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Application of Ultrasonic Technology in Modifying Tapioca Starch for Improving the Quality of Gluten-Free Noodles

Clara Rosalinda [a], Oksilia [b,*], Filli Pratama [b], Tri Wardani Widowati [a]

[a] Department of Agricultural Product Technology, Universitas Sriwijaya, Indralaya, Indonesia
[b] Doctoral Program of Agricultural Science, Universitas Sriwijaya, Palembang, Indonesia

Abstract. *Excessive gluten intake may provoke health problems in susceptible individuals, requiring gluten-free noodle substitutes. Tapioca possesses the potential to serve as an alternative to wheat flour; nevertheless, its inherent stickiness, propensity to soften, and limited elasticity require modification. This study utilized tapioca flour modified by ultrasound at two frequencies (20 kHz and 40 kHz) and three duration intervals (40, 45, and 50 minutes). The altered starch was subsequently employed to prepare noodles including a blend of rice flour, eggs, and salt. The measured metrics comprise texture, water absorption capacity, cooking loss, water solubility index (WSI), and swelling power. Data were examined utilizing ANOVA, followed by an LSD test at a 5% significance threshold. The findings indicated that both sonication frequency and duration significantly influenced all evaluated parameters. Raising the frequency to 40 kHz and extending the sonication duration to 50 minutes enhanced texture (121.50 gf), water absorption capacity (34.48%), water solubility index (WSI) (7.03%), and swelling power (4.05%), while concurrently increasing cooking loss to 58.47%. Ultrasonic modification has proven to be an eco-friendly technique for enhancing the functional attributes of tapioca, with prospective applications in the diversification of gluten-free noodle products.*
Keywords: *contact time; frequency; gluten-free noodle; sonication; tapioca.*

Type of the Paper: Regular Article.

1. Introduction

Noodles are a quick meal prepared from wheat flour. Indonesia ranks among the highest consumers of noodles globally, with 14.54 billion servings annually [1]. Of the 3.6 million tonnes of wheat flour produced annually in Indonesia, approximately 60% is used for noodles: 20% for instant noodles, 30% for fresh noodles, and 10% for dried noodles [2]. Wheat flour, the fundamental component in noodle production, comprises gluten, a protein that influences the chewiness, texture, elasticity, and stickiness of noodles [3]. Gluten, the main protein complex in wheat flour, can cause adverse health effects in susceptible individuals, including bloating, weight loss, diarrhea [4], intestinal damage, and nutrient malabsorption [5], as well as celiac disease and gluten intolerance [6]. Replacing wheat flour with alternative carbohydrate sources, such as tubers, presents a problem in achieving optimal noodle texture. Tapioca is a viable substitute for wheat flour in noodle preparation. It is a starch derived from the cassava tuber (*Manihot esculenta* Crantz) and prepared through extraction, separation, and drying of the natural starch granules. Tapioca

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* First corresponding author
Email: 05013682530009@student.unsri.ac.id

starch is an effective replacement in noodle production due to its affordability and transparent starch composition [7]. Nonetheless, it possesses adhesive properties, complicating the kneading process. Its low amylose content limits gelatinization, causing starch granules to break easily at relatively low temperatures and producing a gel with a weaker structure. Consequently, while tapioca can be used in noodle production, it does not create a firm and elastic dough network. This results in noodles that are overly soft, break readily during cooking, and lack the desired chewiness. Consequently, modifications to tapioca are necessary to enhance these qualities. The adjustment intends to improve gelatinization, minimize retrogradation (which reduces noodles elasticity), lower the noodles' tendency to form gel, enhance texture, boost stability and surface adherence, and improve the clarity of the paste and gel [8]. Starch modification is typically achieved through four primary methods: physical, chemical, enzymatic, and microbiological. Among these techniques, chemical modification (including acetylation [9], oxidation [10], cross-linking [11], and esterification [12]) is extensively employed in industry to enhance the functional qualities of native starch. Nonetheless, chemical approaches are considered potentially hazardous to consumer health and the environment. Consequently, current industrial focus is shifting toward eco-friendly modification technologies, including the physical alteration of starch. Ultrasonic modification (sonication) is one such physical method.

