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PHYSICOCHEMICAL AND SENSORY EVALUATION OF GLUTEN-FREE DUMPLING SKINS: IMPACT OF SWEET POTATO AND TAPIOCA FLOUR RATIOS

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Abstract:

The demand for gluten-free alternatives continues to rise due to increasing awareness of gluten intolerance and celiac disease. This study aimed to develop gluten-free dumpling skins using sweet potato flour (SPF) and tapioca flour (TPF) in three formulations (SP30:TP70, SP50:TP50, SP10:TP90), and to evaluate their physicochemical, textural, and sensory properties. Proximate analysis was conducted to assess moisture and protein content, while texture profile analysis measured hardness, cohesiveness, springiness, and chewiness. Sensory evaluation was performed using a 9-point hedonic scale. Among the formulations, SP50:TP50 (F2) exhibited the most desirable texture and overall sensory acceptability, balancing firmness with favourable mouthfeel. Instrumental chewiness showed partial correlation with sensory chewiness and acceptability, confirming that mechanical parameters alone are insufficient to predict consumer preferences. Formulations with higher sweet potato content showed improved nutritional profiles and enhanced taste perception due to their natural sweetness and moisture retention. These results suggest that sweet potato and tapioca flour blends can produce acceptable gluten-free dumplings with good structural integrity and consumer appeal. Integrating both instrumental and sensory analyses is essential for optimizing gluten-free formulations.

Keywords:

Gluten-Free Dumpling, Sweet Potato Flour, Texture Profile Analysis, Sensory Evaluation

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Introduction

The growing prevalence of gluten-related disorders and the rising demand for alternative diets have driven the innovation of gluten-free products across various food categories. Dumplings, traditionally made with wheat-based wrappers, are a popular staple in many Asian cuisines, but their gluten content poses a challenge for individuals with celiac disease or gluten intolerance. Replacing gluten-rich flour with gluten-free alternatives requires careful attention to texture, elasticity, and consumer acceptance.

Sweet potato (Ipomoea batatas) flour is known for its nutritional value, including dietary fiber, vitamins, and antioxidants, while tapioca (Manihot esculenta) flour contributes a neutral flavour and excellent binding properties due to its high starch content. However, the structural and sensory properties of doughs and final products using these flours can vary significantly depending on their ratios and interactions during cooking.

This study aims to develop a gluten-free dumpling skin using sweet potato and tapioca flours in different ratios and to evaluate their effects on the physicochemical properties, texture, and sensory acceptability of the dumplings. By correlating instrumental texture measurements with sensory panel responses, the research intends to identify an optimal formulation that delivers a balance of desirable mouthfeel, chewiness, and structural integrity.

Literature Review

Sweet Potato Flour

Sweet potato flour, derived from various sweet potato genotypes, is gaining traction in the food industry due to its nutritional benefits and functional properties. This flour is produced through a meticulous process that preserves its colour and nutritional value, making it suitable for diverse applications in food products.

Nowadays, sweet potato flour is increasingly recognized for its nutritional and functional advantages in gluten-free formulations. Its rich composition includes carbohydrates, proteins (approximately 5.41 g/100 g), and essential minerals such as potassium and phosphorus, which contribute to the nutritional enhancement of food products (Zhang et al., 2022; Lu & Gao, 2011). Additionally, sweet potato flour contains significant amounts of phenolic compounds and carotenoids, both of which provide antioxidant properties that can enhance the health appeal of gluten-free foods (Hussien et al., 2024).

Functionally, sweet potato flour improves the texture and volume of gluten-free baked goods by enhancing water retention and reducing staling. These qualities are particularly useful in bread and cookie production, where maintaining softness and freshness is critical (Dereje et al., 2020; Elzoghby et al., 2023). Moreover, sweet potato flour is highly versatile and can be blended with other gluten-free flours such as sorghum or chickpea to improve both nutritional balance and sensory characteristics, particularly in products like cookies and rice bread (Hussien et al., 2024; Elzoghby et al., 2023).

While its distinctive flavour may affect the taste profile of certain products, proper formulation strategies can balance its sensory impact. Overall, sweet potato flour offers promising potential in gluten-free product development, enhancing both the functional and nutritional quality of food while contributing to consumer acceptability.

