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Development of Banana Pseudostem Incorporated Heat-Induced Surimi Gel from *Nemipterus japonicus* and its Characterisation

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Abstract

The present study aimed at developing a fibre-incorporated surimi gel with improved functional properties by incorporating banana pseudostem flour (BPF), an abundant agro-industrial waste, into *Nemipterus japonicus* (Japanese threadfin bream) surimi. Surimi gel with varying concentrations of BPF (0-5%) was prepared using trial and error method and named as S1 (0%), S2 (1%), S3 (2.5%), and S4 (5%). Results indicated that S4 significantly improved ($p < 0.05$) gel strength, water-holding capacity, and sensory acceptability of the gel, although it caused a slight reduction in whiteness. The incorporation of 5% BPF (S4) was found to be optimal for enhancing the dietary fibre content without compromising the quality of the surimi gel. The total dietary fibre content of S4 was 2.52 ± 0.06%. Addition of BPF also significantly improved the thermal stability of surimi gel, as evidenced by an increase in the first endothermic peak temperature from 33.67 °C in S1 to 50.71 °C in S4 in Differential Scanning Calorimetry (DSC) analysis. Thermal stability analysis and structural characterisation were performed to compare the differences between S1 and S4. Scanning electron microscopy revealed a denser, more heterogeneous structure in S4 than in S1. Addition of BPF modified the surimi microstructure by promoting protein–fibre interactions, resulting in a more integrated network that enhances gel strength and water-holding capacity. Fourier transform infrared spectroscopy (FTIR) results confirm that BPF incorporation does not disrupt the fundamental protein structure but rather promotes intermolecular interactions, thereby improving gel network stability and functional properties. Overall, this study demonstrates that banana pseudostem flour, a valuable secondary raw material, can be effectively utilised at an optimal level of 5% to enhance the functional properties of surimi gel.

Keywords: Threadfin bream, surimi gel, banana pseudostem flour, myofibrillar protein, fibre incorporated surimi, gel strength

Introduction

Nemipterus japonicus, commonly known as threadfin bream, is the most dominant and commercially important fish species used for surimi production (Gao et al., 2024). The threadfin bream fishery accounts for nearly 5% of the total marine harvest in India (Manojkumar, Pavithran, & Ramachandran, 2015). This species is considered as premium tropical fish to prepare surimi since the white meat, low fat and year-round availability make them an essential raw material in production (Park & Lin, 2005). Surimi is the refined form of minced meat, obtained from farmed or wild-captured finfish, shellfish, poultry, and red meat produced through several washing and dewatering processes. Surimi is not consumed directly; instead, it is used as raw material for the preparation of various surimi-based products. Therefore, surimi gel act as the foundation material that determine the texture, quality and acceptability of surimi-based products. Surimi-

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based products become popular as the demand for clean-label food rises. The low-fat and high-protein content of surimi serves as an excellent raw material for producing value added foods such as fish cakes, sausages, nuggets and analogue products. Natural additives act as a promising alternative to improve the structural characteristics of surimi gel by modifying or improving protein conformational transformation (Yang et al., 2025).

In response to the global demand for quality surimi and surimi-based products, the search has begun for novel ingredients, which provide desirable physiological properties. Debusca, Tahergorabi, Beamer, Matak, and Jaczynski (2014) reported that the textural properties of surimi were improved by fortification of long chain powdered cellulose as a dietary fibre source and observed that fibre incorporation up to 6% enhanced the physicochemical properties of surimi. Sánchez-González, Rodríguez-Casado, Careche, and Carmona (2009) complemented that wheat fibre induced structural changes to surimi proteins during gelation by modifying protein-water and protein-fibre interactions which lead to stronger gel formation, improved texture and overall stability. Dietary fibres are known for their health benefits. According to the ICMR Guidelines for Management of Type 2 Diabetes (ICMR, 2018), a daily dietary fibre intake of 40 g is recommended for the general population. Adequate dietary fibre intake helps improve digestive health, support weight management, and reduce the risk of chronic diseases and inflammation. Recent research by Lin et al. (2019) showed that insoluble dietary fibre can reduce cooking loss and improve the physicochemical and textural properties of surimi. In contrast, soluble fibres impart antioxidative activity to surimi. They stated that dietary fibre can be used as an ideal additive to lower glucose uptake, reduce low-density lipoprotein, promote stool bulking, and decrease the calorific value of surimi. Nie, Xue, Xiong, Yin, and Huang (2024) stated that the addition of soluble and insoluble fibres improves the gelation properties of surimi and reduces the fishy odour through the adsorption of volatile compounds, offering a more effective approach than conventional methods involving antioxidants and adsorbents. A stronger gel matrix also helps trap volatile compounds and prevent the release of odorous compounds during the heating phase (gelation).

