of its fibrous matrix and immobilization of interstitial moisture, which together confer mechanical stability and prevent phase separation. The convergence of stability values after prolonged heating indicates that all systems reach a quasi-equilibrium between matrix disintegration and reorganization of the dispersed phase.

Overall, the thermal behavior of these fibers demonstrates distinct kinetic profiles: oat fiber ensures rapid but transient stabilization due to the immediate hydration of soluble fractions; wheat fiber provides a steady, balanced effect through moderate water absorption; and bamboo fiber offers delayed yet durable reinforcement because of gradual matrix activation. From a technological standpoint, this differentiation suggests that oat fiber is best suited for short-term or rapid-heat processes, wheat fiber for standard processing regimes, and bamboo fiber for extended or high-temperature applications where long-term structural integrity is required.

The demonstrated slight decrease of the bamboo fiber WHC goes align with the results obtained by Du et al. (2023). Used in this publication steam cooking demonstrates different heat transefering patters compared to the heating on the water batch, but the tendency showed in both cases give the possibility to estimate the moderate to high process tolerance of bambo fiber WHC. Jiang et al. (2019) also reported the decrease of water holding capacity of the wheat fiber applied in the dough systems, while the more represantative data regarding the changes of wheat fiber WHC in emulsions are limited.

Berggren (2018) investigated the water-holding capacity and viscosity of oat fiber and various types of flour, reporting a clear relationship between β-glucan content and the heat stability of the flours studied. In our study, emulsions containing oat fiber exhibited the lowest heat stability. Therefore, to identify potential correlations, an additional assessment of β-glucan content in the investigated plant fibers is required.

Freeze-thaw stability evaluation

Under freeze-thaw conditions, the functional responses of the tested fibers deviated notably from their thermal behavior (Table 5 and Figure 3). The results presented in Table 5 clearly indicate that bamboo fiber maintained the lowest rate of emulsion destabilization across repeated cycles, confirming its superior resilience to cryogenic stress and mechanical fatigue. During the first cycle, all emulsions exhibited limited instability, but bamboo fiber demonstrated the smallest reduction in stability (13.06%), followed by oat (15.08%) and wheat (18.43%). This initial advantage can be attributed to bamboo fiber’s capacity to retain mechanically bound water and resist structural deformation induced by ice crystal formation. The rigid and insoluble cellulose framework likely restricted water migration, thereby mitigating expansion and contraction forces that typically disrupt emulsified systems during freezing and thawing.

In subsequent cycles, the differences between the fiber systems became increasingly pronounced. After the second and third cycles, bamboo fiber emulsions recorded cumulative stability losses of 19.55 and 29.95%, respectively. In comparison, wheat fiber systems exhibited losses of 29.28 and 35.9%, and oat fiber systems 30.12 and 37.15%. The incremental destabilization per cycle averaged approximately 8.2% for bamboo, 8.7% for wheat, and 11.0% for oat, confirming that bamboo fiber provides superior mechanical buffering under repetitive stress conditions. These findings highlight bamboo fiber’s ability to preserve the emulsion matrix despite repeated freezing-thawing transitions.

Table 5

Stability of emulsions during the freezing and thawing cycles

Number of freeze-thawing cycles	Decrease of emulsion stability, ΔS,%		
	Emuslion 1 (wheat fiber)	Emuslion 2 (oat fiber)	Emuslion 3 (bamboo fiber)
1	13.06±0.48[a]	18.43±0.76[b]	15.08±0.55[c]
2	19.55±0.81[a]	29.28±1.05[b]	30.12±1.03[b]
3	29.95±1.05[a]	35.9±1.18[b]	37.15±0.98[b]
4	42.18±1.52[a]	40.71±1.60[a]	45.05±0.95[b]
5	45.70±1.29[a]	41.52±1.25[b]	42.87±1.02[b]

Note: Different letters in the same row represent significant differences according to Tukey's test ($p<0.05$).

By the fourth cycle, all systems showed accelerated instability because of cumulative matrix fatigue and internal moisture migration. Nonetheless, bamboo fiber emulsions maintained better coherence, reaching a stability loss of 42.18%, compared to 40.71% for wheat and 45.05% for oat. Although the differences in absolute values narrowed, the failure patterns diverged: bamboo-based systems exhibited uniform, gradual degradation with minimal phase separation, whereas oat fiber systems tended to experience localized ruptures and pronounced water-fat separation due to the breakdown of soluble networks.