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Tapioca Flour

Tapioca flour, derived from the cassava root, is widely used in gluten-free formulations due to its unique functional properties. It is composed primarily of amylopectin, which contributes to its desirable gelatinization and pasting behaviour, the key characteristics for achieving soft, elastic textures in gluten-free products (Horstmann et al., 2017). The morphology of tapioca starch, including its granule size and shape, influences its water absorption and swelling capacity. These properties are crucial for creating the moist, cohesive structure that consumers associate with high-quality baked or steamed goods (Mauro et al., 2023).

Functionally, tapioca flour improves the texture and volume of gluten-free products. Modified tapioca starch is especially effective in enhancing these qualities and in reducing staling, thereby extending the shelf life of baked goods (Sudheesh et al., 2021; Roman et al., 2020). Furthermore, tapioca is a source of resistant starch, which has been shown to reduce the glycemic index of gluten-free products and making it beneficial for consumers seeking healthier alternatives (Sudheesh et al., 2021).

Sensory studies have demonstrated high consumer acceptance for gluten-free products made with tapioca flour, including bread and biscuits, often outperforming other gluten-free flours in texture and taste (Muzamil et al., 2024; Milde et al., 2012). However, tapioca is nutritionally limited and lacks the protein and micronutrient density of whole grains. Thus, it is often used in combination with other flours to improve the overall nutritional profile. Despite this limitation, its functional versatility makes tapioca a valuable base ingredient in gluten-free product innovation.

Starch and Protein Interaction

Starch and protein interactions significantly influence the texture and moisture content of gluten-free food products, both of which are critical for overall quality and consumer satisfaction. Starch gelatinization is a key process in this interaction. During heating, starch granules absorb water and swell, leading to changes in viscosity and matrix formation that directly impact textural properties such as softness, elasticity, and chewiness. The swelling capacity and amylose solubility during gelatinization are essential for forming a strong, cohesive structure within the food matrix (Wada et al., 1999).

Water absorption capacity also plays a vital role in dough consistency. Higher water levels enhance the viscoelastic properties of gluten-free dough, as demonstrated in pizza crusts where the inclusion of gelatinized starch improved texture without compromising structure, even at lower baking temperatures (Matsumo et al.,2022). These improvements are particularly important in gluten-free systems where gluten is absent to provide structural support.

The flour-to-protein ratio further determines product hardness and elasticity. In studies involving *keropok lekor*, an optimal balance between starch and protein yielded the most desirable textural outcomes (Mohamed et al., 2024). However, excessive protein content can interfere with starch gelatinization, reducing viscosity and resulting in undesirable textures (Terán & Blanco-Lizarazo, 2021). Thus, achieving the right balance between starch and protein is crucial for optimizing gluten-free formulations, especially in products like dumplings where structure, chewiness, and moisture retention are key to consumer acceptability.

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Sensory Evaluation in Food Product Development

Sensory evaluation is a critical tool for understanding consumer preferences and assessing the acceptability of food products. It provides direct insights into how consumers perceive various attributes such as taste, aroma, texture, and appearance all of which are essential for determining product success in a competitive market. By employing structured sensory methodologies, developers can align formulations with consumer expectations and optimize product quality before commercial launch.

One of the key contributions of sensory evaluation is its ability to reveal nuanced consumer perceptions that drive purchasing behaviour. Products that perform poorly in sensory tests are often rejected by consumers, regardless of branding or marketing strategies (Lawless & Heymann, 1999). As such, sensory data are vital not only for quality control but also for shaping marketing and product positioning. Advanced analytical techniques, such as fuzzy logic, have enhanced the quantification of subjective sensory feedback, making the evaluation process more comprehensive and reliable (Vivek et al., 2020).

Common methodologies include discriminative tests, which determine whether consumers can detect differences between products, and descriptive analysis, which captures detailed profiles of sensory characteristics (Yadav et al., 2024). Despite these advances, challenges remain. Consumer behaviour during eating is dynamic and influenced by context, mood, and environment, making it difficult to predict real-world responses with full accuracy (Tugba, 2021). Furthermore, certain sensory attributes, such as texture and aroma, are still underexplored in scientific literature.