Banana pseudostem (BP), an underutilised agricultural raw material, is thrown away as waste after harvesting the banana along with the remaining parts, such as the inflorescence, peel, and leaves. Limited studies are available on the use of banana pseudostem flour, a fibre-rich agro-industrial waste, in heat-induced surimi gel. Previous studies mainly focused on the effects of extracted dietary fibres rather than on the direct addition of agro-industrial waste, such as BP, on techno-functional properties such as gel strength, thermal stability, and the microstructure of surimi gel. Hence, identifying the optimal level of BPF incorporation and understanding its effects on the functional and structural properties of surimi gel remain gaps. Judicious utilisation of such secondary raw materials to develop value-added products will lead to minimal waste and maximum revenue. The earliest report on the potential of banana pseudostem as a functional food ingredient was presented by Aziz et al. (2011), who suggested that its high dietary fibre and polyphenol content make it suitable for functional food development. Later, Zou, Tan, Zhang, Wu, and Shang (2022) further highlighted the potential of BP as a functional food ingredient by emphasising its role in supporting gastrointestinal health, metabolic functions and weight management. Our previous study indicated that banana pseudo-stem flour can be used to improve textural and nutritional properties of surimi nuggets (Edathiruthikkaran, Joseph, George, Prakasan, & Ninan, 2025). Still, limited information is available on its effects on surimi gel. There is a paucity of studies investigating the potential effects of banana pseudostem flour (BPF) on the physicochemical properties of surimi gel. So, the present study explores the potential of BPF as a source of dietary fibre for the development of a fibre-incorporated surimi gel to improve its nutritional, functional, and sensory properties.

Materials and Methods

N. japonicus A grade commercial surimi block with a moisture content of 78 ± 2% and gel strength above 500 g cm was purchased from Shree Ulka LLP, Mangalore, Karnataka, India and stored in frozen condition (-18 ± 2 !) until further use—BP of *Musa acuminata* cv. Palayamkodan was collected after the harvesting of bananas from local farmers of Kottayam district, Kerala, India. The material was washed, shredded, and dried in a cabinet tray dryer at 50 ± 5 !. The dried sample was pulverised using a mixer grinder and passed through a 250 μm sieve to obtain a uniform particle size of 250 microns and packed in polyester-polyethene laminated pouches and stored at ambient temperature (27 ± 2 !).

The partially thawed 2 kg surimi block was chopped with 2.5% (w/w) salt for 2 min using a silent cutter (D-72175 Dortmund, Germany) maintained at 10 ± 2 ºC. The surimi paste was prepared with different concentrations of BPF (S1 (0%), S2 (1%), S3 (2.5%) and S4 (5%) (w/w)). BPF was manually added and mixed for another 2 min in a silent cutter to ensure uniform incorporation. Incorporating BPF reduced the overall protein content, as the total product mass increased with the addition of BPF to the surimi base. The surimi pastes were stuffed into a cellulose casing of 2.5 cm diameter using a hydraulic sausage stuffer (IS V25 IDRA VER., Sirman, Italy) and sealed. The surimi paste was pre-incubated at 40 °C for 30 min and then heat-set at 90 ! for 20 min to form surimi gel. The gel thus obtained was immediately cooled in ice-cold water, maintained at 4 ± 2 ! for 10 h, and further analyses were carried out within 10-16 h (Buda et al., 2021).

Proximate analysis of surimi gel prepared by incorporating different concentrations of BPF (0, 1, 2.5, and 5%) (n=3) was performed using the AOAC method (AOAC International, 2019). The moisture content of the sample was determined using the hot-air oven method. The samples were kept in the hot-air oven (Rivotek, Riviera Glass Pvt. Ltd., Chennai, India) at 101 ± 2 ! for 18 hours, and the total moisture loss was calculated. The crude protein content was expressed as a percentage of nitrogen and measured by the Micro Kjeldahl method. The nitrogen content was multiplied by a factor of 6.25 to obtain the protein percentage and expressed as g/100 g. The fat content was determined using the Soxhlet apparatus with petroleum ether (boiling point 50-70 !) as the solvent. The ash content was determined by incinerating the sample in a silica crucible at 525 ± 5 ! for 6 h in a muffle furnace. Total carbohydrates were estimated using the Anthrone method. The dietary fibre content was evaluated using the enzymatic gravimetric method (AOAC 991.43). Human digestion was simulated by incubating the sample with pancreatic á-amylase and amyloglucosidase for 16 hours at 37 °C in a shaking water bath. The reaction is then stopped by adjusting the pH and heating, and any protein present is digested with a protease. High molecular weight dietary fibre is isolated by ethanol precipitation, washed with ethanol and acetone, dried, weighed, and corrected for protein and ash content.