Ultrasonic modification, an eco-friendly and very effective technique, has been extensively employed in the manufacturing of modified starch [13]. Ultrasonic waves induce cavitation, characterized by the development and collapse of microbubbles, leading to elevated shear forces, localized pressure, and a transient temperature increase. This process disrupts the starch granule structure, fragments polymer chains (particularly amylose), and alters physicochemical properties, including reduced gelatinization viscosity and enhanced solubility [14]. Ultrasonics offers numerous advantages, including environmental sustainability, energy efficiency, and ease of implementation [15]. Ultrasonic treatment has been employed in various studies, including the enhancement of corn starch in steamed bread, resulting in a softer texture [16]; the synergistic application of ultrasound with oxidation, esterification, and cross-linking, which elevated resistant starch content in corn [17]; the modification of tapioca starch, improving clarity, expansion capacity, and gel strength [18]; the alteration of corn starch using ultrasound at 360 kHz, demonstrating that ultrasound disruption of chemical bonds in the starch chain and diminishes of molecular weight [19]; and the treatment of peas with ultrasound and acid, indicating that prolonged application time influenced starch clarity, solubility, and swelling capacity [20]. While ultrasound has been extensively applied to various starch sources, the optimal duration and frequency for changing tapioca starch and its subsequent application in noodle production remain undetermined. This research examined the impact of contact duration and ultrasonic frequency on noodle properties, specifically examining how ultrasonic frequency influences texture and cooking quality.

2. Materials and tools

This study used filtered water, salt, vegetable oil, eggs, rice flour, and "Pak Tani" tapioca flour. Common laboratory glassware and equipment (beakers, flasks, pipettes, analytical balance, oven, and colorimeter [Konica Minolta, Japan]), stove [Madonna MAC0, Indonesian], texture analyzer [Brookfeld], ultrasonic processor were used.

Sample Preparation and Ultrasonication.

Fifty grams of tapioca flour were measured and placed in a polyethylene (PE) plastic bag, then suspended in water at a 1:1 ratio, and subjected to ultrasonication. The sonication approach followed the modified methods of Jambak et al. [21] and Karaman et al. [22]. The sonicator water bath was filled with distilled water to half capacity to maintain consistent thermal conditions. The bath temperature was kept at 30 °C, with an ultrasonic power of 650 W for 30 minutes. The tapioca suspension was sonicated according to the treatment duration (40, 45 and 50 minutes) and at frequencies of 20 kHz and 40 kHz. The suspension was then kneaded into noodles.

2.1. Noodles Making

Thirty-five grams of rice flour were mixed with 15 mL of hot water (100 °C) and kneaded until smooth. One hundred grams of modified tapioca were mixed with 3g of salt, 5 mL of egg, and water to form 40% moisture dough, which was then proofed at 25°C for 30 minutes. The dough mixture was placed into the piping bag, the tip was cut to 0.125 inches, and the dough was extruded and cut into 15 cm lengths. For cooking, ten grams of fresh noodles were boiled in 500 mL of water with 15 mL of cooking oil for the optimal cooking time (2 minutes), until the white core of fresh noodles disappeared [23]. Cooked noodles were immersed in cold water (20°C) for 20 seconds before the texture analysis.

2.2. Measurement Parameters

Texture parameters of cooked noodles were determined using a Brookfield texture analyzer CT 3 (USA). A cylindrical probe with a diameter of 25 mm was positioned directly above the sample. The texture analyzer speed was set with a 5 g trigger, a distance of 2 mm, and a velocity of 5 mm/s. The cylindrical probe applied pressure directly to the center of the sample, and hardness, expressed in grams-force (gf), was recorded on the LCD display [24]. Water absorption was measured after cooking 20 g of fresh noodles in 300 mL distilled water for a suitable cooking time (wheat flour noodles: 8 minutes, potato added noodles: 3-4 minutes to be fully gelatinized), cooling for 1 minute in cold water, and removing the water for 30 seconds. The cooking loss was measured after drying the residual water from the water absorption test at 105°C for 24 hours. The volume increase was measured by filling 300 mL distilled water in a 500 mL mass cylinder and adding 20 g of fresh noodles and cooked noodles, respectively. All analyses were conducted in triplicate. The formulas used in the calculations are as follow:

Water absorption was examined using the procedure of Mulyadi et al. [25]. Five grams of wet noodle sample (A) were weighed using an analytical balance (Ohaus E1140). The sample was cooked in 150 mL of water (100°C) for 5 minutes, cooled in cold water (20°C) for 20 seconds and reweighed (B). Water absorption is calculated using Eq. (1) All analyses were conducted in triplicate.

$$\%\ water\ absorption = \frac{B - A}{A}\ x\ 100\% \qquad (1)$$

Note: A=initial weight of the sample, B =Weight of the sample post-boiling.