While sensory evaluation is invaluable, it should be integrated with market research, branding, and pricing strategies to ensure complete consumer satisfaction and commercial success.

Sensory Evaluation and Instrumental Correlation

Sensory evaluation is essential in food product development as it provides insight into consumer preferences for attributes such as texture, appearance, chewiness, and overall acceptability. While sensory testing relies on subjective feedback from panelists, instrumental texture analysis offers objective data that can enhance the efficiency and reproducibility of product development. The correlation between these two approaches has become a major area of interest, particularly in optimizing gluten-free formulations where traditional gluten structures are absent.

The correlation between sensory evaluation and instrumental measurements in food products is influenced by several critical factors, including the nature of the food matrix, the type of sensory attributes assessed, and the analytical methods used. Understanding these factors is essential for developing predictive models that improve food quality and consumer satisfaction. The characteristics of the food matrix which its chemical composition and physical structure are play a significant role in how sensory properties are perceived. For example, a study on instant noodles found that 68% of the variability in sensory evaluation could be explained by the chemical properties of wheat flours and the dough's physical attributes (Xue et al., 2010). However, some texture-related attributes, such as adhesiveness or mouthfeel, are more difficult to replicate instrumentally, particularly in complex or heterogeneous food systems (Brenner et al., 2014).

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Sensory evaluation methods, such as descriptive analysis, capture nuanced attributes like hardness or viscosity. These may not always align with direct instrumental equivalents such as jelly strength or force-deformation metrics (Shindo et al., 1993). Therefore, validating instrumental techniques against sensory data is essential, keeping in mind that correlation does not imply causation (Cook et al., 2005).

Methodological choices also impact correlation strength. The use of multivariate techniques, such as partial least squares regression, enhances the interpretation of complex datasets and improves model reliability (Xue et al., 2010). Emerging technologies, including electronic noses and tongues, offer promising tools to mimic human sensory perception and enhance predictive accuracy (Kilcast, 2010).

While these tools advance the field, discrepancies remain due to the subjective nature of sensory experiences and the limitations of mechanical measurements. Continued research is essential to refine methodologies and develop more robust, reliable sensory-instrumental correlation models.

Materials and Methods

Materials

Sweet potato flour and tapioca flour were the primary ingredients used in this study. Both flours were commercially sourced and stored in airtight containers at room temperature. Additional ingredients included water and salt, used to form the dough. All chemicals and reagents used in the analytical procedures were of analytical grade and obtained from reputable suppliers.

Preparation of Dumpling Skins

Three formulations of gluten-free dumpling dough were prepared using different ratios of sweet potato flour (SP) and tapioca flour (TP) by table below.

Table 1: Formulation Dumpling Skins

Formulation	Sweet Potato Flour (%)	Tapioca Flour (%)
F1	30	70
F2	50	50
F3	10	90

The flours were weighed and thoroughly mixed. Water was gradually added and kneaded until a smooth dough was formed. The dough was rested for 15 minutes at room temperature before being rolled to a uniform thickness and cut into circular dumpling skins. All samples were steamed under identical conditions (10 minutes, 100°C) and cooled to room temperature before analysis.

Proximate Analysis

The proximate composition of the gluten-free dumpling skin samples was determined using standard procedures outlined by the Association of Official Analytical Chemists (AOAC). Moisture content was measured using the oven-drying method (AOAC 925.10). Approximately 5 grams of each sample were weighed and placed in a hot air oven at 105°C until a constant weight was achieved. The loss in weight was recorded as the moisture content, which is essential for assessing product stability and shelf life.

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Crude protein content was analyzed using the Kjeldahl method (AOAC 981.10), which quantifies total nitrogen content. Each sample underwent acid digestion with concentrated sulfuric acid in the presence of a catalyst to convert organic nitrogen into ammonium sulfate. The digest was then neutralized with sodium hydroxide and distilled. The liberated ammonia was trapped in a boric acid solution and titrated with standardized hydrochloric acid. The total nitrogen value obtained was multiplied by a conversion factor of 6.25 to estimate crude protein content, which is critical for evaluating the nutritional value of the dumpling formulations.