The surimi gel was equilibrated to room temperature, and colour properties were analysed using a Hunter Lab colour analyser (ColorFlex-EZ, s/n CFEZ 0257, Reston, Virginia). Further, the whiteness value was calculated from L* (lightness), a* (redness), and b* (yellowness), as described by Petcharat and Benjakul (2018).

Whiteness value= L*-3b*

The protocol described by Buda et al. (2021) was used to estimate the water-holding capacity of the surimi gel. Approximately 3 g of the sample was weighed using a weighing balance with 0.0001 g readability and accuracy. The sample was placed in a double-layer qualitative filter paper (non-wet-strengthened, 601 equivalents to Grade 1) obtained from HiMedia Laboratories Pvt. Ltd., Nashik, India. It was then transferred into pre-weighed 50 mL plastic centrifuge tubes. The samples were then centrifuged at 5000 × g in a refrigerated centrifuge maintained at 4 ! (Thermo-Fisher Scientific, Waltham, MA, USA) for 15 min. After centrifugation, the samples (n = 3) were removed and weighed.

WHC = (Final weight of surimi gel ×100)/ Initial weight of surimi gel

The gel strength was measured from breaking force and deformation and evaluated by using the TA XT Plus Texture Analyzer (Lloyd Instruments Ltd, Hampshire, UK) with a spherical plunger probe of 5 mm diameter; crosshead speed of 60 mm/min and 40% compression. For the analysis, thawed surimi gel (25 ± 2 !) was cut manually into a cylinder (2.5 cm × 2.5 cm). The elasticity/deformability was analysed by noting the force applied to break the gel and the distance travelled by the probe to trigger the breakage (Mi et al., 2021).

The transformation of *N. japonicus* surimi paste into gel at the optimal concentration of BPF was evaluated using Differential Scanning Calorimetry (DSC) (TA Instruments DSC 25, USA). For the analysis, 10–15 mg of surimi gel was placed in a DSC pan, while an empty pan was used as a reference. The samples were scanned from 0 °C to 90 °C at a heating rate of 10 °C min{ ¹. The melting temperature and enthalpy were recorded using TRIOS software (Debusca et al., 2014).

Scanning Electron Microscopy (SEM) is used for microstructure analysis. For that, a 10 to 15 mg freeze-dried sample was taken and smeared into a brass stub containing adhesive carbon tape and plated with gold JFC 1600 using an ion sputtering device. Scanning was performed at 20 kV accelerating voltage and magnification of 500x, 1500x, and 3000x (JEOL, JSM-6390LV, Tokyo, Japan) (Lin et al., 2019).

Fourier Transform Infrared Spectroscopy (FTIR) measures the infrared radiation emitted by molecules, primarily due to changes in dipole moments. The finely powdered 2 mg sample was loaded directly into a diamond crystal in an ATR attachment sample holder, and the spectra were observed over 4000 to 400 cm{ ^{1} on a Thermo Nicolet iS50. A total of 64 scans were recorded with a resolution of 0.2 cm{ ^{1} (Yin et al., 2019). The spectrum was collected after correcting the atmospheric noise using software.

The surimi gel was sliced into pieces having a 1 cm thickness, microwaved for 30 seconds, and samples were coded randomly. The samples were served on white paper plates, and 20 semi-trained panellists (aged between 20 and 45) were asked to evaluate them for colour, odour, texture, taste, and overall acceptability using a 9-point hedonic scale (Buamard & Benjakul, 2015).

Experimental data obtained from all analyses were expressed as mean ± standard deviation. One-way analysis of variance (ANOVA) was performed to compare the means of different samples/treatments for proximate composition and physical properties of surimi gel using SAS 9.3 (SAS Institute Inc., Cary, NC, USA). Differences among means were evaluated using Tukey's test at a 5% level of significance. Sensory parameters of the different samples/treatments were analysed using the Kruskal–Wallis test, and pairwise comparisons were conducted at the 5% significance level in SPSS 22.

