Review Article

The Potential and Current Applications of Tapioca (*Manihot esculenta* Crantz) Flour and Starch as Functional Ingredients in Food Products – a Review

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ABSTRACT

Tapioca, derived from the cassava plant (*Manihot esculenta Crantz*), stands as a versatile and significant starch source globally. Tapioca flour and tapioca starch present numerous promising opportunities for future applications in the food industry. The review explores tapioca's scientific foundations, examining its chemical composition and potential application in food products. Extensive research showcases tapioca flour's effectiveness as a gluten-free alternative, enhancing texture, moisture retention, and overall quality in gluten-free products. Tapioca's contributions to texture modification in food products, along with its remarkable thickening properties underscore its versatility in diverse food applications. Tapioca's remarkable versatility enhances its reputation as a food ingredient by consistently improving the quality of food products. Additionally, innovations in gluten-free food products using tapioca flour can cater to those with gluten intolerance or celiac disease, offering more diverse and nutritious options. In conclusion, while tapioca flour holds significant promise for future applications in the food industry, overcoming these challenges through research, innovation, and strategic planning will be essential for its successful integration into diverse food products.

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1. Introduction

The growing demand for alternative flour sources in food is largely driven by the dual challenges of climate crisis and violent clash, particularly in regions facing food insecurity (Queiroz *et al*., 2021). A substantial portion of wheat flour in many countries, particularly in Asia, is sourced from Russia and Ukraine. The ongoing conflict between these nations, along with the lingering effects of the COVID-19 pandemic, has intensified food insecurity, leading to a significant increase in hunger rates (Araujo-Encisco & Fellmann, 2020). In developed countries, consumer awareness is increasing regarding the health and environmental benefits of incorporating non-wheat ingredients into bakery products. Ingredients that are low in glycemic index, and rich in dietary fibre, protein, and bioactive compounds are gaining popularity (Wang & Jian, 2022). Gluten intolerance, a primary reason for seeking wheat flour substitutes, is associated with various health issues, including irritable bowel syndrome, autoimmune disorders, heart disease, depression, and conditions such as autism and epilepsy. Celiac disease, wheat allergy, gluten sensitivity, and non-celiac gluten sensitivity affect around 0.3% – 0.6% and up to 3% – 7% of the population, with higher prevalence in regions where wheat is a staple (Jayawarndana *et al*., 2019; Siddiqui *et al*., 2022). As gluten intolerance rises and the demand for healthier flour alternatives grows, there is increasing interest in exploring non-wheat flour options.

Cassava, scientifically known as *Manihot esculenta*, is a vital staple food for millions of people worldwide, particularly in tropical regions of Africa, Asia, and Latin America. This starchy tuberous root vegetable is a rich source of carbohydrates, making it a crucial dietary component for many communities (Falade & Akingbala, 2010; Chisenga *et al*., 2019). Cassava is valued for its ability to thrive in diverse environmental conditions, even in poor soil and low rainfall areas, making it a reliable food source for regions where other crops may struggle to grow (Burns *et al*., 2010). The versatility of cassava in culinary applications is remarkable, with various parts of the plant being utilised for both human food and animal feed (Figure 1). In addition to its role as a carbohydrate source, cassava is also valued for its nutritional content. It is a good source of energy, containing essential nutrients like vitamin C, folate, and minerals such as calcium, phosphorus, and potassium (Edhirej *et al*., 2017; Parmar *et al*., 2017; Bayata, 2019; Mohidin *et al*., 2023). The roots of the cassava plant are processed into various products, including cassava flour, tapioca pearls, and cassava chips.

The production of cassava flour and starch involves distinct processing methods, each tailored to extract specific components from cassava roots. Tapioca flour and starch have gained significant attention and prominence in various food applications due to their versatile properties and functionalities (Marchini *et al*., 2022). Cassava flour is produced through a relatively simple process that involves peeling the cassava roots to remove the outer skin, followed by washing, grating, drying, and milling into a fine powder. This process retains most of the cassava root's components, including fibre and protein, resulting in a whole-food product. In contrast, the production of tapioca starch involves more extensive processing to isolate pure starch granules. After peeling and washing, the cassava roots are crushed or grated to release the starch from the root cells. The resulting slurry is then filtered multiple times to separate the starch granules from the fibre and other impurities. The purified starch is subsequently settled, washed, and dried to obtain the final product (Abotbina *et al*., 2022). This process yields a higly refined product with minimal non-starch components, providing a neutral and highly functional ingredient (Obadi & Xu, 2021; Wulandari *et al*., 2023). Cassava flour and starch processing is exhibited in Figure 2.

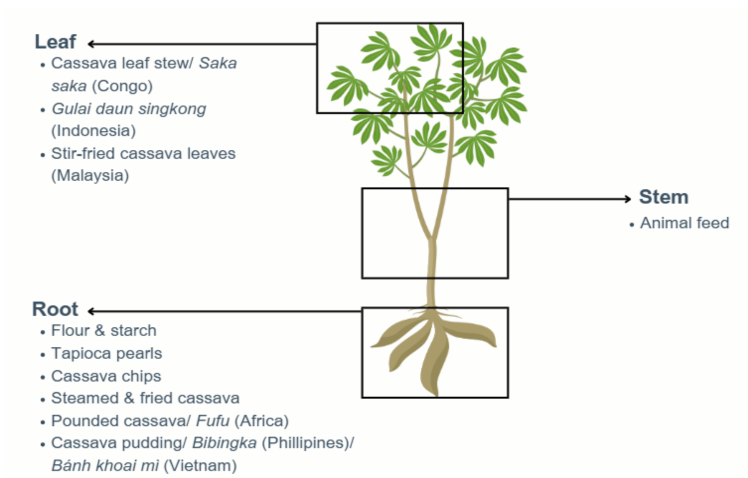

Figure 1 The leaves, roots, and stems of cassava are utilised worldwide for various culinary applications and as a source of animal feed in agriculture

Cassava flour and starch can undergo various modification processes to improve its physicochemical properties, encompasing 1) chemical, 2) physical, 3) enzymatic, and 4) fermentation methods. 1) Chemical modification involves oxidation, esterification, etherification, and acid hydrolysis that can alter the molecular structure of starch, enhancing its thermal stability, viscosity, and resistance to retrogradation (Clasen *et al*., 2018; Sondari & Iltizam, 2018; Wang *et al*., 2022). 2) Physical modification employs processes like heat treatment or pre-gelatinisation, which modify the granular structure without chemical additives, improving water absorption, swelling, gelatinisation properties, and reducing retrogradation tendencies (Dudu *et al*., 2019; Maniglia *et al.*, 2020; Oyeyinka *et al.*, 2021; Udoro *et al.*, 2021). 3) Enzymatic modification uses enzymes such as amylases and glucosidases to rearrange starch molecules, resulting in improved solubility, reduced viscosity, or tailored functional properties for specific applications (Cornejo *et al.*, 2022; Yuan *et al.*, 2022). Lastly, 4) fermentation utilises microbial activity to naturally modify the starch, often enhancing its nutritional profile, reducing anti-nutritional factors, and imparting desirable flavour and textural characteristics (Udoro *et al.*, 2021; Egbune *et al.*, 2023). Unfermented cassava flour is usually white, with no specific scent and a mild taste. Conversely, fermented cassava flour is characterised by its sour taste and distinctive aroma. When these methods are applied to cassava flour, the resulting product is referred to as modified cassava flour (mocaf), a gluten-free ingredient with improved functional properties suitable for various food and industrial applications. Together, these methods provide diverse approaches to tailor tapioca flour and starch for a wide range of uses.

