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Influence of High Protein on the Rheological Properties, Microstructure and X- Ray Diffraction of Crackers Formulations

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Abstract

Crackers are a baked product known for their crisp, dry texture and long shelf life, typically made from wheat flour, water, salt, and various flavoring agents. In recent years, there has been a growing demand for high-protein snacks. This study evaluated the functionality of high-protein composite mixes in cracker formulations using pea protein isolate, soy protein isolate, and a combination of whey protein isolate with skim milk powder. The study analyzes the effects of these protein blends on dough properties, cracker structure, and sensory attributes. Farinograph analysis showed that the pea protein isolate blend had a longer stability time, indicating a higher rate of dough breakdown. The dough development times (DDT) for the control (wheat flour), pea protein, and soy protein blends were similar, at 1.8, 1.5, and 1.9 minutes, respectively, while the whey protein + skim milk powder blend had significantly longer DDT of 16.8 minutes. Scanning electron microscopy (SEM) results revealed that the control crackers had a porous, uneven structure, while all protein-enriched samples had fewer pores and a more compact, smooth appearance. X-ray diffraction showed a slight reduction in crystallinity in protein-enriched crackers compared to the control. Sensory evaluation indicated that the crackers made with composite flour mixes were well-accepted, with panelists particularly favoring the control (scoring 9.5 out of 10) and pea protein isolate blend (scoring 8.5 out of 10) for their superior mouthfeel, color, and texture compared to those made with soy protein isolate or whey protein isolate. This research highlights the potential of incorporating plant-based proteins like pea and soy into cracker formulations as a valuable alternative.

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Abbreviations
DDT: Dough Development Time
SEM: Scanning electron microscopy
USD: United States Dollar
SPI: Soy proteins isolate
PPI: Pea protein isolate
WPI: Whey protein isolate
CCFM: Cracker combination formulation
XRD: X-ray diffraction

Introduction

Baked goods such as crackers are light, handy and popular and are widespread around the world.[1] According to estimates, the worldwide market for crackers is valued at around USD 22.61 billion in 2023.[2, 3] Crackers are mostly known to be dry, thin, and crispy product made from Refined Wheat flour. Functional crackers have been increasingly popular among health-conscious consumers.[4] Crackers provide a quick and delicious method to enhance protein consumption while also supplying vital elements. Incorporating protein into snacks can help stabilize blood sugar levels, giving consistent energy and minimizing the risk of sudden increases and decreases in blood sugar, for individuals with diabetes, balancing carbohydrate intake from supplementing with protein.[5] Protein slows the absorption of carbohydrates, which helps prevent rapid spikes and crashes in blood sugar levels.

Protein is an essential element of a child's diet, serving a pivotal function in the process of growth, development, and general well-being.[3] Proteins are crucial polymers that contribute to the texture and nutritional values of crackers.[6] Protein-enriched crackers that are functional have great significance for youngsters and persons with lifestyle diseases such as Diabetes.[7] As per earlier studies, commercial biscuits and crackers typically contain around 7-8% protein, which is low and does not meet the nutritional needs of individuals looking to increase their protein intake.[8] The inclusion of plant-based protein products in wheat-based baked items has the potential to improve the viscoelastic properties of the dough. Research on the development of functional crackers has explored the use of wholegrain buckwheat, mucilage fortification, and germinated lentil extracts.[9, 10, 11]

Protein malnutrition is a significant public health issue, particularly affecting vulnerable populations, including children and the elderly.[12, 13] These high-quality protein sources are easily digestible and have been shown to support muscle synthesis and overall health.[14] Furthermore, the functional benefits of protein isolates can improve the textural properties of baked goods, ensuring consumer acceptance without sacrificing taste.[15] Incorporating soy protein isolate increased the protein content of crackers from approximately 8% to about 14%, with baking conducted at 180°C for 15 minutes.[16] Adding up to 30% chickpea flour and 10% pea protein resulted in protein content ranging from 10% to 12%, baked at 200°C for 10–15 minutes.[17] Researchers have reported that protein-enriched crackers contained about 12–15% protein due to the inclusion of lentil flour and whey protein, with a baking time of 12–15 minutes at 180°C.[18] Additionally, various baking times from 10 to 20 minutes at 180°C to optimize texture, indicating that longer baking could enhance crunchiness but may reduce protein retention.[19] Based on these findings, the present study opted for a baking time of 10 to 12 minutes at 175°C to balance texture and protein retention.

