

Review Article

Enhancing the Digestion Resistance of Yam Flour: Modifications to Food Applications

^aNuhu, B.L., ^aAkinterinwa, A., ^aDass, P.M. and ^bOladele, E.P.

^aDepartment of Chemistry, Modibbo Adama University, Yola, Nigeria

^bDepartment of Chemistry, Federal University of Technology, Akure, Nigeria

*Corresponding Author Email: buharilamido202020@mau.edu.ng

Article History	Abstract
Received: September 14, 2026 Accepted: October 05, 2026 Published: October 12, 2026	Yam (<i>Dioscorea</i> spp.) flour is a valuable starch-rich ingredient for functional foods, yet cooking triggers gelatinization that destroys its native digestive resistance, causing rapid postprandial glycemic spikes. This review evaluates strategies to alter starch structure and lower enzymatic digestibility, including drying regimes, hydrothermal treatments (heat-moisture treatment and annealing), extrusion, plasma-assisted processing, chemical crosslinking, and complexation with polyphenols or proteins. The functional behavior and nutritional benefits of modified yam flours in food systems, notably wheat-yam noodles, are critically assessed. Outcomes depend heavily on processing parameters, as non-optimized treatments can inadvertently reduce resistant starch yields. Major research gaps include inconsistent <i>in vitro</i> digestion protocols, reliance on isolated starches over whole-flour matrices, insufficient <i>in vivo</i> clinical validation, and limited research on West African white Guinea yam (<i>Dioscorea rotundata</i>). Resolving these issues is essential for developing reliable low-glycemic yam products. Keywords: Digestion-Resistant Starch, Functional Foods, Modification, Yam Flour.

1. Introduction

Yam (*Dioscorea* spp.) is an indispensable staple tuber crop produced predominantly in tropical and subtropical regions, serving as a vital source of dietary energy and income for over 300 million people, particularly across the West African "yam belt" and parts of Asia and Latin America. As the primary dry-matter constituent of yam tubers, comprising up to 60-80 % of total dry weight, starch plays a decisive role in governing the technological, functional, and nutritional characteristics of yam-based products. Beyond its fundamental role as a caloric supply, yam starch strongly dictates the postprandial glycemic response elicited by processed food matrices (He *et al.*, 2025). With the rising global burden of metabolic disorders, such as type 2 diabetes mellitus, obesity, and cardiovascular diseases, food scientists and nutritionists are actively re-evaluating staple carbohydrate sources to engineer functional foods capable of moderating postprandial blood glucose levels. In nutritional physiology, starch fractions are systematically categorized according to their enzymatic hydrolysis kinetics into Rapidly Digestible Starch (RDS), Slowly Digestible Starch (SDS), and Resistant Starch (RS) (He *et al.*, 2025).

RDS undergoes rapid enzymatic cleavage by α -amylase and α -glucosidase in the upper gastrointestinal tract (within 20 minutes of incubation), producing immediate surges in blood glucose and insulin levels (Chang *et al.*, 2026). SDS is hydrolyzed at a more gradual rate (between 20 and 120 minutes), providing a sustained release of glucose that attenuates glycemic spikes and prolongs satiety (Raghunathan *et al.*, 2025). In contrast, RS evades enzymatic hydrolysis in the small intestine altogether and passes into the large intestine, where it undergoes microbial fermentation by colonic microflora (Shi *et al.*, 2025). This colonic fermentation generates short-chain fatty acids (SCFAs), primarily acetate, propionate, and butyrate, which improve gut barrier integrity, enhance insulin sensitivity, and modulate lipid metabolism (Louis and Flint, 2017). Consequently, elevating the combined proportion of SDS and RS in starch-rich foods is physiologically advantageous (Li *et al.*, 2022a). This nutritional outcome is often further amplified by natural dietary fiber networks, which impose physical barriers to enzyme diffusion and contribute to overall glycemic regulation (Li and Ma, 2024).