One of the key advantages of tapioca flour and starch is their ability to serve as effective thickening and binding agents (Chatterjee *et al.*, 2019; Nimitkeatkai *et al.*, 2022). They can be used to thicken soups, sauces, gravies, and other liquid-based food products, contributing to the desired consistency and mouthfeel. Additionally, their binding properties make them useful in gluten-free (GF) baking, where they can substitute for wheat flour and provide structure and texture to baked goods (Aleman *et al.*, 2021; Aslan Türker *et al.*, 2023). Beyond their thickening and binding capabilities, tapioca flour and starch are prized for their clarity and glossy appearance when cooked. This property enhances the visual appeal of dishes, particularly in the case of puddings, pie fillings, and other desserts (Gravelle *et al.*, 2017; Swastike *et al.*, 2020). The neutral flavor of these ingredients allows them to be incorporated into a wide range of food products without significantly altering the overall taste profile (Nimitkeatkai *et al.*, 2022). Furthermore, tapioca flour and tapioca starch are widely used in cooking and baking due to their GF nature. This property makes them particularly valuable for individuals with gluten sensitivities or celiac disease, who require specialised food products that cater to their dietary needs (Horstmann *et al.*, 2017). The GF characteristics of tapioca flour and starch allow them to be used as substitutes for wheat flour in a variety of baked goods, such as breads, pastries, and cakes (Villanueva *et al.*, 2018; Aleman *et al.*, 2021). Hence, tapioca flour and starch are versatile, GF alternatives to wheat flour, making them significant for individuals with gluten sensitivities or celiac disease.

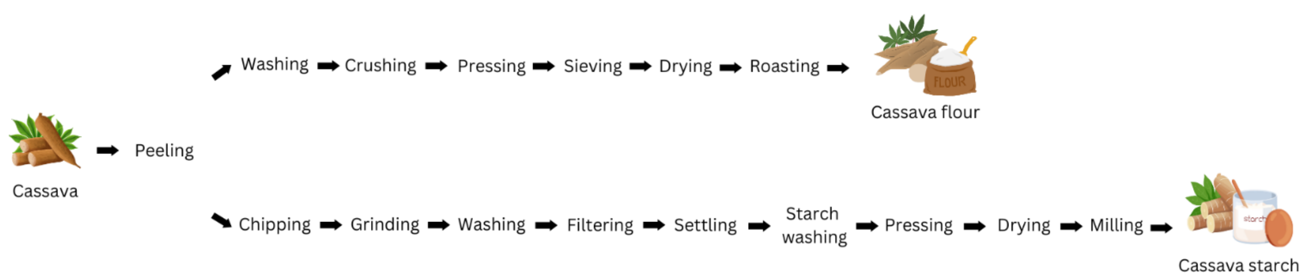

Figure 2 The processing pathways for cassava into cassava flour and tapioca starch

This comprehensive review intends to provide a comprehensive understanding of tapioca's potential and versatility in shaping the future of food science. Furthermore, this review aims to offer insights that can facilitate the optimal integration of tapioca-based ingredients, fostering innovation, and addresing emerging challenges in the dynamic field of food production and consumption. Ultimately, this comprehensive review aims not only to highlight the recent strides in tapioca application but also to emphasise on its significance as a transformative ingredient capable of enhancing food quality, sensory attributes, and nutritional profiles across diverse food categories and consumer preferences.

2. Different Varieties and Global Production of Cassava

Cassava is classified as a perennial plant propagated vegetatively, with starch-rich tuberous roots forming near the soil surface. Cassava has no defined phenological stage for harvesting. It is typically ready for harvest 6 to 7 months after planting. However, under conditions of cold or drought stress, harvesting may only be feasible 18 to 24 months after cultivation (Kongsil *et al.*, 2024). Cassava can taste either sweet or bitter, with most sweet cultivars being safe to consume as a boiled vegetable, while bitter cultivars require processing to reduce cyanide formed from the hydrolysis of cyanogenic glycosides (Alamu *et al.*, 2023). When cassava tissue is harvested or mechanically damaged, linamarin reacts with the enzyme linamarase to produce acetone cyanohydrin. This compound decomposes, releasing hydrogen cyanide (Panghal *et al.*, 2021). Bitter cassava typically contains hydrogen cyanide levels ranging from 15 to 400 mg per kilogram of fresh roots, whereas sweet cassava cultivars have significantly lower levels, between 15 to 50 mg per kilogram.

Cassava is cultivated in numerous varieties worldwide, with their distribution varying by location and country. In Nigeria, principal recommended varieties include TME419, TMS90257, TMS91934, TMS81/00110, and TMS82/0066 (Musa *et al.*, 2022). Thailand has introduced and developed multiple varieties, beginning in 1970 with the importation of five International Center for Tropical Agriculture (CIAT) varieties (CMC9, CMC36, CMC72, CMC76, and CMC84). This was followed by the introduction of 20 additional varieties and over 100,000 botanical seeds between 1975 and 1999, resulting in the release of notable varieties like Rayong 2, Rayong 3, and Rayong 60, with Rayong 3 later serving as a parent for Rayong 5 (Kongsil *et al.*, 2024). In Indonesia, superior cassava varieties include, Adira 1, Adira 2, Adira 4, Malang 1, Malang 2, Malang 4, Malang 6, DarulHidayah, UJ 3, UJ 5, UK 1 Agritan, Litbang UK 2, Vati 1, Vati 2, and Vamas 1, known for their high yield, good eating quality, and resistance to both biotic and abiotic stressors (Ngongo *et al.*, 2022). Similarly, the Democratic Republic of Congo has developed varieties such as Butamu (MV99/0395), Nsansi (9195/0160), RAV (85/297), MVUAMA 83/138, SADISA 91/203, Nambiyombiyo, M'baila, Nganga-na-butu, Nakarasai, M'Shediye, Nalubanda, Nabinzoza, Kanyunyi, Kamegere, and Kabunga (Mondo *et al.*, 2019; Nyaika *et al.*, 2024). In Ghana, key varieties include Tek Bankye, Gblemoduade (TMS 50395), Afsiafi (TMS 30572), Bankye hemaa, Sika bankye, Deboo, and Esi abaya (Owusu & Donkor, 2012; Kondo *et al.*, 2020; Nyaika *et al.*, 2024) while Brazil features the Naitama-31 variety (Mohidin *et al.*, 2023). This distribution highlights the diversity of cassava varieties cultivated worldwide. Table 1 presents cassava varieties from the world's leading cassava-producing countries.

Table 1 Cassava varieties from the world's leading cassava-producing countries

Country/region	Cassava varieties	References
Nigeria	TME419, TMS90257, TMS91934, TMS81/00110, TMS82/0066	Musa *et al.* (2022)
Thailand	CMC9, CMC36, CMC72, CMC76, CMC84, Rayong 2, Rayong 3, Rayong 60, Rayong 5	Kongsil *et al.* (2024)
Indonesia	Adira 1, Adira 2, Adira 4, Malang 1, Malang 2, Malang 4, Malang 6, DarulHidayah, UJ 3, UJ 5, UK 1 Agritan, Litbang UK 2, Vati 1, Vati 2, Vamas 1	Ngongo *et al.* (2022)
Democratic Republic of Congo	Butamu (MV99/0395), Nsansi (9195/0160), RAV (85/297), MVUAMA 83/138, SADISA 91/203, Nambiyombiyo, M'baila, Nganga-na-butu, Nakarasai, M'Shediye, Nalubanda, Nabinzoza, Kanyunyi, Kamegere, Kabunga	Mondo *et al.* (2019); Nyaika *et al.* (2024)
Ghana	Tek Bankye, Gblemoduade (TMS 50395), Afsiafi (TMS 30572), Bankye hemaa, Sika bankye, Deboo, Esi abaya	Owusu & Donkor (2012); Kondo *et al.* (2020); Nyaika *et al.* (2024)
Brazil	Naitama-31	Mohidin et al., 2023

These varieties often exhibit differences in physicochemical properties, influenced by factors such as genotype and environmental growth conditions (Brown *et al.*, 2016; Tappiban *et al.*, 2020). Genetic differences among cassava varieties has been reported to have attributed to the variations in flour particle size even when external factors like cultivation and processing are standardised (Vasconcelos *et al*., 2017; Chisenga *et al*., 2020). This suggests that the variations arise from inherent genetic traits of the cassava genotypes, such as differences in starch structure, root density, or cellular composition which influence the break down level of the roots during milling. In 2021, global cassava production reached 324.7 million tonnes. Africa accounted for the largest share, contributing 64.7% of the total, followed by Asia (26.7%), the Americas (8.5%), and Oceania (0.1%) (Figure 3a). Among individual countries, Nigeria led as the top producer, contributing 19.4% of global output, followed by the Democratic Republic of Congo (14.1%), Thailand (10.8%), Ghana (7.0%), Brazil (5.6%), and Indonesia (5.5%) (Figure 3b) (Sowcharoensuk, 2024).