Results and Discussion

Proximate composition was analysed to check the basic nutritional profile of surimi gel. Generally, surimi contains high levels of moisture and protein and low levels of fat and ash. In this study, the effect of BPF on the proximate composition of surimi gel was analysed as given in Table 1. There was a significant difference in the moisture content of the surimi gel between samples with and without BPF. Still, the difference was noticeable only after adding 2.5% BPF, even though a slight decrease in moisture content was observed in surimi with 1% BPF added. This might be due to the redistribution of immobilised water following BPF incorporation, as BPF competes with proteins for available water during heat setting of surimi gel, resulting in a significant difference in moisture content. However, at lower inclusion levels, the amount was insufficient to cause a statistically significant difference. Alakhrash, Anyanwu, and Tahergorabi (2016) stated that moisture reduction was common in dietary fibre-incorporated surimi gel and was due to moisture uptake by the fibre during surimi gel processing. The protein content of the surimi gel was found to decrease significantly with increasing BPF levels. The percentage decrease in protein in the BPF-incorporated surimi was due to the increased carbohydrate content. Ma (2015) reported the protein content of BPF of *Musa balbisiana* and *Musa acuminata* as 3.2% and 6%, respectively. The protein dilution effect of fibre incorporated surimi gel was previously reported by Sánchez-Alonso, Solas, and Borderías (2007). They observed a slight decrease in the protein content from 12.7% to 8.9% when the fibre concentration increased from 0 to 6% in giant squid surimi gel. Hence, the reduction in protein content with increasing fibre concentration in surimi gel is consistent with previous studies.

Table 1. Proximate composition of surimi gel incorporated with different concentrations of BPF

Sample	Moisture (%)	Protein (%)	Carbohydrates (%)	Fat (%)	Ash (%)	Total dietary fibre (%)
S1	80.01±0.73^a	15.62±0.33^a	3.10±0.25^c	0.17±0.03^d	0.42±0.03^c	0.00±0.00^b
S2	79.57±0.44^a	15.03±0.15^a	3.65±0.11^c	0.34±0.05^c	0.54±0.07^c	0.56±0.01^b
S3	78.34±0.20^{ab}	13.51±0.07^b	5.47±0.38^b	0.86±0.04^b	0.70±0.02^b	1.83±0.03^a
S4	77.07±0.07^b	11.01±0.11^c	7.36±0.51^a	1.13±0.01^a	0.89±0.03^a	2.52±0.06^a

Results are expressed as mean ± standard deviation, where S1 (0%), S2 (1%), S3 (2.5%), and S4 (5%) represent surimi gel with varying concentrations of BPF (0-5%). Different superscripts within the same column indicate significant differences at $p \leq 0.05$.

Surimi is known for its low-fat content. Typically, the fat content of surimi is less than 1% on a wet-weight basis (Wijayanti, Singh, Benjakul, & Sookchoo, 2021). In our study, the addition of BPF resulted in increased fat content. This might be due to the presence of pigments, waxes, oils and fatty acids in BPF extracted during solvent extraction. The presence of fat in the tender core of BPF was previously reported by Aziz et al. (2011), and suggested that it may contribute to the functional properties of BP. The ash content of the control (S1) was 0.42 ± 0.03% and increased with increasing BPF levels. Ho, Aziah, and Bhat (2012) stated that the presence of minerals contained in the BPF, such as sodium (Na), potassium (K), calcium (Ca), magnesium (Mg), phosphorus (P), iron (Fe), zinc (Zn) and manganese (Mn), contributes to ash content. Incorporation of BPF into surimi increased the ash content in S2, S3, and S4 by 28.57%, 66.67%, and 111.90%, respectively, compared with the control. Similarly, Carballo et al. (2021) reported that the addition of 4.5 g/kg banana pseudostem powder in minced pork resulted in a 28.8% increase in ash content, of which potassium contributes 22.1% of the total mineral content. The significant increase in ash content suggests that higher BPF incorporation levels can be attributed to a rich mineral composition, confirming its role as a natural source of essential minerals. Majumder, Chowdhury, Dora, Nath, and Mondol (2017) stated that the carbohydrate content of surimi was primarily contributed by the cryoprotectant used during production. Ma (2015) stated that the major constituent of BPF was carbohydrate, ranging from 62.7% to 68%. Hence, the addition of BPF to surimi gel also increased the total carbohydrate content.