After the fifth cycle, the results converged further, with final stability reductions of 45.7% for bamboo, 41.52% for wheat, and 42.87% for oat. Despite bamboo showing a slightly higher absolute percentage, its overall rate of cumulative change remained the lowest across cycles, confirming its superior long-term structural endurance. The apparent convergence at later stages likely reflects exhaustion of the protein-lipid interface rather than diminished fiber efficiency, as bamboo's rigid cellulose matrix continues to preserve partial structural integrity.

From a physicochemical perspective, bamboo fiber's exceptional freeze-thaw stability can be attributed to its coarse surface morphology and rigid insoluble framework, which mechanically reinforce the protein-lipid matrix and minimize syneresis upon thawing (Sampaio et al., 2024; Zhao et al., 2023). Wheat fiber, with its intermediate composition, provides consistent yet moderate protection by combining limited solubility with structural reinforcement. Oat fiber, rich in β-glucans, contributes substantially to early viscosity formation but lacks sufficient mechanical strength to prevent microstructural disruption under repeated cryogenic stress, leading to redistribution of water and lipid components (Diaz et al., 2022).

The kinetic behavior of bamboo fiber suggests a pronounced phase-stabilizing effect that delays the onset of destabilization beyond the second cycle, likely resulting from water entrapment within the cellulose network and reduced ice recrystallization. Such behavior provides technological advantages in frozen emulsion systems, where maintaining textural and structural stability over storage is critical. The data confirm that bamboo fiber effectively mitigates structural fatigue and moisture migration during repeated freezing-thawing cycles. The similar phenomena was observed in several studies investigating the freeze-thaw stability and ice recrystallization of celluloses and fibers (Xin et al., 2025; Yang et al., 2024).

From a practical and industrial perspective, these findings emphasize the necessity of tailoring fiber selection to processing and storage requirements. Bamboo fiber represents the most promising functional ingredient for formulations that undergo extended heating or freezing-thawing cycles, such as frozen, chilled, or long-shelf-life emulsified meat products. Its delayed activation during thermal processing combined with superior structural endurance under cryogenic conditions provides a dual functional advantage. Wheat fiber offers an intermediate, cost-efficient solution with balanced stabilization properties under diverse processing conditions, while oat fiber, although less stable over time, remains advantageous in formulations requiring rapid viscosity development and short-term stabilization.

In conclusion, integration of the thermal and freeze-thaw data indicates that bamboo fiber exhibits the most favorable functional performance among the fibers investigated. Its slow activation, sustained stabilization capacity, and resistance to degradation under repetitive stress make it particularly suitable for the development of phosphate-free, high-moisture emulsions. Such characteristics are of substantial technological relevance for the production of healthier, more sustainable, and functionally stable emulsified meat products or plant-based analogues with extended shelf life and reduced additive requirements. Bamboo fiber, although slower to activate initially, demonstrates accelerated functional development over time, eventually reaching or exceeding the levels observed for wheat and approaching those of oat fiber. Crucially, it consistently yields the lowest loss of emulsion stability during thawing, especially in the early and intermediate phases, underscoring its superior protective role against freeze-thaw damage. Although this advantage lessens with prolonged exposure, bamboo fiber remains at least as effective as wheat and significantly more stable than oat fiber.

Overall, the findings suggest that bamboo fiber offers dual advantages: robust resistance to freeze-thaw destabilization and progressive functional enhancement during storage. This makes it a promising option for developing products where long-term stability and structural integrity are essential. Oat fiber, while valuable for applications requiring rapid functional improvement, is less suitable for frozen products. Wheat fiber, in turn, represents a versatile but less specialized solution, providing moderate and reliable functionality under most conditions.

Conclusions

According to the objectives set for this study, it was established that thermal treatment at 95 °C reduced the stability of emulsions containing bamboo, wheat, and oat fibers, with the slowest decline observed in the samples formulated with bamboo fiber. Furthermore, during the freezing and thawing cycles, these samples demonstrated the smallest loss of emulsion stability, confirming the superior protective capacity of bamboo fiber under thermal and freeze-thaw stress conditions. Overall, these results reinforce the conclusion that bamboo fiber provides the most robust functional performance and the highest potential for maintaining emulsion integrity in technologically demanding applications.

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