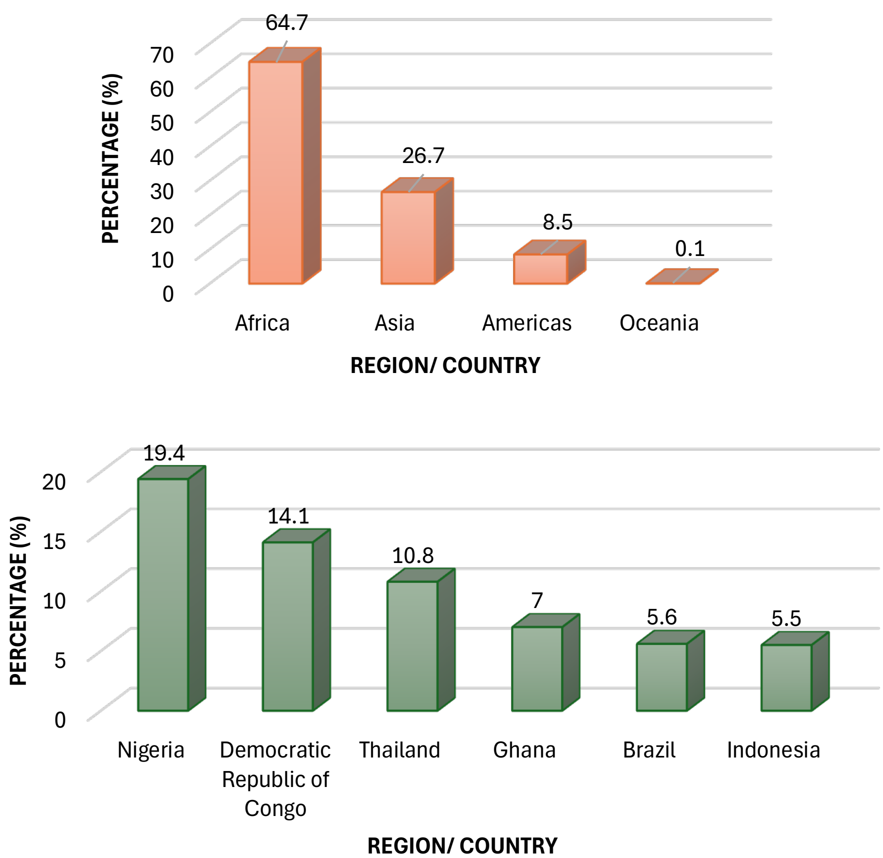

Figure 3 Cassava production in 2021 by region (top) (Figure 3a) and by top-producing countries (bottom) (Figure 3b)

3. Nutritional Composition and Health Benefit

The nutritional composition of tapioca is influenced by several factors, including geographic location, cultivated variants, plant maturity, processing techniques, and environmental variables (Mamat *et al*., 2020; Hasmadi *et al*., 2021). Tapioca roots are rich in calories derived from carbohydrates, with dried forms containing a high percentage of total starch (76.4 – 94.34%) in the form of amylose and amylopectin (Pereira & Leonel, 2014; Lu *et al*., 2019; Rachman *et al*., 2020). On average, amylose constitutes about 15–30% of the carbohydrate content, while amylopectin accounts for approximately 70–80% (Oladunmoye *et al*., 2014; Aidoo *et al*., 2022). Tapioca flour and starch are generally low in protein (0.13–5.71%), fat (0.17–3.36%), and ash (0.36–2.78%). Ash content reflects the mineral composition of food samples. In sweet varieties, approximately 17% of the carbohydrate content is sucrose, with small amounts of fructose and dextrose also present. Although low in proteins, the amino acid profile of tapioca root is comparable to other root tubers in essential amino acids like lysine and threonine. Tapioca is also high in aspartic acid, glutamic acid, and arginine (Montagnac *et al*., 2008; Salvador *et al*., 2014). Fibre content in tapioca flour is higher (4%) compared to that of raw tapioca (1.7%) (Salvador *et al*., 2014). Dried tapioca contains significantly more carbohydrates (80 – 90%) than its raw counterpart (32 – 35%). Despite these benefits, the use of tapioca as a food source remains limited due to its low levels of protein, vitamins, and minerals compared to other cereals, legumes, and some root as well as tuber crops. Rudo *et al*. (2017) suggested that biofortifying tapioca with essential nutrients such as vitamins, minerals, and protein could make it a viable option for providing complete nutrition in a single meal, especially for the impoverished and malnourished. The nutritional composition of tapioca flour is shown in Table 2.

Moreover, postharvest processing techniques like solid-state fermentation with *Sporotrichum pulverulentum* have been reported to increase the crude protein content of tapioca while reducing its cyanogen content by 95%. This prebiotic activity could enhance gut health and overall digestive well-being. Furthermore, tapioca flour has been identified as a rich source of phenolic compounds (Nilusha *et al*., 2021). Native cassava starch can be modified through physical, chemical, and enzymatic methods to produce resistant starch. Such modifications may influence the nutritional composition of cassava-based resistant starch. Falade *et al*. (2019) reported a decrease in apparent amylose content following citric acid modification, which was attributed to the hydrolysis of the crystalline and amorphous regions of starch. In contrast, Ramya *et al*. (2018) observed an increase in amylose content and the formation of longer amylose chains due to cross-linking when 20% and 60% citric acid concentrations were used during modification. These differing outcomes may be attributed to variations in citric acid concentrations of differences in cassava varieties utilised in the studies.

Table 2 Nutrient composition of tapioca flour and starch

Cassava products	Nutritional composition (%)					
	Moisture	**Ash**	**Fat**	**Protein**	**CHO**	**References**
Flour	6.35	2.78	3.36	5.71	80.07	Aderinola *et al*. (2023)
	4.45 – 9.91	1.01 – 2.06	0.21 – 0.64	1.09 – 1.70	86.28 – 93.13	Nilusha *et al*. (2021)
	5.97 – 6.33	2.19 – 2.43	0.55 – 0.68	2.07 – 2.69	26.39 – 27.02	Hasmadi *et al*. (2020)
Starch	5.6	0.74	-	1.12	-	Aro & Aletor (2012)
	-	0.36 – 0.37	0.37	0.13 – 0.17	-	Abioye *et al*. (2017)
	7.1	0.45	0.17	0.32	90.8	Chinma *et al*. (2011)

4. Tapioca Flour and Tapioca Starch in Food Products

Tapioca flour and starch are highly versatile ingredients widely utilised in the food industry. Renowned for their distinctive properties, they are incorporated into various food applications, including gluten-free baking and innovative snack production. Table 3 highlights the applications of tapioca flour and starch in different food products.

4.1 Bakery products

4.1.1 Biscuits

Biscuits have become a staple in the bakery industry, holding a significant position due to their appealing qualities and widespread popularity. As a versatile snack, biscuits offer numerous benefits that contribute to their success in the food market (Arepally *et al.*, 2020). Cassava and its blends are widely utilised in biscuits due to their baking qualities. Incorporating cassava flour in biscuit recipes can improve nutritional value, provide a GF option, and offer a cost-effective alternative (Di Cairano *et al.*, 2018; Xu *et al.*, 2020; Siddiqui *et al.*, 2022). Cassava flour is ideal for biscuit production due to its GF nature, neutral flavour, excellent binding properties, and high starch content (Chisenga *et al.*, 2019; Salehi, 2020). The quality of cassava flour or starch for biscuit production is influenced by factors such as the cultivar, pre-processing storage of the tubers, storage conditions of the flour or starch, and the maturity of the crop (Akingbala *et al.*, 2005; Akingbala *et al.*, 2009).

Ling *et al.* (2024) developed healthier biscuit alternatives by combining tapioca, desiccated coconut, and wheat flours in the following ratios of 30:20:50 (F1), 30:30:40 (F2), 30:40:30 (F3), and 30:50:20 (F4), respectively. F3 formulation emerged as the best formulation based on a hedonic test. In comparison to the control (100% wheat flour), F3 showed higher moisture, crude fibre, and carbohydrate content, and had a comparable spread ratio, colour, and pH. The study demonstrated that these flour blends yielded promising outcomes, suggesting their potential to enhance both the nutritional quality of biscuits and consumer satisfaction.