The banana pseudostem is primarily composed of cellulose, hemicellulose, and lignin, which contribute to its dietary fibre content. The structural complexity of these components confers notable functional and nutritional properties in surimi gel. The total dietary fibre content (TDF) of surimi gel incorporated with BPF at varying concentrations (S1, S2, S3, and S4, w/w) was evaluated, and the results are shown in Table 1. The TDF content of surimi gel increased proportionally with increasing BPF concentration, indicating that BPF contributed to the dietary fibre content of surimi gel. Similar findings have been reported by Cardoso, Mendes, Vaz-Pires, and Nunes (2009) in fibre-incorporated mackerel surimi gel, where the addition of inner pea fibre and chicory root inulin significantly improved the fibre profile and carbohydrate content of the final product. BPF generally contains 21-46.5% TDF, depending on the banana variety and processing methods. For example, Carballo et al. (2021) reported 46.5 g/100 g TDF in commercial banana pseudostem powder. Bhaskar, Mahadevamma, Chilkunda, and Salimath (2011) reported that *Musa* sp. var. elakki bavle pseudostem contained 28.8 g/100 g dietary fibre. Ma (2015) reported that *Musa balbisiana* and *Musa acuminata* contain TDF levels of nearly 21.5 g/100 g and 14.5 g/100 g, respectively. The TDF content varied among *Musa* sp. However, the presence of TDF highlighted BPF's potential as a valuable dietary fibre source for the development of functional foods. Nevertheless, further incorporation of BPF was not attempted, as higher inclusion levels might adversely influence the sensory attributes, texture, and overall acceptability of the surimi. Studies conducted by Debusca et al. (2014)

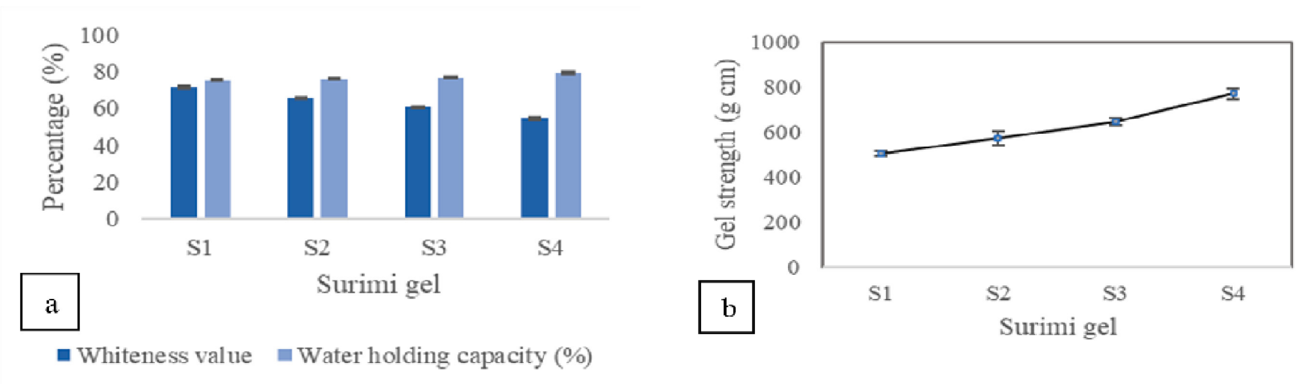

Fig. 1. Physicochemical properties (a) whiteness value and water holding capacity (%) (b) gel strength) of surimi gel incorporated with different concentrations of BPF. S1-Surimi gel without BPF, S2- surimi gel with 1% BPF, S3- surimi gel with 2.5% BPF, S4- surimi gel with 5% BPF.

also reported that adding fibre up to 6 g/100 g improves the physicochemical properties of surimi gel, whereas higher concentrations adversely affect quality. Our study indicated that incorporating up to 5% BPF is optimal for enhancing dietary fibre content without compromising surimi gel quality. Therefore, the incorporation of BPF can be considered an effective strategy to improve the product's dietary fibre content.

Evaluating the physicochemical properties of surimi is essential to ensure its gel-forming ability, texture, colour, and stability, which directly determine product quality, shelf life, and consumer acceptability. It also helps to optimise processing conditions and maintain consistency in value-added products.

The whiteness value of surimi is considered as a grading criterion to assess the quality of surimi, and it is calculated from the L*a*b* value. Fig. 1a summarises the significant difference ($p < 0.05$) in the whiteness value of the control and the BPF-incorporated surimi gel. Higher lightness (L*) value and lower yellowness (b*) value are the characteristics of surimi (Hsu & Chiang, 2002). However, addition of BPF to surimi resulted in a decrease in the L* value and an increase in the b* value, as the BPF-incorporated samples exhibited a slight brown colour compared to the control. Zhu et al. (2023) reported that the reduction in whiteness value might be due to the interaction of the amino groups in the protein with polysaccharides to form melanin-like substances, resulting in a darker colour of surimi gel. The presence of the enzyme polyphenol oxidase (PPO) in BPF also contributed to the darker colouration of surimi gel (Chandrakala, Gundev, & Singh, 2017). Buda et al. (2021) observed that the fibres influence the whiteness value of surimi. Some fibres were found to decrease the whiteness value, whereas others improved both the whiteness and texture properties of surimi.