In its native, raw, ungelatinized state, yam starch exhibits high intrinsic resistance to enzymatic cleavage, existing primarily as Type 2 Resistant Starch (RS2) with B-type or C-type semi-crystalline polymorphic structures (He *et al.*, 2025). However, raw yam flour is unpalatable and structurally unsuitable for direct consumption. Standard culinary practices and industrial processing methods, such as boiling, steaming, baking, and wet milling, routinely subject yam flour to intense hydrothermal conditions (Olanrewaju *et al.*, 2026). These processes induce extensive starch gelatinization: water permeates the amorphous regions of the granules, uncoiling amylopectin double helices, disrupting crystalline lamellae, and leaching amylose chains into solution (Sudheesh and Pillai, 2025). This structural collapse destabilizes native RS2 domains, converting slow-digesting or resistant fractions into highly bioavailable RDS and leading to rapid postprandial glycemic excursions upon consumption.

Because yam flour must undergo hydrothermal processing before consumption, a central challenge in functional food engineering is designing physical, chemical, non-thermal, or non-covalent modification strategies capable of preserving or regenerating non-digestible structural domains (such as retrograded RS3, chemically modified RS4, or non-covalent complexes) post-cooking (Olatide *et al.*, 2026). Addressing this challenge requires an understanding of how processing variables reorder glucan chains, alter granular integrity, and modify enzyme accessibility. Consequently, recent research has prioritized physical treatments (such as controlled drying, heat-moisture treatment, and annealing), shear-thermal unit operations (extrusion), advanced non-thermal technologies (cold plasma and plasma-activated water), and matrix-complexation approaches involving phenolics or proteins, where the strategies have also been evaluated in flour prepared from different varieties of yam (Shi *et al.*, 2025). This review systematically evaluates these modification techniques, explains their structural mechanisms, assesses their performance in final food systems, and highlights critical gaps that must be addressed to advance functional yam-based food production.

2. Modification Strategies and Digestion Mechanisms

2.1. Structural Basis of Digestion Resistance

Enzymatic susceptibility depends on architectural features ranging from intact granular surfaces to double-helical packing and short-range molecular order. At the granular level, intact outer membranes limit α -amylase adsorption. At the molecular level, relative crystallinity, double-helical packing density, amylose-to-amylopectin ratio, and branch-chain length distribution dictate catalytic cleavage rates. Processing methods that promote chain realignment, such as double-helix stabilization and amylose retrogradation, expand the SDS and RS fractions, whereas granular fragmentation and crystalline destabilization accelerate hydrolysis. Debranched starch studies confirm that short-range molecular order acts as a primary determinant of resistance to enzymatic breakdown (Bora *et al.*, 2023).

Fourier-Transform Infrared (FTIR) spectroscopy provides a useful method for assessing short-range molecular order in modified starch. The absorbance ratio of bands near 1047 and 1022 cm^{-1} is commonly used as an indicator of the relative proportion of ordered and amorphous regions, with higher 1047/1022 ratios generally indicating greater short-range order (Aussanasuwannakul and Singkammo, 2025; Hirata *et al.*, 2025). Combining FTIR ratios with gelatinization enthalpy measurements clarifies how specific thermal regimes, such as microwave freeze-drying at 1.5 W/g, retain higher RS content relative to alternative drying profiles (Li *et al.*, 2022b).

In native flours, starch coexists with native proteins, non-starch polysaccharides, and endogenous phenolics. These components impede enzymatic access via physical entrapment or non-covalent binding (Zhang *et al.*, 2023). However, because much of the mechanistic literature relies on purified starches, these findings must be applied cautiously to whole yam flour systems, where complex matrix effects can amplify, attenuate, or alter structural outcomes.

2.2. Drying and Hydrothermal Modifications

2.2.1. Drying Methods

Drying acts as the initial thermal unit operation in yam flour production and establishes the baseline crystalline structure prior to downstream modification. Far from being a passive dehydration step, drying influences starch digestibility by altering granular packing, lamellar organization, and molecular mobility.