Laguna *et al.* (2012) utilised N-Dulge (a mix of tapioca dextrin and tapioca starch) (ND) to enhance the texture and sensory profile of low-fat shortbread biscuits. To counteract texture changes from ND substitution, resistant starch (RS) was added, replacing part of the flour. RS significantly improved texture, particularly with higher RS (40% wheat flour replacements) and lower ND (10% shortening replacement, making the biscuits' texture comparable to the control. Furthermore, Adelakun & Abiodun (2017) examined the impact of soy malt addition on the properties of cassava-wheat composite flour and its suitability for biscuit production. It was found with varying ratios of cassava, wheat and soy malt increased the protein, vitamin and mineral. In addition, the composite flour of wheat-cassava-soymalt with ratio 70:15:15 was the most favourable and comparable with control (100% wheat flour).

Moreover, the demand for GF products has significantly expanded in recent years due to heightened awareness of celiac disease, gluten sensitivity, and the growing popularity of GF diets for supposed health advantages. Out of all these goods, GF biscuits have attracted considerable interest (Zhao *et al.*, 2023; Silva-Paz *et al.*, 2024; Goh *et al.*, 2024). Biscuits stand out among GF baked items due to their exquisite mix of texture, flavour, and nutritional content. Muzamil *et al.* (2024) developed and assessed the organoleptic properties of GF biscuits made from tapioca and corn flour blends. The study showed that T4 formulations of GF biscuits, produced with a 50:50 ratio of tapioca to corn flour, demonstrated superior sensory qualities and greater consumer acceptability compared to the control made with wheat flour and samples made with either tapioca or corn flour individually. This indicates that tapioca blends could be promising alternatives for developing GF products. Similar findings were reported by other researchers (Akubor & Ukwuru, 2003; Obadina *et al.*, 2014; Aly and Seleem, 2015; Ratnawati *et al.*, 2024).

4.1.2 Cookies

Cookies are generally characterised by their high sugar and shortening content and are typically classified as baked goods made from soft wheat flour with a relatively low water content (Manley, 2011). Tapioca flour and tapioca starch have emerged as valuable ingredients in the production of cookies (Ayuningtyas *et al.*, 2019; Xu *et al.*, 2020; Jannah *et al.*, 2021; Khurshida & Deka, 2021; Stoin *et al.*, 2021; de Souza *et al.*, 2022). In GF formulations, the addition of flour and starch helps to provide structure and texture in the absence of wheat flour, making them crucial components for cookies developed for individuals with celiac disease or those adhering to a GF diet (Abdi *et al.*, 2023; Sresatan *et al.*, 2024).

Previous study by Montes *et al.* (2015) developed cookies using tapioca and rice flours. The combination of tapioca and rice flour has been shown to result in cookies that are well-accepted by consumers, with a softer and more palatable texture compared to cookies made solely with wheat flour. The higher proportion of tapioca flour (75%) in the formulation resulted in higher sensory scores compared to a 50:50 tapioca-to-rice flour ratio, indicating that tapioca flour can be effectively used in various formulations to achieve desirable sensory properties. In addition, these cookies have been found to have higher specific volume compared to the control, reflecting lighter weight and greater volume expansion after baking. In addition, to its technological sensory benefits, tapioca flour can also enhance the nutritional value of cookies (Hartati & Royanda, 2021). Moreover, Lee *et al*. (2013) evaluated the effects of tapioca starch (TS) and tapioca modified starch (TMS) as additives (5%, 10%, 15% w/w) on rice cookie quality. TMS addition significantly reduced dough hardness, as well as cookie hardness compared to TS. Cookies with TMS had higher spreadability, lighter colour, and lower bulk density. Sensory evaluation revealed 10% TS rice cookies scored highest in overall acceptability, taste and texture, while 15% TMS cookies excellent in flavour and brittleness. Overall, adding TS and TMS improves rice cookies' quality and sensory attributes.

Three-dimensional (3D) food printing is gaining interest in the food industry for its ability to create customised products that meet individual sensory and nutritional requirements. Tapioca flour has shown promise as an ideal material for cookie production, especially in extrusion-based 3D printing (Chen *et al*., 2024). Pulatsu *et al*. (2020) studied the factors influencing the printability and post-processing of cookie dough in extrusion-based 3D printing, without the use of gums or stabilisers. Various flours, including wheat, rice, and tapioca were investigated for their printability and post processing capabilities. The results revealed that tapioca flour was the most effective, yielding cookie samples that were easy to print, had better visual outcomes, and maintained structural integrity after baking.

4.1.3 Crackers

Crackers play a vital role in the snack food industry, valued for their nutritional content and versatility as a convenient vehicle for cereals in snack form. They are classified as either fermented or non-fermented, with the protein content of the flour being the defining factor (Manley, 2011). Each component in the cracker-making process is essential in determining the final product's quality, with flour, as the main ingredient, determining the fermentation status of the resulting cracker (Tiwari *et al*., 2023). Tapioca flour has indeed become a popular ingredient in the production of high-quality crackers due to its unique properties and benefits.

Liu *et al*. (2023) evaluated the feasibility of using damaged cassava starch (DCS) for staple food production. DCS was obtained through mechanical activation with varying levels of damage. The results revealed that DCS formed a cohesive dough structure when the damage level was above 11.51%. The texture of DCS dough at 11.51% and 15.37% damage resembled wheat flour dough. Interestingly, DCS crackers exhibited sensory qualities comparable to wheat flour crackers. These findings highlight the potential of DCS for developing staple foods. Moreover, Otero-Guzmán *et al*. (2023) examined modified cassava starch as a fat substitute in crackers. Among the modified starches used in the formulation, the treatment with enzymatic starch (amyloglucosidase) and the physical treatment (pregelatinised starch) produced a product with a texture, specific volume, weight loss, water holding capacity, and sensory characteristics closer to the control, achieving a total fat reduction of 49.51% in the final product. The study's results indicate that enzymatically and physically modified starches can serve as effective fat replacers in the production of various bakery products.

4.1.4 Bread

Tapioca flour and starch have garnered considerable interest in bread production due to their distinctive properties and advantages (Balic *et al*., 2017; Aristizábal *et al*., 2017). These ingredients can be effectively utilised in bread making to enhance specific attributes of the final product. Known for their neutral flavour and odour, they offer excellent thickening, and binding properties while producing a clear, translucent appearance upon cooking, thereby enhancing the bread's visual appeal (Rodriguez-Sandoval *et al*., 2017; Chisenga *et al*., 2020). Benefits include improved crumb texture, softness, volume, and sensory qualities. Moreover, tapioca-based ingredients positively influence dough rheology, resulting in more extensible and manageable doughs during bread preparation (Pongjaruvat *et al*., 2014).

The replacement of wheat flour with alternative types of flour in bread making holds significant quality importance. Eduardo *et al*. (2013) evaluated the quality characteristics of bread made from cassava-wheat-maize flour blends. The study utilised cassava flour at concentrations of 20% to 40% (w/w) and incorporated high-methylated pectin (HM-pectin) at levels of 1% and 3% (w/w). The findings demonstrated that adding pectin facilitated the production of bread with acceptable quality, even at higher cassava flour concentrations (up to 40% in the blend). The inclusion of pectin notably improved the volume of bread made with high levels of roasted cassava flour. Furthermore, crumb firmness comparable to that of wheat bread was achieved using both sun-dried and roasted cassava flours. Chisenga *et al*. (2020) investigated the effects of incorporating cassava flours from six Zambian varieties into wheat flour at ratios of 90:10, 80:20, and 70:30 for bread making. The study concluded that wheat can be substituted with cassava flour from Mweru, Kariba, and Katobamputa varieties at levels up to 10% without significantly reducing bread quality. Notably, cassava inclusion generally reduced bread weight loss. Further research is essential to explore higher substitution levels.