This study addresses the growing consumer demand for nutritious, protein-rich, ready-to-eat foods by enhancing the nutritional profile of crackers. While traditional crackers are typically low in protein, previous research has shown the benefits of fortifying baked goods with both plant- and animal-based proteins.[20, 21] However, limited research exists on the use of composite flours—specifically Pea Protein Isolate, Soy Protein Isolate, Skim Milk Powder, and Whey Protein Isolate—in cracker formulations. This study aims to bridge this gap by developing protein-enriched crackers using these ingredients, while also evaluating the dough's rheological properties, addressing formulation challenges from high protein content, and assessing consumer acceptance through sensory analysis in comparison to a control.

Materials and Methods

Raw Materials

Wheat flour, sugar, invert syrup, and palm oil were sourced from local markets. Soy protein isolate (SPI) was obtained from Shiv Health Foods LLP, Kota, while pea protein isolate (PPI) was procured from Yantai Shuangta Food Co., Ltd., located in Shandong Province, China. Whey protein isolate (WPI) was acquired from Polmleksp, Poland.

Table 1: Composite flour mix - High Protein Crackers

Composite flour mix - High Protein Crackers				
Ingredients in Kgs	**CONTROL (Control)**	**CCFM 2**	**CCFM 3**	**CCFM 4**
Wheat flour	100	53.8	61.5	53.9
Pea isolate	-	46.2	-	-
Soy isolate	-	-	38.5	-
Skim Milk Powder	-	-	-	15.4
Whey protein isolate	-	-	-	30.7
Total	100	100	100	100

Cracker Combinations Preparation

The combinations prepared to make protein rich crackers along with control are provided in Table 1.

Rheological Properties

Farinograph studies were carried out according to standard AOAC methods.[22] The rheological parameters of all cracker formulations and Control were assessed utilizing the Brabender farinograph-E (Brabender OHG, Duisburg, Germany).

Proximate Analysis

Proximate analysis was conducted for the composite flour samples following standard procedures to determine the moisture, ash, fat, protein, carbohydrate, and dietary fiber content of the cracker samples. The moisture content was assessed according to AOAC Method 925.09 using the oven-drying method, where samples were weighed before and after drying at 105°C until a constant weight was achieved. Ash content was determined following AOAC Method 942.05, which involves incinerating the samples in a muffle furnace at 550°C to measure the inorganic residue. Fat content was extracted using the Soxhlet method as per AOAC Method 920.39, employing petroleum ether as the solvent, followed by evaporation of the solvent to obtain the fat content. Protein content was analyzed using the Kjeldahl method outlined in AOAC Method 981.10, which involves digesting the samples, followed by distillation and titration to quantify nitrogen content, subsequently converted to protein using a conversion factor of 6.25. Carbohydrates were calculated by difference using the formula: Carbohydrates = 100% - (Moisture + Ash + Fat + Protein). Dietary fiber content was determined following AOAC Method 991.43, utilizing the enzymatic-gravimetric method. All analyses were done in triplicate to confirm accuracy and consistency of the results.

Scanning Electron Microscopic (SEM) Studies

The structural morphology of the cracker composite formulations was studied using a scanning electron microscope (Hitachi S 3400 N, Japan) at the Research Lab, University with Potential for Excellence (UPE), University of Mysore, Karnataka, India. The microstructure of the samples was analyzed at five different magnifications, with a power level set at approximately 5 kV for sample analysis. The attained SEM images were further evaluated using ImageJ software to assess the size and structural characteristics of the crackers.