Cooking loss was measured using Mulyadi et al.'s approach [25]. After determining water absorption, the remaining water was dried at 100°C for 24 hours. All analyses were conducted in triplicate. Cooking loss was computed using Eq. (2).

$$\%\ cooking\ loss = \frac{weight\ of\ residue}{weight\ of\ sample} x\ 100\% \qquad (2)$$

Water solubility index was calculated using the Onyango et al. technique [26]. A 0.1 g sample was placed in a screw-cap test tube, and 10 mL of distilled water was added. The tube was heated in a water bath at 60°C for 30 minutes and manually swirled for 5 seconds at 5, 15, and 25 minutes intervals. The tube was centrifuged at 1,000 rpm x g for 15 minutes, then the supernatant was removed and the remaining sediment was weighed (Ws). The supernatant was dried to a constant weight (W1) in an oven at 100°C, defined as no further change in mass between two consecutive weight measurements. The water solubility index and swelling power were computed using Eq. (3) and (4).

$$\text{WSI orWater solubility index (\%)} = \text{W1}/0.1 \times 100\ \% \qquad (3)$$

$$Swelling\ powder = \frac{\text{Ws}}{0.1\ \text{x}\ (100\% - \text{WSI})} \qquad (4)$$

2.3. Data Analysis

The experiment was designed as a factorial Completely Randomized Design (CRD) with two treatment factors: frequency (20kHz and 40 kHz) and contact time (40, 45 and 50 minutes), each with three replicates. Data were analyzed using R studio. Analysis of variance was performed to determine significance of interaction variables at $p \leq 0.05$. Treatments showing significant effect were further analyzed using a 5% LSD.

3. Results and Discussion

3.1. Hardness

The average hardness of modified tapioca-based noodles ranged between 62.67 gf to 144.6 gf. The lowest hardness (62.67 gf) was observed at 20kHz for 40 minutes, while the highest (144.6 gf) occurred at 40kHz for 50 minutes (Fig. 1). High frequency combined with long contact time increases texture value due to increased granule damage, depolymerization, and temperature rise within the ultrasonic field, shifting molecular structure, decreasing water content, and hardening the noodle dough [27].

Table 1. Result of interaction between frequency and contact duration on the hardness, water absorption and cooking loss of noodles

Treatments	Hardness (gf)	Water absorption (%)	Cooking loss (%)
A1B1 (20 kHz, 40 min)	62.67 ± 0.81[a]	24.37±0.12[a]	33.42±0.17[a]
A1B2 (20 kHz, 45 min)	73.23 ± 1.27[ab]	29.36±0.63[b]	43.15±0.08[b]
A2B1 (40 kHz, 40 min)	88.63 ± 8.32[bc]	33.30±0.36[d]	58.38±0.65[e]
A1B3 (20 kHz, 50 min)	98.40 ± 1.46[c]	29.17±0.11[b]	45.46±0.14[c]
A2B2 (40 kHz, 45 min)	100.83 ± 2.57[c]	32.06±0.52[c]	51.93±0.84[d]
A2B3 (40 kHz, 50 min)	144.60 ± 9.60[d]	35.65±0.12[e]	58.55±0.22[e]

The 20 kHz treatment differed significantly from the 40 kHz treatment (Table 1). Ultrasonic waves are sound waves that produce cavitation energy, which is affected by frequency, incubation duration, and temperature [28]. Cavitation generates bubbles that explode upon bursting, damaging or rupturing starch granules due to the forces generated [29,30]. Elevated frequencies enhance cavitation energy, potentially causing augmented granule damage, depolymerization, and a reduction in starch molecular weight. Mechanical vibrations and cavitation disrupt the intramolecular hydrogen bonds in tapioca, destabilizing its molecular structure [31].

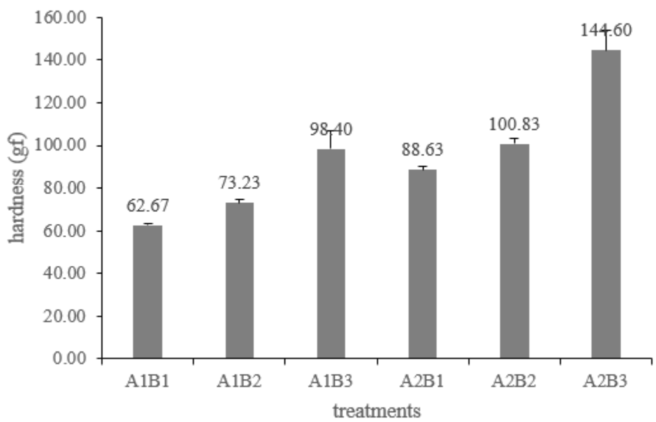

Fig 1. The average hardness value of modified tapioca-based noodles

Tapioca contains approximately 70% amylopectin and 30% amylose. Cavitation energy from ultrasonic waves damages the branch chains (amylopectin) at the starch peripheries, producing a straighter configuration. An increased number of straight chains, or amylose, correlates with a greater water absorption capacity [32]. Cavitation also induces granule swelling, making tapioca more hygroscopic. Mulyadi et al. [25] reported that noodles made from flour with elevated amylose levels yield a stiffer texture. Flour with elevated amylose content absorbs more water [25], and amylose's interaction with water creates a non-elastic structure; upon cooling, amylose reorganizes, leading to firmer noodles [33].