Milde *et al*. (2012), investigated the use of a composite blend of tapioca starch and corn flour (80:20), supplemented with vegetable fat, egg, and soybean flour. This formulation demonstrated 84% acceptability among wheat bread consumers and 100% among individuals with celiac disease, producing spongy, high-volume bread with excellent sensory qualities. Sigüenza-Andrés *et al*. (2021) investigated the impact of incorporating various forms of cassava (flour, native starch, and sour starch) into GF bread by substituting 20% of a maize starch or rice flour mixture with cassava products. The addition of 10% cassava products improved bread quality and volume but increasing the cassava content to 20% diminished these improvements and reduced the specific volume. Cassava starch breads were softer compared to the control breads, even after 7 days. Additionally, Padalino *et al*. (2016) highlighted that tapioca flour and starch help prevent bread from becoming dry and crumbly while acting as a binder to improve cohesion and stability in gluten-free bread formulations.

4.1.5 Cake

A cake is a confectionary product produced through baking a mixture of flour, sugar, eggs, and butter or oil, combined with other flavourings such as vanilla, chocolate, or fruits (Conforti, 2014). Cakes can vary greatly in texture and appearance, ranging from airy and delicate to dense and indulgent. These differences are primarily determined by the choice of ingredients and the baking techniques used (Wilderjans *et al*., 2013). Several studies have explored the use of tapioca flour and tapioca starch (Olanrewaju and Moriyike, 2013; Tsatsaragkou *et al*., 2015; Aslan Türker *et al*., 2023). These ingredients play a significant role in cake production, particularly in GF baking, where they serve as essential functional components. Chaiya and Pongsawatmanit (2011) explored the use of tapioca starch (TS) as a partial substitute for wheat flour in sponge cake preparation. The results showed that increasing TS substitution aided in the incorporation of more air into batter, subsequently increasing the specific volume and softness, as well as achieving higher overall liking scores compared to the control (100% wheat flour). Chaiya *et al*. (2015) optimised a wheat flour-based sponge cake formulation containing TS and xanthan gum (XG). The study investigated the effects of substituting 5 – 15% TS for wheat flour and adding 0.1 – 0.3% XG. The optimal formulation consisted of 11.09% – 11.88% TS and 0.1% – 0.11% XG, achieving the desired physical properties and the highest overall sensory liking scores.

4.2 Noodles

Tapioca flour and starch have emerged as a versatile ingredient in the production of noodles, offering a range of benefits and applications (Eguchi *et al*., 2014; Pato *et al*., 2016; Kamsiati *et al*., 2022; Hamidah *et al*., 2023; Nurdin *et al*., 2023). In noodle formulations, tapioca flour is commonly used in composite flour blends, often in combination with whole wheat flour and defatted soy flour (Vijayakumar & Boopathy, 2014; Huh *et al*., 2019). These flour combinations help to create noodles with desirable quality characteristics, leveraging the unique properties of each ingredient (Olorunsogo *et al*., 2023).

One of the main benefits of adding tapioca flour to noodle recipes is its ability to enhance the texture and elasticity of the final product. Tapioca starch contributes to a desirable soft and elastic mouthfeel, delivering the ideal combination of softness and elasticity that consumers associate with high-quality noodles (Fukuzawa *et al*., 2016; Li *et al*., 2020). Pokharel *et al*. (2023) investigated the impact of adding porous tapioca starch on the cooking quality and texture of white salted (udon) noodles. This study utilised enzyme-ultrasound treatment to produce porous tapioca starch. The results showed that adding 5% porous starch was optimal, leading to shorter cooking times, higher water absorption, and reduced cooking loss compared to the controls. Additionally, texture analysis revealed reduced noodle hardness while maintaining desirable characteristics. Abidin *et al.* (2013) suggests that tapioca flour can be a viable alternative to wheat flour in noodle formulations. The study found that noodles made with tapioca flour contain relatively low fat content of 0.72%, compared to the typical range of 1% - 2.5% found in other wet noodles, meeting the growing market demand for lower-fat products. The sodium content, at 0.7%, constitutes 29.5% of the recommended daily intake of 2400 mg, indicating a moderate sodium level. Furthermore, the protein content of 5.1% surpasses the typical range of 4.6% - 6% in traditional wet noodles, highlighting its protein-rich composition. The carbohydrate and water content of this noodle product also fall within favourable ranges, further enhancing its nutritional profile and market appeal.

On the other hand, Wahjuningsih *et al*. (2023) studied the role of mocaf and latoh in noodle production and found that adding these ingredients to wheat noodles improved their physical and chemical quality while increasing consumer acceptance. The mocaf-latoh noodles had low fat but high carbohydrate content, making them suitable as a quick energy source. These noodles exhibited excellent gel characteristics and contained 15 amino acids, including 7 essential ones. However, due to lower wheat flour content, elasticity was reduced, but the noodles were still deemed acceptable by the panellists. In general, the optimum formula was 63% mocaf, 36% wheat, and 1% latoh, suggesting that mocaf and latoh can help reduce reliance on wheat in noodle production. These findings highlight the potential of porous tapioca starch as a functional ingredient in noodle development. Jang *et al*. (2023) aimed to determine the chemical, physical, and organoleptic characteristics of shirataki noodles made from different ratios of porang and tapioca flours (100:0, 80:20, and 70:30). The study revealed that the optimal formulation consisted of 70% porang flour and 30% tapioca flour, resulting in balanced texture, moisture content, and overall quality. Reducing the amount of porang flour decreased elasticity and rehydration properties.

4.3 Pasta

The pasta industry has recently experienced innovations and trends focused on improving health benefits, addressing dietary restrictions, and offering new flavours (Gao *et al*., 2018; Bianchi *et al*., 2021; Sissons, 2022). The use of tapioca flour in pasta production offers a promising path for innovation in the food industry, driven by the demand from health-conscious consumers (Carpentieri *et al*., 2022; Wang *et al*., 2022; Bińkowska *et al*., 2024). Additionally, it is known for its GF properties and can serve as a valuable substitute for wheat flour, offering a versatile and inclusive option for individuals seeking GF pasta alternatives (Ramírez *et al*., 2019; García-Caldera & Velázquez-Contreras, 2019; Bolarinwa & Oyesiji, 2021). The nutritional benefits of adding tapioca flour to pasta are substantial, as it is a rich source of carbohydrates, enhancing the overall nutritional value of the final product (Ferraro *et al*., 2016; Rachman *et al*., 2019; Galassi *et al*., 2023). Sensory evaluations of pasta made with tapioca flour have consistently shown high consumer acceptability, highlighting its positive impact on the quality and sensory experience of pasta (Padalino *et al*., 2016; Culetu *et al*., 2021). Furthermore, the cost-effectiveness of using tapioca flour in pasta production adds to its attractiveness. Tapioca flour is relatively inexpensive compared to traditional wheat flour, offering a practical and economical solution for manufacturers looking to diversify their product range (Breuninger *et al*., 2009).

Many previous studies have shown promising results regarding the cooking properties and acceptability of composite pasta containing tapioca flour. Milde *et al*. (2020) developed a GF pasta using 80% cassava starch and 20% corn flour, with varying concentrations of XG (0.4%, 0.6%, and 0.8%) to optimise the product. The study found that XG improved dough handling and overall pasta quality. The 0.6% XG concentration showed the best results, reducing cooking loss and improving texture parameters such as firmness, cohesiveness, chewiness, springiness, and cutting force. In many African countries, cassava roots are fermented to improve shelf life, nutritional value, and sensory properties. Fermented tapioca flour has shown benefits in pasta production, enhancing texture, flavour, and overall quality. Odey & Lee (2020) studied the effects of cassava root fermentation on flour and pasta quality. Longer fermentation (12, 36, 60 hours) increased moisture, carbohydrate content, water absorption, swelling, and solubility index. It also improved pasting viscosities. Pasta made from cassava fermented for 36 hours had the best textural properties and eating qualities.

4.3 Snacks

Cassava flour and starch, known for their ability to modify the rheological properties of food systems, are indispensable in snack formulations, significantly improving the quality and sensory appeal of snack products (Euan-Pech *et al*., 2024). Tapioca flour is also noted as an effective thickening agent, contributing to the desired consistency and texture in various snacks (Sajilata & Singhal, 2005; Fuongfuchat *et al*., 2012). Its versatility makes it suitable for different formulations to achieve optimal texture and sensory qualities (de Oliveira Gonçalves *et al*., 2024). These ingredients are widely utilised in various snack preparations including fish crackers (Akonor *et al*., 2017; Yahya *et al*., 2017; Ramesh *et al*., 2018; Yahya *et al*., 2023), fried chips (Ahza *et al*., 2015; Pornpraipech *et al*., 2017; Sobukola *et al*., 2021), fried chips snack bar (Prazeres *et al*., 2017; dos Prazeres *et al*., 2020; Murdiani *et al*., 2022), extruded products (Obadina *et al*., 2013; Patel *et al*., 2016; Chinellato *et al*., 2016), and ready-to-eat snacks (Yewale & Chattopadhyay, 2013).