X-Ray Diffraction Analysis

The crystallographic structure of the cracker composite formulations was investigated using X-ray diffraction (XRD) analysis with a Rigaku Smartlab (Japan), available at the Research Lab, University with Potential for Excellence (UPE), University of Mysore, Karnataka, India. The analysis was conducted at a power level of 3 kV, with samples positioned in a rotating anode set to 60 A. The system utilized a HyPix-3000 high-energy resolution 2D HPAD detector. The resulting XRD curves were analyzed using Match software to determine the degree of crystallinity, as well as the 2θ and d values for all four samples.

Cracker Preparation Ingredients

The ingredients added to make protein rich crackers along with control are provided in Table 2. This combination resulted in 20 to 22% protein in the final cracker product. The cracker preparation is provided through flow diagram in Figure 1. The Schematic representation of making of crackers is also presented in Figure 2.

Table 2: Ingredient percentage per 100 g of cracker

Ingredients	Per 100 g of cracker			
	CCFM 1	CCFM 2	CCFM 3	CCFM 4
Refined Wheat flour	63.28	33.29	38.19	33.22
Pea protein Isolate	0.00	28.53	0.00	0.00
Soy protein isolate	0.00	0.00	23.87	0.00
Whey Protein isolate + Skim milk powder	0.00	0.00	0.00	28.48
Palm oil	11.20	10.94	10.98	10.92
Sugar	16.55	16.55	16.23	16.14

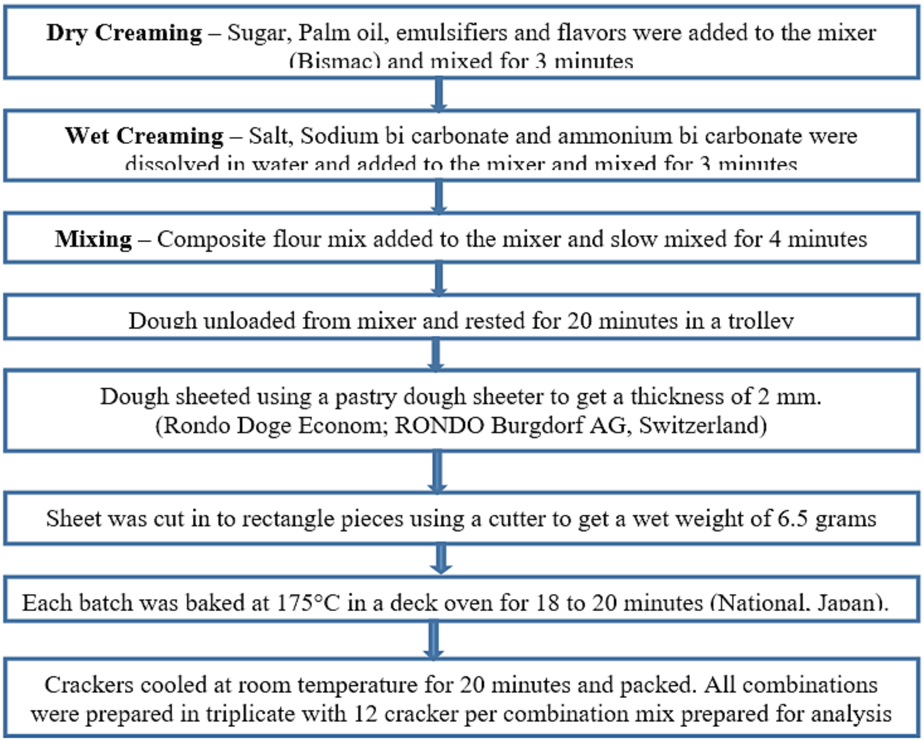

Fig.1: Flow diagram describing the crackers preparation

Sensory Evaluation

Descriptive sensory analyses with eighteen panelists were performed for the final products. Smaller group was chosen as trained experts provide more reliable and consistent results than a large group of untrained consumers. The hedonic evaluation of the crackers' sensory attributes which included appearance, aroma, taste, texture, and after taste and overall acceptability were done and mean values were noted. Informed consent was secured from all participants in the sensory evaluation, comprising both male and female individuals aged 25 to 56 years. They received thorough information about the study's objectives, methods, and any potential risks associated with their participation.

a)

b)

c)