Crude fat content was determined using Soxhlet extraction with petroleum ether as the solvent (AOAC 920.39). Dried and ground samples were placed in a thimble and subjected to continuous solvent extraction for approximately six hours. The extracted fat was collected, and the solvent was evaporated to leave behind the residual lipid content. This parameter is important for understanding the energy contribution and mouthfeel of the final product. All analyses were performed in triplicate to ensure accuracy and reproducibility.

Texture Profile Analysis (TPA)

Instrumental texture analysis of the gluten-free dumpling skins was performed using a texture analyzer (Brookfield CT3 Texture Analyzer) equipped with a cylindrical probe. The objective of this analysis was to quantify key mechanical properties associated with the textural quality of the dumpling wrappers. Prior to testing, samples were cut into uniform rectangular pieces to ensure consistency in measurement. All measurements were carried out at room temperature and in triplicate for each formulation to ensure reproducibility and minimize experimental error. For each evaluation, triplicate samples from each formulation were positioned beneath the cylindrical P/36 R probe and subjected to compression in the Texture Profile Analysis (TPA) mode. The parameters for measurement were established as follows: a pre-test speed of 2 mm/s, a test speed of 0.8 mm/s, a post-test speed of 0.8 mm/s, a triggering force of 5 g, and a compression rate of 75%. The outcomes from the two duplicate measurements were documented, and the average value was calculated to represent the final result for each formulation. (Li et al., 2008).

The parameters evaluated included hardness, cohesiveness, and chewiness. Hardness was defined as the maximum force required to compress the sample during the first bite, indicating the firmness of the dumpling skin. Cohesiveness was determined by calculating the ratio of the area under the second compression curve to that under the first, reflecting the internal bonding strength of the sample and its ability to withstand a second deformation. Chewiness was derived as the product of hardness, cohesiveness, and springiness, representing the energy required to masticate the sample before swallowing.

These parameters provided insight into the physical structure and textural behaviour of the dumpling formulations, which are critical for both sensory quality and consumer acceptance. The data obtained were further correlated with sensory evaluation scores.

Sensory Evaluation

Sensory evaluation was conducted using an untrained panel comprising 35 members to assess the acceptability of the gluten-free dumpling skin formulations. Each panelist evaluated the samples using a 9-point hedonic scale, where 1 represented "dislike extremely" and 9 represented "like extremely." The sensory attributes evaluated included colour, surface texture, chewiness, taste, aroma and overall acceptability. These parameters were selected to reflect

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key consumer-relevant qualities in dumpling products, particularly in the context of gluten-free alternatives.

To reduce bias and ensure objectivity, the samples were presented in random order using three-digit codes. The evaluations were conducted in a sensory analysis laboratory under standardized conditions of lighting, temperature, and ventilation to eliminate external influences on perception. Panelists were instructed to rinse their palates with water between samples. The data obtained from the panel were statistically analyzed to determine significant differences among the formulations and to examine correlations with instrumental texture measurements.

Statistical Analysis
Data were analysed using one-way analysis of variance (ANOVA), with significance set at $p < 0.05$. Tukey's HSD test was used for mean comparisons. Pearson correlation analysis was performed to evaluate the relationship between instrumental texture parameters and sensory scores. All analyses were carried out using SPSS software (version 17).

Results and Discussion

Effect of Sweet Potato–Tapioca Flour Ratio on Physicochemical and Textural Properties
The combination of sweet potato flour (SPF) and tapioca flour (TPF) significantly influenced both the proximate composition and textural attributes of the gluten-free dumpling skins (Tables 2 and 3). These two aspects are interdependent, as compositional variations—particularly in moisture and protein directly affect dough structure, elasticity, and chewiness.