One of the most notable attributes of tapioca flour and starch is their ability to enhance the texture and structure of snack products. Ketipearachchi *et al*. (2023) investigated the use of cassava flour as a supplementary ingredient alongside wheat flour in snack production. Five different ratios of cassava to wheat flour (100:0, 75:25, 50:50, 25:75, and 0:100) were evaluated. The study found that a 25:75 ratio of cassava to wheat flour was the most preferred based on sensory attributes. Moreover, tapioca flour has been shown to increase the expansion ratio while reducing bulk density and hardness in snack products compared to sorghum flour. This results in a lighter, crispier texture, which is often desirable in extruded snacks (Patel *et al.*, 2016).

Furthermore, tapioca flour plays a crucial role in the production of GF snacks, offering a viable alternative to wheat flour for individuals with gluten sensitivities or dietary restrictions. Leonel *et al*. (2019) explored the application of cassava-derived ingredients in the production of GF salty expanded snacks. Composites of cassava sour starch and leaf flour were processed using a single-screw extruder under varying conditions. The optimal formulation, which included 6% cassava leaf flour mixed with cassava sour starch, yielded snacks that were highly crisp, light in colour, and well-received in sensory evaluations. These results highlight the potential of cassava sour starch and leaf flour as valuable ingredients for developing extruded GF products.

4.4 Meat products

Tapioca flour and tapioca starch play a vital role in improving the quality and functionality of meat products in many applications (Devadason *et al*., 2010; Handayani *et al*., 2023; Ristanti *et al*., 2023; Wei *et al*., 2023; Nuhriawangsa *et al*., 2023; Puechkamutr and Arsa, 2024). An important function of tapioca in meat processing is its ability to improve the texture of the meat. In general, flour or starch added to the meatball mixture serves as a filler and binder, enhancing the texture, increasing water-holding capacity and elasticity, and minimising shrinkage during cooking (Widati *et al*., 2022 Salsabila *et al*., 2024).

Chatterjee *et al*. (2019) compared tapioca flour with traditional meat binders (potato flour, garbanzo flour, and egg white) in chicken breast patties. Tapioca flour showed comparable sensory attributes to potato and garbanzo flours but reduced meat cohesiveness, hardness, and chewiness. Improvement in water-holding capacity enhanced the texture, making it comparable to or better than other binders. Moreover, incorporating tapioca flour into meat products can alter their physical properties, sensory texture, and flavour (Tee and Siow, 2017; Swastike *et al*., 2020; Damanik *et al*., 2022). Handayani *et al*. (2023) examined the effect of tapioca flour (0, 5, 10, 15 and 20%) on ready-to-eat ground beef jerky. The study found that 10% tapioca flour produced jerky with optimal water and protein content, good sensory attributes, and compliance with Indonesia's microbial safety standards. Moreover, Ayandipe *et al*. (2022) developed GF chicken sausages using a composite flour of 20% high-quality cassava flour (HQCF) and coconut flour. Sensory evaluation showed no significant difference in aroma, appearance, taste, or tenderness compared to sausages made with wheat flour and HQCF alone. The study concluded that 4.80% coconut flour and 15.20% HQCF effectively replace wheat flour, offering a GF alternative. On the other study, Pereira *et al*. (2019) studied the effects of rice flour (RF), glutinous rice flour (GRF), and tapioca starch (TS) on the properties of emulsion-type sausages. TS significantly improved emulsion stability, cooking yield, and moisture retention, outperforming RF and GRF. While RF and GRF reduced fat loss and fluid release, TS also formed a firmer, more uniform gel and immobilised more water in the sausage. This shows that TS is a superior ingredient, with RF and GRF offering functional benefits. Additionally, tapioca serves as a fat mimetic in low-fat formulations, providing a similar mouthfeel without the added calories or cholesterol (Jalal *et al*., 2013; Brewer, 2012; Olcay, 2020; Kumar *et al*., 2023). In the study by Nissar *et al*. (2009), the effects of 2%, 3%, and 4% TS on low-fat buffalo meat patties (LFBMP) and high-fat patties (HFBMP) were evaluated. The results showed that LFBMP with 3% TS had the highest moisture content, improved cooking yield, reduced shrinkage, and lower calorie content. It also scored highest in juiciness, texture, and overall acceptability. The study concluded that 3% TS effectively replaced fat in buffalo meat patties.

4.5 Prebiotic products

Tapioca flour has been gaining attention not only for its versatility in various culinary applications but also for its potential as a source of prebiotics (Kaulpiboon *et al*., 2015; Gurbanov *et al*., 2021). Prebiotics are substrates that are selectively utilised by the host's microorganisms, resulting in benefits for metabolic health, the gastrointestinal system, bone health, and mental health (Alves-Santos *et al*., 2020). Tapioca flour contains resistant starch, which acts as a prebiotic by resisting digestion in the small intestine and reaching the colon intact. Here, it serves as food for beneficial gut bacteria, promoting a healthy balance of gut microbiota (Nabeshima *et al*., 2020; Pranoto, 2022). In addition, the resistant starch in tapioca flour supports the growth of beneficial bacteria such as *Bifidobacteria* and *Lactobacilli* in the gut. Thus, improving digestive health, reducing inflammation, and enhancing immune function (Wen *et al*., 2022).

5. Challenges of Tapioca Flour in The Food Industry

Despite its potential, the use of tapioca flour and starch in the food industry faces several challenges, with nutritional limitations being a primary concern. While tapioca serves as a high-energy food source, it is nutritionally inadequate due to its low levels of protein, vitamins, and minerals (Montagnac *et al*., 2009). This restricts its appeal to health-conscious consumers or markets emphasising nutrient-dense food products. Numerous past studies have focused on fortifying and enriching tapioca-based food products, providing evidence of efforts to address its limitations as a nutritionally restricted functional ingredient. Various fortification strategies have been explored, including incorporation of protein-rich ingredients such as defatted groundnut cake, tiger nuts, and almond seed (Arinola *et al*., 2013; Adeoti *et al*., 2017; Adeboye *et al*., 2018). Parente *et al*. (2021) investigated the fortification of traditional Brazilian cassava gum and tapioca pancakes with carotenoids from carrots to increase the carotenoid content. Similarly, Nurdin *et al*. (2023) developed fortified tapioca noodles using a mixture of turmeric, cinnamon, and guava leaf powders, enhancing the noodles' phenolic and flavonoid content. To increase dietary fibre, Sirinjullapong *et al*. (2024) enriched GF tapioca crackers with banana peel. These products generally received excellent acceptance in terms of sensory quality, with significant increases in dietary fibre and phenolic compounds. While current studies are making progress in this area, further exploration of innovative fortification strategies is needed to fully address the existing nutritional limitations.

The production of tapioca flour is hindered by the unstable supply of cassava raw materials (Santosa *et al.*, 2022). This instability can be traced to various factors, such as inaccurate production planning, the type and age of cassava affecting yield and quality, unpredictable weather conditions that disrupt harvests, and delays in the arrival of raw materials (Petrescu *et al.*, 2020; Dewi *et al.*, 2022). Additionally inadequate infrastructure and technology limit the ability to enhance production efficiency and product quality. Consequently, farmers prioritise selling fresh cassava roots quickly for subsistence instead of investing in value-added processing, like producing flour or other products. The lack of standardised products further exacerbates this issue, limiting market potential and hindering the development of a competitive cassava bioeconomy (Oruonye et al., 2021). To address this challenge, supporting farmers with improved cassava varieties, fertilisers, crop protection products, and training in better farming practices is essential for increasing production and income (Dewi *et al.*, 2022). Furthermore, developing standardised processing techniques will ensure consistent quality in tapioca flour, while innovations in drying and milling technologies can reduce quality fluctuations and improve their functional properties in food applications. This standardisation will be critical as tapioca flour is increasingly used in diverse products, such as GF and health-focused foods, where consistency is key.