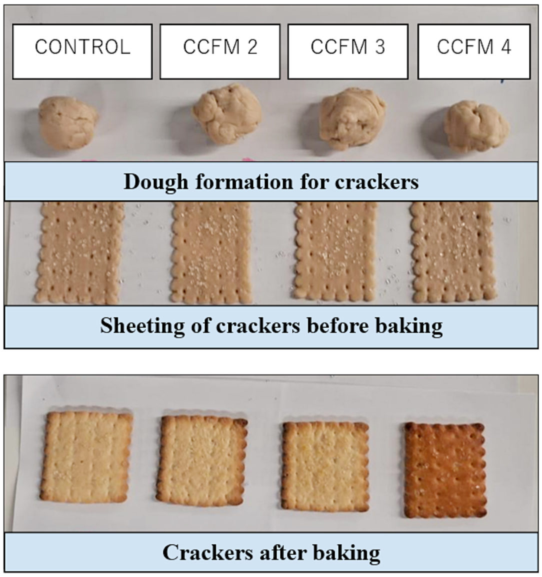

Fig.2: Schematic representation of making of crackers

Graphical Presentation

MS Excel software (version 2016) was used to draw graphs of sensory attributes

Results

Rheological Properties

Farinograph characteristics of cracker combinations are given in Table. 3. Water absorption of control and composite flour samples varied from 48.3 to 64.8%. Isolated pea protein cracker formulation (CCFM 2) exhibited the highest water absorption (64.8%) which is consistent with other research on pea protein. Composite flour with milk proteins (CCFM 4) had the lowest water absorption (48.3%) aligns with the properties of animal-based proteins. Milk proteins in dough formulations absorbed around 45-50% water, consistent with the water absorption of 48.3% for CCFM 4.

Table 3: Farinograph results of Cracker formulations

Parameter	CCFM1 (Control)	CCFM2	CCFM3	CCFM4
Consistency - Brabender units (BU)	495±6	590±4	690±6	655±6
Water Added	58±3	57±2	63±3	55±2
Water absorbed default consistency (%)	60±3	60.2±2	67±3	52±2
Water Absorbed for default moisture (%)	58±3	56.9±3	64.8±3	48.3±3
Development time (Minutes)	1.8±0.3	1.5±0.2	1.9±0.5	16.4±1
Stability (Minutes)	7.4±0.7	1.8±0.7	0.4±0.08	1±0.3
Time to break down (Minutes)	9.2±0.5	1.8±0.3	2.3±0.3	17.4±1

Note: The average of triplicates value is reported with ± Standard Deviation

Dough development time (DDT) of the samples CCFM 2 is lesser than that of control and CCFM 3 is similar to control. The DDT of the sample CCFM 4 (16.4 mins) is almost 9 times of the control sample (1.8 mins) which is having whey as a protein source. The stability time of the control sample is higher (7.4 mins) when compared with CCFM 2 (1.8 mins), CCFM 3 (0.4 mins) and CCFM 4 (1 min). CCFM 2 and 3 were having good dough stability whereas it was difficult to form dough from CCFM 4, compared with control. Post-hoc analysis using the Least Significant Difference (LSD) test revealed that CCFM3 had significantly higher consistency (690 BU) compared to CCFM1 (495 BU) and

CCFM2 (590 BU), while CCFM4 (655 BU) did not significantly differ from the control. Additionally, CCFM4 required a significantly longer development time (16.4 minutes) than CCFM2 (1.5 minutes) and CCFM3 (1.9 minutes). These differences indicate that ingredient composition notably affects the processing parameters of the cracker formulations.