Table 2. LSD test at a 5% significant level for the impact of frequency and contact duration on the measured parameters.

Treatments	Texture (gf)	Water absorption (%)	*Cooking loss* (%)	*Water solubility index* (%)	*Swelling power* (%)
Frequency					
20 kHz	78.10±16.4[a]	29.01±3.8[a]	44.99±10.6[a]	5.47±0.4 [a]	3.26±12.5[a]
40 kHz	111.36±25.9[b]	31.30±2.8[b]	51.98±5.6[b]	7.51±0.7 [b]	3.96±6.5[b]
LSD 5%	6.22	0.37	0.46	0.52	0.34
Contact time					
40 minutes	75.65±14.2[a]	26.77±2.6[a]	39.44±6.5[a]	6.07±1.2 [a]	2.98±8.5 [a]
45 minutes	87.03±15.2[b]	30.71±1.5[b]	47.54±4.8[b]	6.37±1.1[ab]	3.80±6.2 [b]
50 minutes	121.50±26.5[c]	34.48±1.3[c]	58.47±0.4[c]	7.03±1.1[b]	4.05±0.1[b]
LSD 5%	9.35	0.57	0.72	0.754	0.49

Note: Different letters signify a substantial difference.

The 40-minute contact time differed considerably from the other treatments (Table 2), while the 50-minute treatment has the greatest texture value at 121.50 gf. Ultrasonic acoustic energy can be absorbed by molecules in a medium (for example, transformed into heat), with a portion generating acoustic cavitation, which is the formation, growth, and collapse of bubbles inside a liquid [34]. Increased contact time amplifies cavitation energy, causing greater damage to polymer structures and starch granules, as indicated by the higher number of bubbles formed [29]. The longer tapioca is exposed to ultrasound, the higher the sound waves and temperature, which are the primary factors driving its physical and chemical transformations.

3.2. Water Absorption

Water absorption refers to the noodle's ability to absorb the maximum amount of water while cooking. In this investigation, the water absorption capacity of noodles made from modified tapioca ranged between 24.37% and 35.65%. The greatest value was 35.65% at 40 kHz for 50 minutes, while the lowest was 24.37% at 20 kHz for 40 minutes (Table 1). Enhanced frequency and contact time increased water absorption in modified tapioca-based noodles. The cavitation energy from ultrasonic waves disrupts amylopectin's double helix folds, facilitating intermolecular interactions. Higher frequency and longer exposure increase cavitation energy, improving starch water absorption and swelling capacity [31].

Granule size also influences water absorption. Tapioca granules are spherical, averaging 10-15 µm, slightly larger than rice starch but smaller than other starches. Sonication damages granule structure, causing swelling and surface smoothing. Such damage alters the starch's physical and chemical properties, particularly its ability to absorb water. The sonication frequency utilized in starch modification increases water absorption [27].

3.3. Cooking Loss.

The average cooking loss varied from 33.42% to 58.55%, with the highest value of 58.55% at 40 kHz for 50 minutes, while the lowest at 20 kHz and 40 minutes (Table 1). Cooking loss increases with frequency and contact duration. Granule damage from sonication causes swelling, making starch granules more porous and prone to water absorption, but also easier to release, resulting in increased cooking loss [35]. Increased cooking loss is commonly associated with leaching of soluble starch fractions (e.g., amylose) into the cooking water. The concentration of the infusion or cooking water serves as a qualitative indicator of a significant cooking loss. Higher cooking loss in modified-tapioca noodles suggests weaker network integrity and greater solubilization of starch components, often resulting in a more brittle texture [27]. Frequency influences the natural structure of tapioca, causing granules to break down [31]. Granule damage from cavitation bubble implosion alters starch's physical properties, fragmenting polymer chains into shorter lengths [29,31]. The linkages between starch molecules in noodles significantly influence cooking loss; high-frequency-induced granule damage increases porosity and reduces bonding between starch molecules, leading to greater cooking loss.