Consumer acceptance is another critical factor (Rahman *et al.*, 2021). The familiarity, as well as the taste and texture of tapioca-based products, play a critical role in shaping consumer acceptance, highlighting the need for continuous improvements in formulations. This is particularly evident in meat products, where the addition of tapioca flour or starch can reduce textural properties. For instance, Nimitkeatkai *et al.* (2022) reported that wheat flour outperformed tapioca starch and modified tapioca starch as a substitute in beef snacks, providing a firmer texture with less hardness. Products made with wheat flour were also preferred by sensory panellists in terms of appearance, flavour, texture, and overall acceptability. Also in bread, whereby Rodriguez-Sandoval *et al.* (2017) discovered that bread containing modified cassava starch binary blend at a 5% wheat flour replacement had low sensory acceptance due to its higher firmness crumb. Future research should focus on optimising and modifying techniques to enhance the textural properties of tapioca-based product, thereby improving consumer acceptance. In addition, raising awareness about the benefits of tapioca flour and its application in GF and health-oriented products can enhance consumer acceptance. Effective strategies should include targeted campaigns and active stakeholder involvement. Strategies such as social media advertisements and community-based education can effectively reach diverse audiences. Collaborating with food manufacturers and farmer cooperatives is also vital for maximising impact (Harlina *et al.*, 2023). Additionally, programs emphasising the profitability of cassava-based diversification, as highlighted by Saediman *et al.* (2015), can encourage producers and consumers to adopt tapioca flour and starch for innovative GF applications, ultimately promoting economic growth.

Economic feasibility remains a challenge, as maintaining competitive pricing for tapioca flour and modified cassava-based products relative to other flours is critical for encouraging their broader use. For instance, competition with cheaper alternatives, such as rice and corn flour, makes it difficult for tapioca products to gain a strong foothold, especially in price-sensitive markets. Isaskar *et al.* (2019) reported that product quality does not significantly influence customer satisfaction, but price has a notable positive effect. This suggests that, when purchasing tapioca-based products, especially niche products like mocaf, consumers might view affordability as a primary determinant of value. Hence, to increase the market potential of tapioca flour and products, strategies such as combining cost efficiency with quality assurance can be considered, to ensure products remain accessible without compromising on value. Additionally, offering a tiered product line at different price points could cater to both budget-conscious consumers and those willing to invest in premium-quality products, broadening the market appeal and fostering greater acceptance.

Regulatory and safety considerations are critical challenges for tapioca flour production (Díaz *et al.*, 2020). Cassava, the primary raw material, contains cyanogenic glycosides, which can release toxic cyanide if not adequately processed. To ensure product safety, methods such as soaking, fermenting, or drying are essential for detoxification (Moses *et al.*, 2024). Noncompliance with these safety standards risks consumer health, eroding trust and hindering market growth. Additionally, navigating diverse regulatory frameworks across regions complicates international trade approvals (Miles *et al.*, 2011). Standards such as permissible levels of residual toxins require stringent quality controls and collaboration with regulatory bodies. Overcoming these challenges necessitates adopting advanced processing technologies, enforcing standardised safety measure, and providing regulatory compliance training for producers. Such proactive strategies ensure product safety, boost consumer confidence, and facilitate access to global markets.

6. Future perspectives of tapioca in food production

Tapioca flour and starch hold significant potential for future innovations in food production, particularly in sustainable and functional applications. One promising avenue is the development of cassava-starch based films for food packaging (de Farias *et* al., 2021; Mangaraj *et al*., 2022). Starch-based packaging materials offer several advantages, including biodegradability, renewability from sustainable sources, and excellent oxygen barrier properties. In addition, these films also offer good stretchability, transparency, and minimal odour as well as taste interference (Hernández-García *et al*., 2021). They are ideal for packaging fresh produce and dry goods, although their mechanical strength, transparency and water resistance need improvement (Dai *et al*., 2019; Cheng *et al*., 2022). By incorporating nanotechnology or blending with other polymers (Matheus *et al*., 2023), the performance of tapioca starch films can be enhanced, paving the way for broader adoption in reducing plastic waste within the food industry.

Another futuristic application involved tapioca starch as a component in edible inks for 3D food printing. This technology could revolutionise personalised nutrition, confectionery, and food decoration. By integrating natural colour and flavours, tapioca starch-based inks could align with the rising demand for sustainable, customisable, and clean-label food products. Optimising its formulation for 3D printing processes could further expand its utility in the food development. Although tapioca starch has been a focus of recent research (Xu *et al*., 2024; Xu *et al*., 2023), its application in 3D printing is hindered by specific limitations, including excessive viscosity, which reduces printing accuracy and complicates extrusion during the printing process (Maniglia *et al*., 2019; Ji *et al*., 2022). To improve the suitability of starch gels for 3D printing, integrating non-starch materials such as casein, beeswax, and polyphenols has been identified as a promising approach (Shi *et al*., 2021; Zheng *et al*., 2021; Ji *et al*., 2022). These additives can improve printability and overall performance. Future studies should focus on leveraging these enhancements to optimise the used of cassava starch in 3D printing applications.

Additionally, tapioca starch has shown promise as a base for edible coatings, offering a sustainable solution to extend the shelf life of perishable foods. Edible coatings are thin layers made from polysaccharides, protein, lipids, bioactive compounds, or composites, applied directly to food surfaces through dipping or spraying methods (Banghi *et al*., 2022). In general, these coatings offer several benefits, including protection from ultraviolet radiation, a protective barrier against moisture loss, gas exchange, and microbial growth, ensuring food quality and safety (Yaashikaa *et al.*, 2023). Fortifying these coatings with antioxidants or antimicrobial agents could further enhance their functionality (Jeevahan *et al*., 2020). With growing interest in reducing synthetic additive and waste in food packaging, tapioca starch-based edible coating could play a pivotal role in sustainable food preservation.

7. Conclusions

The food industry has significant potential for tapioca flour and starch applications, particularly with the growing interest in alternative flour sources. Concurrently, rising consumer awareness of health benefits and the increasing prevalence of gluten intolerance have accelerated the demand for non-wheat flour options. Tapioca's carbohydrate-rich profile, enhanced by essential amino acids and potential biofortification, positions it as a valuable food source, despite its low protein and micronutrient levels. Advances in fermentation and starch modification enhance their nutritional and functional properties, offering promising avenues for broader applications.

Tapioca flour demonstrates significant potential across a variety of food products, such as bakery items, pasta, noodles, snacks, meat products and even prebiotic products. Its neutral flavor and excellent binding properties make it an effective substitute for wheat flour, particularly in GF products, offering more options for individuals with celiac disease. Additionally, tapioca flour's functional properties, including its resistant starch content, make it a valuable ingredient in the production of prebiotics that support gut health. Innovations in snack formulations and their use in meat products further enhance their appeal, adding diverse textures, flavors, and nutritional benefits. Overall, tapioca flour shows great promise in improving the quality, functionality, and nutritional profiles of a wide range of food products.

Despite this, several challenges related to nutritional limitations, unstable cassava supply, inadequate infrastructure, inconsistent product quality hindering its market development and consumer acceptance remain. Economic feasibility is also a challenge due to competition from cheaper alternatives and the need for affordable tapioca-based products, as well as safety concerns regarding toxicity of cassava. However, with continued innovation and investment in sustainable practices, cassava holds significant potential for expanding its role in global food markets. Addressing these barriers through innovative strategies, improved processing technologies, and stringent safety measures is crucial for unlocking its full potential and valorising cassava as a key ingredient in future food systems.