Table 4: Proximate analysis (%) of Composite flour samples

Sample Code	Moisture	Ash	Fat	Protein	CHO	Dietary Fiber
CCFM1	12.9^{c}±0.9	0.65^{a}±0.2	4.3^{d}±0.9	9.6^{a}±0.9	73^{c}±3	3.1^{a}±0.5
CCFM2	8.1^{a}±0.3	1.8^{b}±0.4	1.2^{a}±0.3	51^{d}±2	39.5^{ab}±2	2.5^{a}±0.2
CCFM3	11.2^{b}±0.9	1.3^{b}±0.2	3^{c}±0.5	39.3^{b}±1	47^{b}±3	3.9^{b}±0.5
CCFM4	8.5^{a}±0.5	3.2^{c}±0.5	1.2^{b}±0.2	41^{c}±2	46.9^{b}±3	3.5^{ab}±0.5

Data stated are as-is basis and expressed as Average ±SD of three determinations

Averages of the same group charted by different alphabets are significantly different (p>0.05)

Proximate Analysis

The nutritional composition of the developed cracker samples is summarized in Table 4, highlighting variations in moisture, ash, fat, protein, carbohydrates, and dietary fiber contents.

Sample CCFM1 exhibited a moisture content of 12.9%, with a protein level of 9.6% and high carbohydrates at 73%. In contrast, CCFM2 displayed a significantly higher protein content of 51%, indicating its potential as a high-protein snack, albeit with lower moisture (8.1%) and fat (1.2%) levels. Samples CCFM3 and CCFM4 contained protein levels of 39.3% and 41%, respectively, along with substantial dietary fiber content of 3.9% and 3.5%.

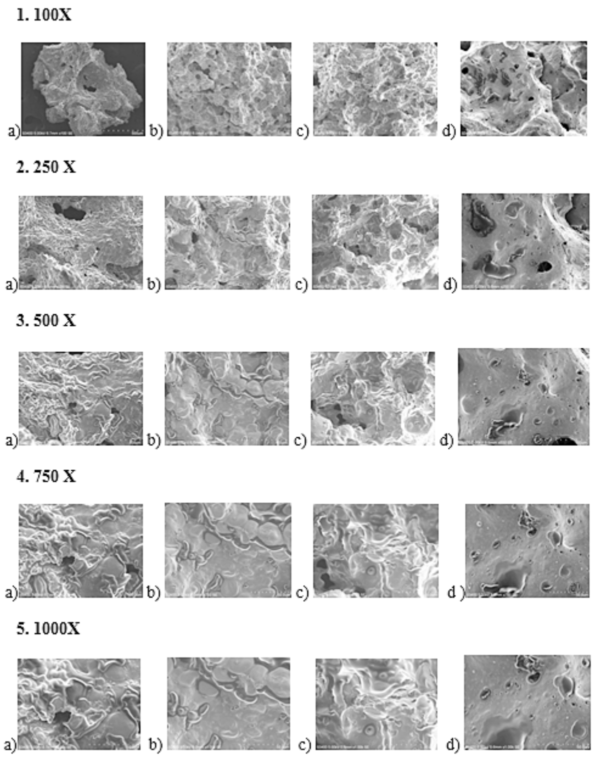

Fig 3: SEM images of the cracker samples at different magnifications

Microstructural Studies of Cracker Combination

Microstructural images at different magnifications of Control, CCFM2, CCFM3, and CCFM 4 samples, photographed at 100X, 250X, 500X, 750X and 1000X magnification at an accelerating voltage of 5kV are represented in Figure 3 (1a, 2a, 3a, 4a, and 5a).

The inclusion of Soy protein in the wheat flour (CCFM 2) resulted in the production of uneven and porous cell structures. The microstructural characteristics of CCFM3 are expected to be influenced by the presence of soy protein.

X-Ray Diffraction Analysis of Cracker Combination

The X-Ray Diffraction Analysis of Cracker combinations are provided in Table 5. The X-ray diffraction analysis was performed using a Rigaku Smart Lab diffractometer, which operates over a scanning range of 0° to 160° in 2θ and with adjustable scanning rates between 0.02° and 5° per minute.

In the analysis of the control sample, the peaks appeared thinner, with a minimum observed at 17.68° and a maximum at 70.49°. For the CCFM 2 sample, the highest peaks were recorded at 20.74° and 21.74°. In CCFM 3, the 2θ values were obtained at 19.00°, while CCFM 4 showed a minimum peak at 13.35° and a maximum peak at 17.18°. Based on the degree of crystallinity values, the values are similar in range with the breakdown of 18.29% for Control, 15.92% for CCFM 2, 14.84% for CCFM 3 and 13.30% for CCFM 4.