Hot-Air Drying (HAD at 50 °C) has been evaluated alongside Microwave Freeze-Drying (MFD at varying power densities) using Chinese yam (*D. opposita*) flour. HAD flour retained the highest RS fraction ($\approx 47\%$), whereas MFD flours exhibited lower RS values ($\approx 25\text{--}37\%$) accompanied by higher proportions of RDS and SDS (Li *et al.*, 2022a). The elevated RS retention under HAD is attributed to an inherent annealing effect: sustained

exposure to mild heat at elevated moisture contents facilitates chain mobility within amorphous regions, promoting alignment into denser, enzyme-resistant double-helical networks (Bora *et al.*, 2023).

Among the MFD parameters, a microwave power density of 1.5 W/g preserved the highest RS content. This structural preservation was supported by higher 1047/1022 cm⁻¹ FTIR absorbance ratios and reduced liquid-water residence times during microwave exposure, which minimized unwanted thermal gelatinization (Li *et al.*, 2022a). Conversely, techniques such as microwave vacuum-drying induce rapid internal heating that triggers widespread gelatinization, causing loss of RS2 reserves and increasing starch digestibility (Liu *et al.*, 2024). These trends show that advanced drying techniques do not automatically produce low-glycemic flours. Digestion kinetics are instead governed by the interaction between moisture content, thermal exposure, and energy transfer modes. Optimizing early-stage drying parameters is therefore essential to preserving a resilient semi-crystalline matrix (Liu *et al.*, 2024).

2.2.2. Heat-Moisture Treatment and Annealing

Heat-moisture treatment (HMT) and annealing are physical modification methods that alter starch structure below the gelatinization temperature without chemical reagents (Bora *et al.*, 2023). Both methods reorganize glucan chains, but operate under distinct moisture and thermal conditions. Comparative evaluations on *Dioscorea alata* and *Dioscorea esculenta* starches demonstrated that HMT (20-30% moisture, 110 °C for 3 h) and annealing (1: 2 and 1: 4 starch-to-water ratios, 50 °C for 24 h) both restricted swelling power and solubility, suppressed the RDS fraction, and increased SDS and RS contents (Bora *et al.*, 2023).

Despite producing similar nutritional profiles, the two methods yielded contrasting thermodynamic and pasting behaviors. Annealing increased gelatinization enthalpy (ΔH) and setback viscosity, whereas HMT suppressed both parameters. Annealing also induced greater alterations in paste rheology, indicating stronger molecular associations. Thus, while both methods lower digestibility, selection should depend on the structural and textural requirements of the final food matrix (Lu *et al.*, 2026). Because these findings were gathered from purified starches, further study is needed to verify whether non-starch matrix components in whole yam flour yield similar structural behavior (Bora *et al.*, 2023).

2.3. Shear, Thermal, and Advanced Non-Thermal Processing

2.3.1. Extrusion Processing

Extrusion cooking applies high temperature, hydrostatic pressure, and mechanical shear simultaneously. When applied to isolated starches (such as maize or potato), extrusion destabilizes native crystalline domains and degrades polymer chains, increasing water solubility and enzymatic susceptibility (Ali *et al.*, 2020). In yam processing, historical research focused on optimizing feed moisture to enhance instantization and functional hydration properties. Extrusion alone does not inherently increase digestion resistance. Its nutritional impact depends on tuning barrel temperature, moisture levels, screw configuration, shear force, and co-ingredient interactions (Ouyang *et al.*, 2023).

2.3.2. Plasma-Activated Water and Cold Plasma

Plasma-activated Water (PAW), rich in Reactive Oxygen and Nitrogen Species (RONS), has emerged as a non-thermal reagent for altering starch supramolecular architecture (Okoye *et al.*, 2022). Early studies demonstrated that applying PAW during HMT alters double-helical packing and *in vitro* digestibility in conventional and waxy maize starches (Yan *et al.*, 2020). Recent applications in yam flour combined PAW with extrusion processing (PAW-TSE) to modify structural, physicochemical, antioxidant, and digestive profiles (Yan *et al.*, 2024). Additionally, cold atmospheric plasma pretreatments prior to drying alter the functional properties of Chinese yam starch (Shen *et al.*, 2024).

In food applications, incorporating PAW-TSE modified yam flour into wheat noodles at inclusion levels up to 25% increased RS content to $\approx 34\%$, while reducing RDS relative to control formulations (Shi *et al.*, 2025). These nutritional gains were attributed to the higher baseline RS of the modified flour. Standardizing plasma dosage parameters, extrusion variables, and digestion protocols will be important for cross-study comparison as these technologies develop (Shi *et al.*, 2025).