The proximate analysis showed that F2 (SP50:TP50) recorded the highest moisture content (42.61 ± 0.36%), followed by F3 (35.70 ± 0.10%), while F1 (34.99 ± 0.04%) exhibited the lowest. This pattern supports findings by Zhang et al. (2022) and Hussien et al. (2024), who reported that sweet potato flour has a strong water-binding capacity due to its fiber and complex carbohydrate composition. Sweet potatoes generally contain 18–25% inherent moisture and 16.4–21.2% starch (Shi et al., 2021), which together enhance hydration and gelatinization behaviour. The high starch content promotes viscosity and gel strength during heating, while the fibrous matrix retains water within the dough network (Allan et al., 2023). Thus, enhanced moisture retention in F2 likely improved dough softness, flexibility, and resistance to staling where a key textural attributes for gluten-free doughs that rely on starch gelatinization rather than gluten structure.

Protein content ranged from 0.22 ± 0.01% (F1) to 1.88 ± 0.02% (F2), suggesting that the inclusion of SPF modestly improved the protein profile. While sweet potato flour has a lower protein content than wheat (~3.33%) (Yulianti et al., 2019), it contributes functional amino acids and bioactive compounds such as β-carotene and dietary fiber (Shih et al., 2006; Truong et al., 2018). These components enhance nutritional value and antioxidant capacity while improving the colour and sensory appeal of gluten-free products. Meanwhile, fat content decreased with increasing SPF proportion, with F2 (2.35 ± 0.06%) showing a reduction compared to F3 (3.59 ± 0.09%), consistent with the naturally lower lipid levels in sweet potato relative to tapioca.

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Texture profile analysis revealed parallel trends between composition and mechanical behaviour. Formulation F2 exhibited the highest hardness (2325.00 ± 2228.80) and chewiness (485.59 ± 485.94), coupled with superior cohesiveness (0.84 ± 0.05), suggesting an optimal structural balance for dumpling applications. This outcome likely results from the synergistic interaction between the fibrous matrix of sweet potato starch and the high amylopectin content of tapioca, which strengthens gel formation and internal binding (Akintayo et al., 2019). The high starch content in SPF promotes gelatinization and viscosity development, while its fiber contributes to matrix reinforcement and moisture stabilization. In contrast, F1 demonstrated the lowest hardness (47.00 ± 29.70) and chewiness (11.41 ± 9.25), indicating a weak network and excessive softness due to limited protein and water-holding capacity.

The moderate hardness and chewiness of F2 are desirable, as excessive firmness may reduce consumer acceptance, while insufficient structure compromises handling quality. Meng et al. (2022) similarly reported that sweet potato inclusion enhances textural firmness up to an optimal substitution level, beyond which the product becomes excessively dense. The observed correlation between high moisture and chewiness in F2 further confirms that starch–water interactions govern texture formation, influencing both mechanical and sensory outcomes.

Overall, the SP50:TP50 blend (F2) achieved the most balanced profile—combining enhanced hydration, cohesive structure, and moderate chewiness. This equilibrium underscores the critical role of physicochemical compatibility between sweet potato and tapioca starches in optimizing both functional and nutritional attributes in gluten-free dumpling formulations. The inherent moisture-retention capacity, high starch content, and bioactive composition of sweet potato flour make it a functional ingredient capable of improving the texture, elasticity, and nutritional value of gluten-free dough systems (Shi et al., 2021; Truong et al., 2018).

Table 2: Result of Proximate Analysis

Formulation	Moisture (%)	Protein (%)	Fat (%)
F1(SP30:TP70)	34.99 ± 0.04	0.22 ± 0.01	2.97 ± 0.07
F2(SP50:TP50)	42.61 ± 0.36	1.88 ± 0.02	2.35 ± 0.06
F3(SP10:TP90)	35.70 ± 0.10	1.84 ± 0.02	3.59 ± 0.09

Table 3: Result of Texture Profile Analysis

Formulation	Hardness	Cohesiveness	Springiness	Chewiness
F1(SP30:TP70)	47.00 ± 29.70	0.81 ± 0.41	0.3 ± 0.00	11.41 ± 9.25
F2(SP50:TP50)	2325.00 ± 2228.80	0.84 ± 0.05	0.25 ± 0.07	485.59 ± 485.94
F3(SP10:TP90)	2070.00 ± 2757.72	0.71 ± 0.05	0.25 ± 0.07	364.54 ± 497.54