Table 5: XRD analysis of Cracker formulations

Samples	2θ in degree	d [Å]	Degree of crystallinity (%)
CONTROL	Min- 17.68°	Min- 5.0113	18.29
	Max- 70.49°	Max - 1.3348	
CCFM 2	20.74°	4.2788	15.92%
	21.74°	4.0842	
CCFM 3	19.00°	4.4585	14.84%
CCFM 4	Min- 13.35°	Min- 6.6292	13.30%

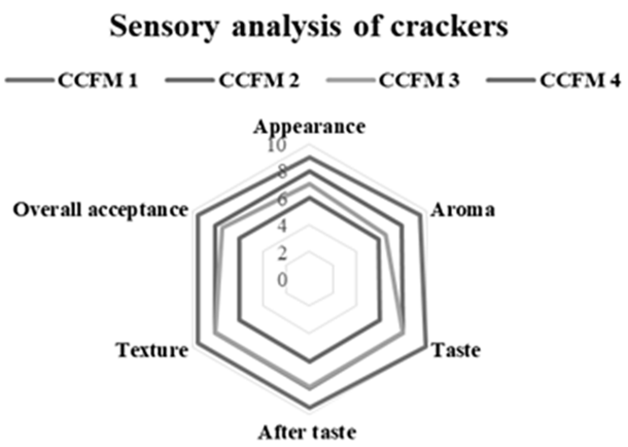

Fig 4: Sensory analysis of crackers combination using hedonic scale

Sensory Analysis

Figure 4 shows the hedonic scale evaluation of the crackers' sensory attributes. Control scored the highest (9) for appearance, while CCFM 4 received the lowest score (6). Control scored highest for aroma around 9.5 compared to other combinations. CCFM 2 and CCFM 3 had similar score of 8 for taste where Control scored the highest value of 10. Control has the after-taste value of 9.5. The textural profile had a significant impact on crackers' palatability. With a value of 9.5, the control sample (CCFM1) received the highest score, followed by CCFM 2 and CCFM 3 with a value of 8. All crackers had a sufficiently favourable and higher response from the panellists in the context of general acceptability, with scores ranging from 8 to 9.5. Control obtained the highest score of 9.5. CCFM 2 has the score of 8.5 and CCFM 4 was the least recommended sample with the lowest score (6). The panellists like the combination of Control and CCFM 2 the most because of the mouth feel, colour, and texture.

Discussion

Rheological Properties

Farinograph studies have shown that pea protein isolates have high water-binding capacities due to the presence of hydrophilic groups in their structure. Pea protein contains a higher content of polar amino acids (such as glutamic acid), which promotes strong water interactions.[23] Additionally, the fibrous nature and high surface area of pea proteins enable greater water retention compared to other proteins. Pea protein isolates have showed water absorption capacities in the range of 62-68%, similar to current findings in this study.[24]

Isolated soy protein exhibiting moderate water absorption (56.9%) aligns with the existing literature. Soy protein isolates are known for their relatively high-water absorption capacities, but they tend to absorb slightly less water than pea protein.

Table 6: Comparison of Farinograph studies of different formulations

Variations	DDT	Stability	Implications
CCFM 1 (Control	Normal dough development time	Moderate stability	Good emulsifying properties, and its ability to interact
CCFM 2 (Isolated Pea Protein)	Lower than the control sample.	The reduced DDT indicates that the dough achieved optimal consistency more quickly than the control, suggesting good stability.	The quicker development time suggests that the pea protein's water absorption and hydration capabilities` enhance the formation of a cohesive dough structure[26]
CCFM 3 (Isolated Soy Protein)	Similar to the control sample	The similarity in DDT to the control indicates moderate stability. This implies that the soy protein's ability to integrate into the dough matrix is comparable to that of wheat flour.	Soy protein has good emulsifying properties, and its ability to interact with gluten helps in maintaining dough stability[25]
CCFM 4 (Composite Flour with Whey protein isolate + Skim milk powder)	Significantly longer (16.4 minutes), almost 9 times that of the control (1.8 minutes).	The very long DDT indicates poor stability and a weaker dough structure.	The prolonged dough development time with milk proteins, particularly whey, suggests that the whey protein isolates disrupt the gluten network. This weakening leads to reduced elasticity and more extended mixing times to achieve an optimal dough consistency[27]