2.4. Complexation and Matrix Interactions

2.4.1. Starch-Polyphenol Complexes

Non-covalent complexation between starch and polyphenols is an effective strategy for reducing starch digestibility and delaying enzymatic hydrolysis (He *et al.*, 2025). Polyphenols can form inclusion complexes within amylose helices and non-inclusion complexes through hydrogen bonding and hydrophobic interactions

with starch molecules, including amylopectin (Wu *et al.*, 2024). In addition, many polyphenols inhibit digestive enzymes such as α -amylase and α -glucosidase, further slowing starch digestion. Because thermal processing disrupts native starch structures and can diminish RS2, starch-polyphenol complexation has emerged as a promising approach for preserving digestion resistance in cooked starch-based foods (Raza *et al.*, 2023; Wu *et al.*, 2024).

Direct complexation of yam starch with selected phenolics decreased thermal stability but enhanced *in vitro* bile-acid binding capacity, slowed starch cleavage, and elevated RS content (Zhang *et al.*, 2023). FTIR analyses showed that complexation was driven primarily by non-covalent interactions (hydrogen bonding and hydrophobic forces). The observed decline in thermal stability alongside reduced digestibility suggests that phenolic molecules disrupt native long-range order while creating steric barriers that hinder enzyme access (Zhang *et al.*, 2023).

The molecular structure of polyphenols is a key determinant of starch-polyphenol complex formation. Factors such as molecular size, hydroxyl-group distribution, hydrophobicity, and starch structure influence binding affinity and complex stability, making polyphenol selection an important consideration when designing starch-based delivery systems and low-digestibility foods (Raza *et al.*, 2023; Echave *et al.*, 2024; Wu *et al.*, 2024). Systematic evaluations across diverse phenolic classes are required in whole yam flour matrices to assess matrix interference.

2.4.2. Starch-Protein Interactions During Extrusion

Exogenous protein hydrolysates offer another approach to lowering starch digestibility. Extruding yam starch with soy protein isolate hydrolysate (up to 10% w/w) limited enzymatic access, increasing RS content from 8.31% to 23.39%. Structural analyses showed an increase in relative crystallinity from 17.45% to 22.45%, improved short-range order, and physical adhesion of hydrolysate fragments to damaged granule surfaces (Shi *et al.*, 2025). This study indicated that protein hydrolysates can offset shear-induced crystalline disruption during extrusion. Validating these effects in whole yam flours remains an open research need.

2.4.3. Matrix Network Improvers in Composite Doughs

Replacing wheat flour with gluten-free yam powder weakens the viscoelastic gluten matrix in composite doughs. To address this, transglutaminase (TGase), vital wheat gluten (VWG), and an egg white powder-sodium alginate (EWP + SA) complex were evaluated in 30% yam-powder composite noodles (Hu *et al.*, 2025). The additives produced distinct nutritional and structural effects. VWG alone slightly increased RDS (from 55.21% to 57.70%). TGase alone reduced total starch digestibility and increased RS content from 20.47% to 28.35%. Combining TGase with EWP + SA yielded the highest SDS content (33.81%). The effect of TGase was attributed to enzymatic protein cross-linking that entrapped starch granules within a dense network, whereas sodium alginate formed a hydrocolloid barrier and competed for available water. The TGase-VWG combination produced the best overall microstructure and technological quality while maintaining lower starch digestibility than unmodified controls (Hu *et al.*, 2025).

2.5. Chemical and Enzymatic Approaches

Chemical modification is a promising strategy for increasing Resistant Starch (RS) in yam flour. Type-4 Resistant Starch (RS4) can be produced through crosslinking or esterification reactions that strengthen starch structure and reduce susceptibility to enzymatic hydrolysis. While phosphate crosslinking has been widely studied in other botanical starches (Li *et al.*, 2022a), research on modified yam flour is still emerging. Recent studies by Olatide and colleagues demonstrated that citric acid esterification significantly reduced the α -amylase digestibility of white and yellow yam flours. Digestibility decreased as citric acid concentration, reaction temperature, and reaction time increased, with optimized treatments reducing digestibility by more than 90%, indicating the formation of highly digestion-resistant starch structures (Olatide *et al.*, 2024). Subsequent work further expanded investigations into chemically modified yam flour systems and their potential for developing functional, lower-digestibility starch ingredients (Olatide *et al.*, 2026).