The WHC of the myofibrillar protein gel was determined based on the ability of the protein to hold water in its three-dimensional network. There was a significant increase in the WHC of S4 compared to that of S3, S2 and S1 (Fig. 1a). The WHC increased from 75.39% to 79.45% in surimi gel incorporated with 5% BPF. This increase may be attributed to the water-retention properties of the dietary fibre present in the flour, which enhances the WHC of the surimi gel. These findings complement the results of Singh, Benjakul, Prodpran, and Nuthong (2021), who reported that incorporating 1% psyllium husk powder into threadfin bream surimi had improved the moisture content. Compared to other flours, BPF exhibits a higher water-holding capacity (WHC), typically ranging from 9.0 to 11.0 g water per g of dry matter, with no significant differences observed among its varieties (Ma, 2015). The increase in water-holding capacity (WHC) is associated with an increase in fibre content or fibre components present in BPF, which enhance moisture retention within the surimi gel matrix.

Gel strength indicates the aggregation ability of proteins, and it was determined from the breaking force and breaking deformation. Upon addition of 1% BPF, the gel strength significantly increased by 13.81% (505.29 to 575.08 g cm). Furthermore, incorporation of 5% BPF markedly improved the gel strength of surimi by 52.57%, reaching 770.97 g cm as shown in Fig 1b. According to Chen et al. (2020), the increase in gel strength indicates that there is no interruption of hydrocolloids in the cross-linking of surimi protein during gelation. Likewise, Huang et al. (2021) reported that a 1% increase in the concentration of inulin improved the gel strength of silver carp surimi by 7.7%, which might be due to the presence of the hydroxyl group and the cross-linking effect of the protein-polysaccharide molecule. It is interesting that the addition of polysaccharides into the protein matrix promotes gelation process by acting either as a filler or as a crosslinker of hydrogen and hydrophobic bonds (Buda et al., 2021). This demonstrates the potential of fibre to optimise surimi quality through protein-polysaccharide cross-linking.

Differential Scanning Calorimetry (DSC), Scanning Electron Microscopy (SEM), and Fourier Transform Infrared Spectroscopy (FTIR) analyses were performed only for S1 and S4. S4 was selected as it showed the best overall functional and textural properties among all treatments, indicating it as the optimised concentration of BPF incorporation. S1 was used as the control for comparison to clearly evaluate the structural and thermal changes induced by BPF addition.

Differential Scanning Calorimetry (DSC) is a useful tool for evaluating the thermal properties of products, such as thermal stability, enthalpy, and heat capacity. DSC detects 2 distinct endothermic peaks upon heating of surimi paste (Debusca et al.,

Table 2. Endothermic peak values of surimi gels incorporated with different concentrations of BPF

Sample	Peak I		Peak II		Peak III	
	Peak temperature (ºC)	Enthalpy (J/g)	Peak temperature (ºC)	Enthalpy (J/g)	Peak temperature (ºC)	Enthalpy (J/g)
S1	33.67	0.017	51.60	0.204	66.71	0.019
S4	50.71	0.223	68.32	0.045	84.66	0.065

S1 (0%) represents surimi gel without BPF and S4 (5%) represents surimi gel with BPF

2014). The 1st peak observed between 32 °C and 65 °C consisted of several overlapping peaks resulting from the thermal denaturation of the different myosin domains (Herrera, Pastoriza, & Sampedro, 2001), while the 2nd peak observed between 40 °C and 85 °C can be attributed to the denaturation of actin (Moosavi Nasab, Alli, Ismail, & Ngadi, 2005). However, Esturk and Park (2014) reported 3 distinct endothermic peaks in threadfin bream surimi, where the 1st peak represents the unfolding of light meromyosin (LMM) and heavy meromyosin (HMM) chains, the 2nd peak corresponds to myosin aggregation, and the 3rd peak is associated with denaturation of actin.

In the present study, three distinct endothermic peaks were observed, which are consistent with the findings of Esturk and Park (2014). The first endothermic peak was recorded at 33.67 ! for S1, whereas it shifted to 50.71 ! in S4 (Table 2). The significant upward shift in peak temperature indicates that higher thermal energy was required for protein denaturation, suggesting improved thermal stability of surimi protein after BPF incorporation. Similar increase was observed in the second and third peaks, further confirming the stabilising effect of BPF on the myofibrillar protein system.