Sensory Acceptability Based on Hedonic Evaluation

Sensory evaluation through a nine-point hedonic scale assessed colour, surface texture, chewiness, taste, aroma, and overall acceptability of the gluten-free dumpling formulations. Results showed no significant differences in colour scores (5.7–6.0), indicating that varying sweet potato to tapioca flour ratios did not affect visual appeal. Surface texture and chewiness were rated moderately (~4.5) across samples, suggesting acceptable yet limited elasticity typical of gluten-free systems lacking gluten's viscoelastic structure (Horstmann et al., 2017; Kilcast, 2008). Notably, F2 (SP50:TP50) achieved higher ratings for texture and chewiness, consistent with its superior moisture retention and cohesiveness, which enhanced softness and mouthfeel (Tortoe et al., 2017).

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Taste scores differed significantly ($p < 0.05$), with F2 rated highest, likely due to the natural sweetness and flavour-enhancing compounds in sweet potato flour (Shih et al., 2006). Although aroma and overall acceptability did not differ significantly among formulations, F2 again received the highest mean scores, reflecting its balanced textural and sensory qualities. These findings suggest that moderate incorporation of sweet potato flour improves both sensory and nutritional attributes without compromising structural integrity. Overall, the SP50:TP50 blend demonstrated the most favourable balance between texture, flavour, and consumer appeal in gluten-free dumpling development.

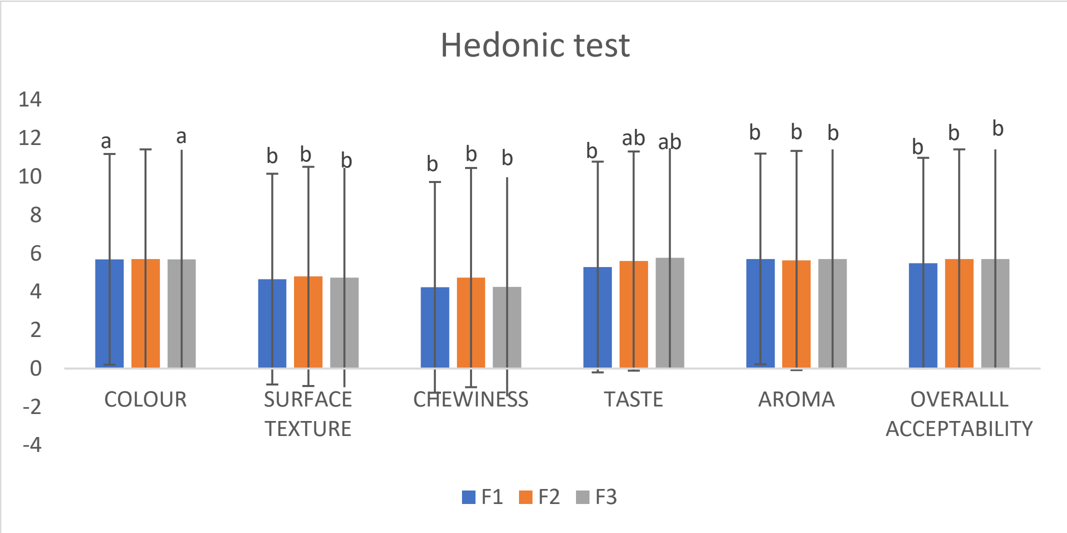

Figure 1: Sensory Acceptability by Hedonic Test

Correlation Between Instrumental Chewiness and Sensory Perception

Instrumental chewiness in food texture analysis represents the mechanical resistance of a product during mastication and is closely linked to the sensory perception of firmness, elasticity, and mouthfeel. Quantitatively, chewiness is derived from parameters such as hardness, cohesiveness, and springiness obtained through Texture Profile Analysis (TPA) (Loredo & Guerrero, 2011). While instrumental measurements provide objective indicators of mechanical properties, their relationship with sensory experience is often complex and non-linear (Meullenet & Gross, 1999; Zhi et al., 2016).