Table 3 The application of tapioca flour and starch in food products

Food products	Focus	Outcomes	References
Biscuits	• Optimised biscuit formulations using blends of tapioca flour, desiccated coconut flour, and wheat flour.	• Best formulation: 30% wheat, 40% tapioca, 30% coconut flour. • Improved nutritional quality and consumer satisfaction.	Ling *et al.* (2024)
	• Utilised ND and resistant starch to enhance the texture and sensory profile of low-fat shortbread biscuits.	• Substituting 10% ND and 40% RS makes the biscuits' texture comparable to the control.	Laguna *et al.* (2012)
	• Soy malt addition on the properties of cassava-wheat composite flour in biscuits.	• Increased the protein, vitamin and mineral. • Wheat-cassava-soymalt with ratio 70:15:15 was the most favourable and comparable with control (100% wheat flour).	Adelakun & Abiodun (2017)
	• Assessed the organoleptic properties of GF biscuits made from tapioca and corn flour blends.	• GF biscuits produced with 50:50 (tapioca:corn flour) demonstrated superior sensory qualities and consumer acceptability.	Muzamil *et al.* (2024)
Cookies	• Developed cookies using tapioca and rice flours.	• 75% proportion of tapioca flour in the formulation resulted in higher sensory scores. • Composite flour cookies have higher specific volume compared to the control, indicating good expansion after baking.	Montes *et al.* (2015)
	• Evaluated the effects of TS and TMS as additives (5%, 10%, 15% w/w) on rice cookie quality.	• TMS significantly reduced dough and cookie hardness compared to TS. • Cookies with TMS had higher spreadability, lighter colour, and lower bulk density. • 10% TS rice cookies scored highest in overall acceptability, taste and texture, while 15% TMS cookies excellent in flavour and brittleness.	Lee *et al.* (2015)
	• Studied the factors influencing the printability and post-processing of	• Tapioca flour was the most effective, easy to print, had better visual outcomes, and maintained structural integrity after baking.	Pulatsu *et al.* (2020)

	cookie dough in extrusion-based 3D printing.		
Crackers	• Evaluated the feasibility of using DCS in crackers.	• DCS formed a cohesive dough structure when the damage level was above 11.51%. • Exhibited sensory qualities comparable to wheat flour crackers.	Liu *et al.* (2023)
	• Examined modified cassava starch as a fat substitute in crackers.	• Modified enzymatic starch (amyloglucosidase) and physical treatment (pregelatinised starch) produced a product with a texture, specific volume, weight loss, water holding capacity, and sensory characteristics closer to the control. • Achieved a total fat reduction of 49.51% in the final product.	Otero-Guzmán *et al.* (2023)
Bread	• Evaluated the quality characteristics of bread made from cassava-wheat-maize flour blends.	• Pectin facilitated the production of bread with acceptable quality. • Bread with up to 40% cassava flour had acceptable quality. • Crumb firmness comparable to wheat bread was achieved using both sun-dried and roasted cassava flours.	Eduardo *et al.* (2013)
	• Investigated the effects of incorporating cassava flours from six Zambian varieties into wheat flour.	• Cassava flours up to 10% showed no significant quality degradation in bread. • Cassava inclusion generally reduced bread weight loss.	Chisenga *et al.* (2020)
	• Investigated the use of a composite blend of tapioca starch and corn flour (80:20) in bread making.	• Demonstrated 84% acceptability among wheat bread consumers and 100% among individuals with celiac disease. • Produced spongy, high-volume bread with excellent sensory qualities.	Milde *et al.* (2012)
	• Studied the impact of incorporating various forms of cassava (flour, native starch, and sour starch) into GF bread.	• The addition of 10% cassava products improved bread quality and volume. • However, the addition of 20% cassava products reduced the specific volume.	Sigüenza-Andrés *et al.* (2021)

Cake	• Explored the utilisation of tapioca starch (TS) as a partial substitute for wheat flour in sponge cake.	• Increasing TS substitution helped incorporate more air into the batter. • Increased the specific volume and softness. • Achieved higher overall liking scores compared to the control.	Chaiya & Pongsawatmanit (2011)
	• Optimised a wheat flour-based sponge cake formulation containing TS and XG.	• Optimal formulation consisted of 11.09% – 11.88% TS and 0.1% – 0.11% XG. • Achieved the desired physical properties and the highest overall sensory liking scores.	Chaiya *et al*. (2015)
Noodle	• Investigated the impact of porous tapioca starch on the cooking quality and texture of white salted (udon) noodles.	• Optimal 5% porous starch addition: shorter cooking times, higher water absorption, and reduced cooking loss compared to controls.	Pokharel *et al*. (2023)
	• Evaluated the effects of wet noodles made from cassava flour.	• Lower fat content and higher protein content compared to the control.	Abidin *et al.* (2013)
	• Studied the role of mocaf and latoh in noodle production.	• The optimum formula was 63% mocaf, 36% wheat, and 1% latoh. • Mocaf-latoh noodles had low fat but high carbohydrate content. • They exhibited excellent gel characteristics and were abundant in amino acids.	Wahjuningsih *et al*. (2023)
	• Determined the chemical, physical, and organoleptic characteristics of shirataki noodles made from different ratios of porang and tapioca flours (100:0, 80:20, and 70:30).	• The optimal formulation consisted of 70% porang flour and 30% tapioca flour. • Produced balanced texture, moisture content, and overall quality.	Jang *et al*. (2023)
Pasta	• Developed GF pasta using 80% cassava starch and 20% corn flour, with varying concentrations of XG (0.4%, 0.6%, and 0.8%)	• The 0.6% XG concentration showed the best results. • Reducing cooking loss and improving texture parameters (firmness, cohesiveness, chewiness, springiness, and cutting force).	Milde *et al*. (2020)

	• Studied the effects of cassava root fermentation on flour and pasta quality.	• Pasta made from cassava fermented for 36 hours had the best textural properties and eating qualities.	Odey & Lee (2020)
Snacks	• Investigated cassava flour as a supplementary ingredient with wheat flour in snacks.	• A 25:75 ratio of cassava to wheat flour was most preferred based on sensory evaluation. • Tapioca flour increased the expansion ratio, while reducing bulk density and hardness in snack products.	Ketipearachchi *et al.* (2023)
	• Examined the use of cassava-derived ingredients for creating GF salty expanded snacks.	• Optimal formulation was 6% cassava leaf flour blended with cassava sour starch. • Yielded snacks that highly crisp, light in colour, and well-received in sensory evaluations.	Leonel *et al.* (2019)
Meat products	• Compared tapioca flour with traditional meat binders (potato flour, garbanzo flour, and egg white) in chicken breast patties.	• Tapioca flour showed comparable sensory attributes to potato and garbanzo flours but reduced meat cohesiveness, hardness, and chewiness. • The improvement in water-holding capacity enhanced the texture.	Chatterjee *et al.* (2019)
	• Examined the effect of tapioca flour (0, 5, 10, 15 and 20%) on ready-to-eat ground beef jerky.	• The 10% tapioca flour produced jerky with optimal water and protein content, good sensory attributes.	Handayani *et al.* (2023)
	• Developed GF chicken sausages using a composite flour of 20% HQCF and coconut flour.	• Sensory quality was comparable to the control and HQCF alone. • 4.8% coconut flour and 15.20% HQCF effectively substituted wheat flour.	Ayandipe *et al.* (2022)
	• Studied the effects of RS, GRF, and TS on the properties of emulsion-type sausages.	• TS significantly improved emulsion stability, cooking yield, and moisture retention. • RF and GRF reduced fat loss and fluid release from the sausage. • TS formed a firmer, more uniform gel and immobilised more water in the sausage.	Pereira *et al.* (2019)
	• Evaluated the effects of 2%, 3%, and 4% TS on LFBMP and HFBMP.	• 3% TS had the highest moisture content, improved cooking yield, reduced shrinkage, and lower calorie content.	Nissar *et al.* (2009)

		• 3% TS effectively replace fat in buffalo meat patties.	
Prebiotic products	• Health benefits of prebiotics.	• Benefits metabolic, gastrointestinal, bone, and mental health.	Alves-Santos *et al*. (2020)
	• Resistant starch as prebiotic.	• Regulates blood sugar, improves metabolic health, supports beneficial gut bacteria growth.	Nabeshima *et al*. (2020), Pranoto (2022)
	• Resistant starch in tapioca flour supports the growth of beneficial bacteria.	• Improves digestive health, reduce inflammation, and enhance immune function.	Wen *et al*. (2022)

Note: ND: N-Dulge, RS: resistant starch, GF: gluten-free, TS: tapioca starch, TMS: tapioca modified starch, DCS: damage cassava starch, XG: xanthan gum, HQCF: high-quality cassava flour, RF: rice flour, GRF: glutinous rice flour, LFBMP: low-fat buffalo meat patties, HFBMP: high-fat buffalo meat patties

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