Soy protein isolates contain fewer hydrophilic amino acids than pea proteins, resulting in a somewhat lower ability to bind water. Researches indicated that soy protein isolates generally exhibit water absorption between 50-60%, depending on factors such as protein structure and pH conditions during processing.[25] This correlates well with current results, where soy protein absorbed less water compared to pea protein but still had higher absorption than control wheat flour. Milk proteins, such as casein and whey, generally have lower water absorption compared to plant-based proteins due to their structural composition.

Water is required for hydration, which also matches the observation of a 16.4-minute dough development time for this formulation. Dough development time (DDT) is the amount of time needed to mix dough to achieve its optimal consistency and is associated with physical modifications to the dough's protein structure.[28] Whey protein isolate weakens and disrupts the dough's gluten network, making the dough less elastic and softer interfering with the structure and development of gluten.[29, 30] This may prevent gluten from properly attaching and forming networks, which would result in softer dough, less elasticity, and changing dough rheology ultimately resulting in more DDT.6 Dough stability is directly related to the quantity and quality of gluten proteins.[30, 31] Breakdown time is the time after reaching peak development when the dough starts to weaken or degrade and loses its ideal consistency.[32]

Proximate Analysis

The nutritional composition suggests that the incorporation of various protein sources and flours can effectively enhance the nutritional profile of crackers, making them a viable option for consumers seeking healthier snack alternatives. The variations in protein and fiber content across the samples highlight the flexibility in formulation strategies to achieve desired nutritional outcomes while maintaining acceptable sensory characteristics.

Microstructural Studies of Cracker Combinations

SEM pictures reveal that the control samples of crackers have an uneven and porous appearance. A study indicates that the microstructure of wheat-based products typically shows a porous structure, resulting from the formation of gluten networks during baking.[33] The uneven porosity observed in the control sample is consistent with this finding, as the development of gluten creates air pockets that contribute to the product's texture. Upon the addition of protein to the wheat flour, the surface of the crackers undergoes a transformation, becoming smooth and tightly bound with minimum pores. A study found that the incorporation of pea protein in dough formulations results in a more uniform microstructure, often characterized by smaller pores compared to wheat flour-based products.[26] One of the study supports the current research by demonstrating that soy protein can contribute to a finer microstructure in dough systems, which may result in a smoother and less porous appearance in the final product, contrasting with the control's more uneven texture.[34]

The microstructure may reveal characteristics that indicate poor stability or structural integrity due to the inclusion of milk proteins. Researchers found that whey proteins can disrupt the gluten network during dough mixing and baking, leading to a more irregular microstructure and potentially larger air pockets.[27] This aligns with the current findings that the inclusion of milk proteins might yield a less cohesive structure.

X-Ray Diffraction Analysis of Cracker combinations

The interactive surface plot of the cracker samples illustrates the topography of their surfaces, where the x and y axes represent physical locations and the z-axis denotes height or depth at specific points. The presence of prominent peaks in the plot suggests a rough or uneven surface texture, highlighting how ingredient and process variations affect the crackers' texture.[4] Nearly 18.29 % of the cracker samples of Control are not in well-ordered crystalline structure, which can contribute to textural properties. The remaining percentage of the sample is likely amorphous, meaning the atomic arrangement is more disordered. This amorphous phase can influence factors like elasticity and water absorption in the cracker.[35] CCFM 2, CCFM 3 and CCFM 4 have slight reduction in the degree of crystallinity compared with the control sample due to the proteins interfering with starch crystallization during baking.[36] Generally, a higher degree of crystallinity is associated with a crispier texture. In this case, with a moderate crystallinity of 18.29%, the cracker might have some level of crispness but may also have softer, less ordered regions. The degree of crystallinity was greatly influenced by the type of flour, presence of fats and sugars, and other components. Baking temperature, time, and cooling process can all play a role in determining the final crystallinity of the crackers.