3.4. Water solubility index.

The water solubility index values ranged from 5.03% to 8.10%, with the lowest value observed at 20 kHz for 40 minutes (5.03%) and the highest at 40 kHz for 50 minutes (8.10%) (Fig. 2). The water solubility index values for ultrasonically modified tapioca at 20 kHz and 40 kHz differed significantly ($p<0.05$). Higher frequencies produced greater water solubility index value (Table 1). This increase reflects the effect of sonication disruption via cavitation energy, which breaks down tapioca granules and alters their crystalline structure and covalent chains. As a result, water molecules can more readily interact with the hydroxyl groups of amylose and amylopectin through hydrogen bonding, resulting in increased water solubility index of ultrasonically modified tapioca [29,31].

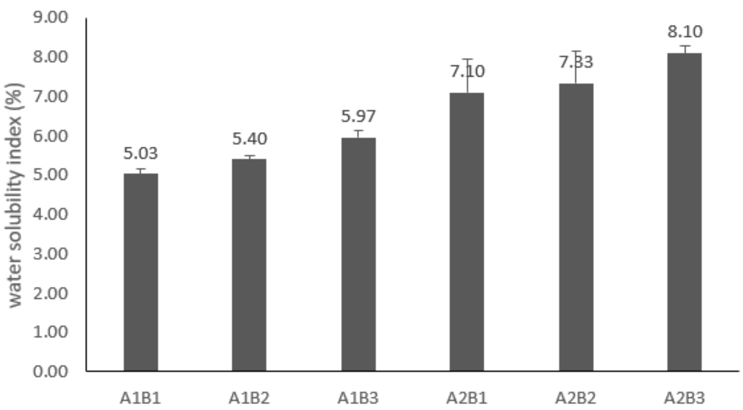

Fig 2. The water solubility index values

Tapioca's water solubility index value increases with longer ultrasound contact time (Table 1). The rise is induced by granule surface smoothing caused by significant physical changes in native tapioca, such as granule deformation and swelling [31]. Elevated temperature accelerates cavitation energy-generated microjet bubbles movement, promoting depolymerization of long polymer chains and breaking polymer crosslinks. Depolymerization converts amylose into shorter, straight chains, enhancing water solubility [29].

3.5. Swelling Power (SP)

Swelling power refers to the greatest rise in volume and weight of starch in water. It is primarily determined by amylopectin content and is an important metric in noodle manufacture. In this study, the average swelling power value ranges between 2.44% and 4.33%, with the highest value (4.33%) observed at 40 kHz for 50 minutes and the lowest (2.44%) at 20 kHz for 40 minutes (Table 1).

Swelling power at 40 kHz was significantly higher than at 20 kHz (Table 1). Ultrasonically modified tapioca has a larger swelling power with higher frequency. A higher SP value implies greater water uptake by the starch. Cavitation energy released from the collapse of ultrasonic-generated micro bubbles loosens and weakens the granular structure. Tapioca starch's swelling power increases at higher frequencies due to small fissures and indentations on the granules' surfaces, which enhance expansion. High-frequency treatments (ultrasound/microwave) effectively diminishes starch granules aggregation, restricting the development of a dense gel network and reducing viscosity through fragmentation and depolymerization of polymer chains [36]. Swelling power increases with contact time, as the cavitation energy of ultrasonic bubbles depolymerizes more polymer chains. Microjet formation from collapsing bubbles alter the granule structure, promoting leaching and increasing the SP value. Longer contact period elevates sonicator temperature, further enhancing granule leaching [31,37]. Swelling power is affected by water absorption capacity; higher water absorption leads to greater starch formation [38].

4. Conclusions

The application of ultrasonic technology to change tapioca starch directly influenced its physicochemical features. The treatment augmented water absorption capacity, elevated the solubility index, enhanced swelling power, and improved the texture of the noodles. Increased frequency (40 kHz) and extended contact lengths (45–50 minutes) amplified these results, although this also resulted in higher cooking loss.

Abbreviations

Not applicable.

Data availability statement

The author's article contains all of the data, which is listed in the references. If data needs to be shared, it will be done at the reader's request.

CRediT authorship contribution statement

Clara Rosalinda: conceptualization and methodology. Oksilia: writing review, editing, project administration. **Filli Pratama**: supervision, conceptualization and data curation. **Tri Wardani Widowati**: supervision, Conceptual.

Declaration of Competing Interest

The authors of this manuscript have no conflicts of interest to declare.

Declaration of Use of AI in the Writing Process

Nothing to disclose.

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