In this study, the correlation between instrumental chewiness and sensory attributes—specifically sensory chewiness and overall acceptability—was evaluated across the three dumpling formulations (F1, F2, F3). The results (Figure 2) demonstrate that instrumental data aligned reasonably well with sensory perception, particularly for the F2 (SP50:TP50) formulation, which exhibited the highest instrumental chewiness (485.59 ± 485.94) and correspondingly received the highest sensory chewiness (4.74) and overall acceptability (5.71) scores. This positive relationship suggests that a moderate to high degree of chewiness contributes to consumer satisfaction when accompanied by favourable elasticity and moisture release.

Conversely, F1 (SP30:TP70) displayed both the lowest instrumental chewiness (11.41 ± 9.25) and the lowest sensory chewiness (4.23), indicating that insufficient structural firmness can lead to a perception of excessive softness and reduced palatability. Interestingly, F3 (SP10:TP90), despite exhibiting a relatively high instrumental chewiness (364.54 ± 497.54),

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achieved only moderate sensory chewiness and similar acceptability to F2. This outcome reflects the concept of diminishing sensory returns—beyond an optimal mechanical threshold, increases in chewiness may not enhance sensory perception and can even lead to an overly firm or dense texture (Everard et al., 2006; Kilcast, 2008).

These findings corroborate earlier studies emphasizing that while instrumental chewiness strongly relates to measurable mechanical resistance, sensory chewiness also depends on dynamic oral processing factors such as deformation, elasticity, and moisture release (Mihafu et al., 2020; Jeronimidis, 1991). The alignment between instrumental and sensory data in this study reinforces that moderate chewiness—as achieved in the SP50:TP50 formulation—optimizes the balance between structure and palatability.

Overall, the results highlight that instrumental texture parameters, particularly chewiness and hardness, serve as useful predictive benchmarks for sensory quality but cannot fully capture the complexity of human perception. As also emphasized by Lee et al. (2025), integrating sensory and instrumental analyses provides a more holistic framework for food texture optimization, especially in gluten-free formulations where viscoelastic properties differ markedly from those of gluten-containing systems.

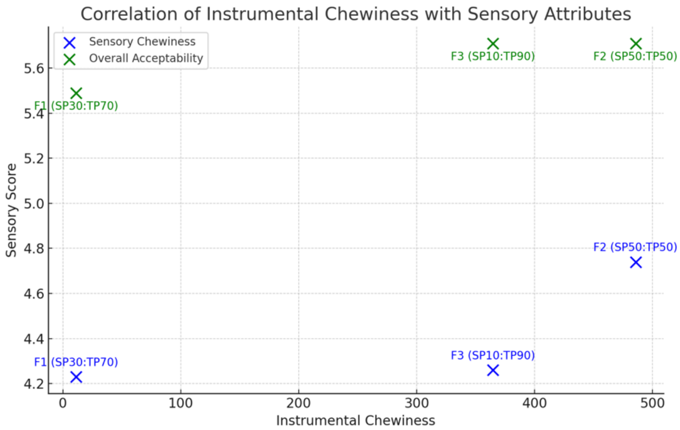

Figure 2: Correlation Between Instrumental Chewiness and Sensory Attributes

Conclusion

This study successfully formulated gluten-free dumpling skins using varying ratios of sweet potato flour (SPF) and tapioca flour (TPF) and demonstrated how compositional balance affects product quality. The findings show that flour ratio significantly impacts moisture, protein, and texture parameters, with the SP50:TP50 blend (F2) achieving superior performance in both instrumental and sensory dimensions.

The SP50:TP50 formulation exhibited optimal firmness, cohesiveness, and chewiness while maintaining high consumer acceptability, confirming the importance of flour synergy in gluten-free dough systems. Sensory evaluation further revealed that instrumental chewiness aligns with consumer preference up to a threshold, beyond which increased firmness may reduce acceptability.

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From an industrial perspective, the results highlight the potential of sweet potato–tapioca blends as sustainable, functional alternatives to wheat in gluten-free dumpling production. The combination provides improved moisture retention, better taste, and enhanced nutritional value, addressing both health and market demands.

Future work should explore hydrocolloids or plant-based proteins to enhance elasticity and simulate gluten's viscoelastic properties, as well as assess product scalability and storage stability. These directions could advance commercial gluten-free innovation, supporting the growing demand for inclusive, health-oriented food products.

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