The increase in enthalpy (“H) values, particularly for Peak I in S4, further indicates stronger protein–matrix interactions and enhanced structural integrity, possibly due to BPF’s water-binding capacity and network-forming ability. However, the variation in enthalpy observed for Peak II suggests partial structural rearrangements in actin fibres or changes in protein availability for denaturation. The process of surimi gelation relies on the heat-induced irreversible denaturation of proteins or the protein endothermic transition, and such shifts indicate modifications in the gel network. The study conducted by Debusca et al. (2014) on the interaction of surimi with fibre confirmed that long-chain fibre can bind with water molecules without interfering with the thermal transition/denaturation of surimi protein, and the present findings further support that BPF enhances thermal stability while maintaining the fundamental denaturation behaviour of surimi proteins.

The surface morphology of BPF, control surimi gel without BPF (S1), and surimi gel with 5% BPF (S4) was analysed using SEM (Fig 2). Fig. 2A depicts the morphology of BPF, which shows a smooth, intact, and continuous fibre structure without significant surface deposition. The control surimi gel, S1, in Fig. 2B, exhibits an irregular, flaky gel network with several pores, indicating a less compact structure. However, Fig 2C indicates the modification of surimi after the addition of BPF. The fibre particles were completely covered by surimi gel, the aggre-

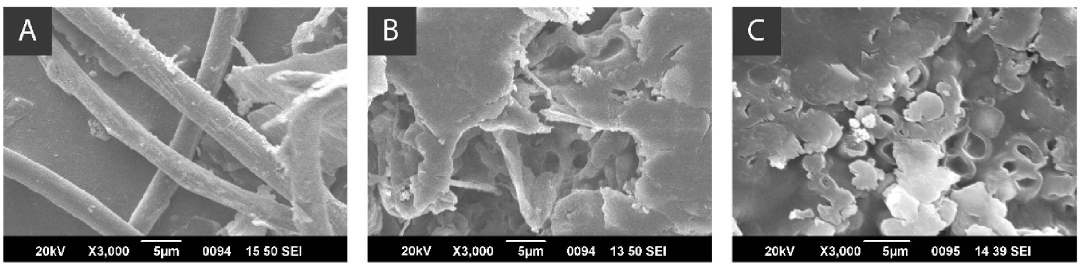

Fig. 2. Surface morphology of BPF, control surimi gel without BPF (S1), and surimi gel 5% BPF (S4)

gated particles and spherical shapes with several voids indicate the protein-fibre interaction and mechanism behind improving gel strength and water holding capacity of surimi gel. These voids have the capability of modifying the physicochemical properties, like water holding capacity and oil absorption capacity or textural properties of the surimi gel (Lin et al., 2019). With the increase in the concentration of BPF, an increase in small, ellipsoidal objects was noticed on the surface of the fracture plane. Zhuang et al. (2019) mentioned that the white areas in the binary images obtained from SEM graphs depict aggregation of protein, and black areas represented the water channels, holes and cavities. The distinctive structural transformation among samples might be responsible for the physicochemical and structural properties, such as water holding capacity and gel strength of fibre incorporated surimi (Lin et al., 2019). This indicates that the SEM image obtained for the surimi gel aligns with the previously reported works.

FTIR is an absorption spectroscopy and is used to characterise the structural and functional groups at the molecular level. FTIR spectra of BPF, control surimi gel (S1) and surimi gel incorporated with 5% BPF (S4) are shown in Fig 3. The BPF exhibited characteristic absorption frequencies at 558 to 817 (multiple absorption peaks), 1030, 1300, 1590, 1740, 3310 cm^{-1}, corresponding to O-H out-of-plane bending, C-H deformation, C-H in-plane bending, aromatic ring stretching, HC=O, and OH, respectively. S1 showed absorption bands at 870, 1050, 1240, 1390, 1440, 1520, 1620, 3040, and 3290 cm-1, corresponding to C-O, C-O, aromatic C-O, aromatic ring structure, conjugated C=C, vinyl C-H, and OH, respectively. Similarly, S4 exhibited two specific OH absorption peaks at 690 and 768 cm-1, rather than multiple absorptions in the BPF. The absorption related to CH in-plane bend was shifted from 1300