Sensory Analysis of Crackers

The baked crackers shows both enzymatic browning and Maillard reactions which have a major impact on their appearance.[37] The possibility that some aromatics were trapped and not released into the saliva accounts for the other combinations' lowest flavor score. Crackers prepared from wheat flour and pea protein isolate extrudes have increased intensity of pea flavour, a firmer and more fragile texture, a darker colour, and a less consistent shape and exterior appearance.[38, 39] The addition of whey protein concentrate (WPC) to wheat flour-based goods such as crackers can greatly increase their protein content, enhance the digestibility of proteins in a laboratory setting, and boost the levels of important amino acids such as lysine, aspartic acid, and glutamic acid.[32, 40]

In addition, the inclusion of whey protein isolate can cause alterations in the protein composition of the dough, resulting in a decrease in gluten content and an increase in water-soluble proteins. This eventually impacts the stability of the dough and the fermentation processes. Furthermore, including protein isolates into wheat-based goods can effectively preserve their functioning and nutritional properties, resulting in an improved overall product quality.[41] By carefully integrating whey protein isolate; it is possible to enhance the structure and nutritional content of wheat flour-based crackers while also achieving ideal textural qualities.

Conclusion

This study successfully formulated protein-enriched functional crackers using composite flour blends with both plant- and animal-based proteins. The three composite flour mixtures (CCFM 2, CCFM 3, and CCFM 4) demonstrated promising alternatives to traditional wheat-based crackers by significantly enhancing protein content and nutritional value. Rheological analysis showed that CCFM 2, containing pea protein isolate, had the highest water absorption capacity and shortest dough development time, attributed to the hydrophilic nature of pea proteins that accelerate dough formation. In contrast, CCFM 4, with whey protein isolate, exhibited a longer dough development time, suggesting interference with gluten structure. Microstructural analysis revealed that pea and soy proteins led to a more cohesive and less porous cracker texture, while whey protein in CCFM 4 resulted in a looser structure. X-ray diffraction supported these findings, showing altered crystallinity levels with pea protein contributing to a softer texture.

Sensory evaluation indicated that while control crackers (CCFM 1) received the highest scores overall, CCFM 2 was also well-received, particularly for its taste and texture, making it a viable, protein-rich alternative. CCFM 4 scored lower, reflecting its microstructural limitations. In conclusion, the study demonstrates the feasibility of developing functional crackers with enhanced protein profiles using composite flours, with CCFM 2 emerging as a promising formulation for health-conscious consumers.

High-protein content crackers can significantly address protein deficiency and undernourishment, particularly in communities affected by wasting and stunting. These crackers provide an accessible and cost-effective source of protein, especially in areas where traditional protein sources are limited. Their convenience and palatability make them attractive snacks for various age groups, encouraging higher consumption rates among children. Regular intake of these protein-rich snacks supports healthy growth and development, reducing the risk of stunting and improving overall health outcomes. By incorporating high-protein crackers into public health initiatives and dietary practices, communities can effectively combat undernourishment and enhance nutritional intake among vulnerable populations.

Future research could explore the long-term stability and health impacts of these formulations, potentially catering to dietary needs and nutraceutical properties enriched for especially individuals with diabetes or children requiring high-protein snacks.

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Ethics Statement

This research did not involve human participants, animal subjects, or any material that requires ethical approval.

Informed Consent Statement

The informed consent was obtained for sensory evaluation from panellists.

Clinical Trial Registration

This research does not involve any clinical trials.

Permission to Reproduce Material from other Sources

Not Applicable.

Author Contributions

- **Suresh Madhavan:** Conceptualization, Methodology, Visualization, Formal analysis, Investigation, Validation, Data curation, Writing-original draft, Writing-review and editing.
- **Hemalatha Mysore Sreekantaiah:** Supervision, Resources, Conceptualization, Formal analysis, Validation, Visualization, Investigation, Data curation, Writing-review and editing.

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