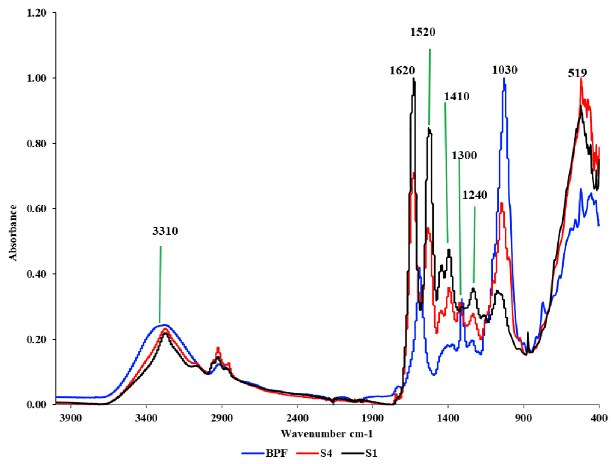

Fig. 3. The FTIR spectra of BPF, control surimi gel (S1) and surimi gel incorporated with 5% BPF (S4)

cm^{-1} to 1320 cm^{-1} of BPF in S4. Aromatic ring structure and conjugated C=C in surimi gel with BPF were shifted to 1540 and 1630 cm^{-1}, respectively. The wide OH stretching vibration in the 3300 cm^{-1} became sharper in S4, along with significant shifts in the C-H vibrations associated with CH_2 and CH_3. The absorption peak between 3200-3300 cm^{-1} has been associated with the á-helix structure of proteins (Fan et al., 2017). A narrow peak with shoulders in the range of 3000-2900 cm^{-1} was observed in all the combinations and was attributed to the C–H stretching vibration of CH_2 groups (Diarsa & Gupte, 2021). This might be due to protein-polysaccharide interaction. The results clearly indicated that the OH functional groups of BPF interacted significantly with the aromatic system in the surimi, as reflected simultaneously in the OH and aromatic stretching vibrations. The aromatic skeletal ring structure vibrations at 1590 cm^{-1}, probably from lignin part, underwent a significant shift in the composite, and

Table 3. Sensory analysis of surimi gel with different concentrations of BPF

	Appearance	Flavour	Taste	Texture	OAA
S1	8.45±0.48^{a}	7.50±0.54^{c}	7.25±0.47^{c}	7.20±0.36^{c}	7.65±0.50^{b}
S2	8.10±0.39^{ab}	7.65±0.41^{bc}	7.75±0.42^{bc}	7.65±0.33^{bc}	7.75±0.26^{a}
S3	7.90±0.39^{ab}	8.25±0.26^{ab}	8.10±0.39^{ab}	8.00±0.33^{ab}	8.05±0.28^{a}
S4	7.75±0.54^{b}	8.50±0.33^{a}	8.50±0.47^{a}	8.50±0.40^{a}	8.30±0.22^{a}

Results are expressed as mean ± standard deviation. Different superscripts within the same column indicate significant differences at $p \leq 0.05$. S1 (0%), S2 (1%), S3 (2.5%), and S4 (5%) represent the surimi gel with varying concentrations of BPF ranging from 0-5%.

this was evident from the comparison of peaks at 1620 and 1520 cm^{-1} (Lin et al., 2019). The ratio of intensities of 1620/1520 in surimi gel and surimi gel with BPF, respectively, was 1.17 and 1.27, indicating that aromatic rings from BPF contributed to the formation of surimi gel with BPF composite. These results clearly established that the BPF successfully interacted with surimi gel through O-H and aromatic ring structure, either through hydrogen bonding or ð-ð interaction.

The sensory acceptability score showed a significant difference between surimi gel with and without BPF, as shown in Table 4. It was found that the degree of acceptance increased with the addition of BPF. However, the addition of BPF reduced the colour similarity of the surimi gel but improved its taste and textural properties compared with the control sample. Nevertheless, surimi gel incorporated with 5% BPF was found to be acceptable to the majority of panellists, as it masked the surimi's sweetness and fishy odour. Despite a slight reduction in whiteness, Buamard and Benjakul (2015) reported that adding 0.15% coconut husk extract improved the likeness score of sardine surimi gel. In contrast, Sánchez-Alonso et al. (2007) reported that the addition of approximately 6% wheat fibre had no detrimental effect on the appearance of squid surimi gel. However, it affected the surimi gel's taste and texture.

The incorporation of BPF as a dietary fibre source significantly enhanced the textural, sensory, and nutritional properties of surimi gel. Overall, the addition of BPF helped to improve the integrity of the gel by improving its water-holding capacity. Among the concentrations evaluated, the 5 % BPF level exhibited the most desirable overall properties. Therefore, inclusion of BPF at this level is recommended as a functional ingredient for the large-scale production of surimi-based products, contributing to both functional and nutritional benefits.

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