Another promising approach is the production of Type-3 Resistant Starch (RS3) through enzymatic debranching followed by retrogradation. Enzymes such as pullulanase and isoamylase cleave amylopectin branch points, generating short linear glucan chains that reassociate into ordered double-helical structures during cooling, thereby enhancing resistance to enzymatic digestion (Oktaviani *et al.*, 2023). Studies across various starch sources have consistently shown that pullulanase debranching combined with retrogradation significantly increases resistant starch content, although the magnitude of the effect depends on processing conditions and starch source (Isra *et al.*, 2023; Oktaviani *et al.*, 2023).

Recent research further indicates that the formation of highly ordered crystalline and semi-crystalline structures is a major factor governing digestion resistance in debranched starch systems (Ma *et al.*, 2026). While most evidence comes from maize, rice, and legume starches, a recent study demonstrated that pullulanase debranching of yam starch increased amylose content and altered crystalline structure, resulting in products with a lower estimated glycemic index (Huang *et al.*, 2025). However, the application of enzymatic debranching-retrogradation strategies to whole yam flour remains largely unexplored. Therefore, further research is needed to determine whether these approaches can increase resistant starch content while preserving the functional and nutritional properties of yam-based products.

3. Food Applications and Technological Trade-Offs

3.1. Noodles

Composite noodles are the primary food application evaluated for modified yam flour. Because yam flour lacks gluten-forming proteins, substituting wheat flour affects rheology, cooking quality, and sensory attributes. In PAW-TSE modified yam flour noodles, higher inclusion levels darkened noodle color, decreased optimal cooking time (from 3.0 to 2.1 min), and increased cooking loss, but improved tensile elasticity and chewiness. An inclusion level of 20% was identified as the practical balance between structural quality and nutritional performance (Shi *et al.*, 2025). Formulations must balance nutritional gains against sensory and cooking trade-offs.

3.2. Bakery and Traditional Foods

Yam flour is also used in baked items, traditional reconstituted pastes (such as West African *Àmàlà*), and thickening agents. Drying conditions can be selected to yield either high-viscosity thickeners or low-digestibility functional ingredients, demonstrating versatility across end-use applications (Li *et al.*, 2022a). Quantitative digestion data for modified yam flours in commercial baked goods, extruded snacks, and gluten-free matrices remain limited compared to noodle systems.

4. Future Prospect

Many mechanistic findings rely on purified starches. Future work should evaluate promising treatments directly on whole yam flour and final food matrices (*Àmàlà*, noodles, baked products) to account for interactions with lipids, proteins, and dietary fiber. Existing studies depend mostly on *in vitro* enzymatic assays (Zhang *et al.*, 2023). Promising modified flours should undergo glycemic index (GI) testing in human clinical trials or animal models to validate *in vitro* predictions. The focus of future studies should be on understudied cultivars such as the West African white Guinea yam (*Dioscorea rotundata*). Comparative studies should evaluate baseline amylose content, crystalline properties, and modification efficiency across underutilized species under identical processing conditions. Nutritional improvements should be weighed against organoleptic performance. Studies should report sensory evaluations, color space values (L^* , a^* , b^*) cooking quality, textural profiles, and techno-economic parameters alongside RS yields (Shi *et al.*, 2025). Single modifications have operational limits. Factorial designs should explore sequential or dual modifications (e.g., HMT combined with polyphenol complexation, or PAW extrusion paired with protein hydrolysates) to evaluate potential synergy. Chemical crosslinking (STMP/STPP) requires systematic study in yam matrices to determine modification degrees, functional properties, and compliance with food safety limits for residual reagents (Zhang *et al.*, 2023).

Technologies like cold atmospheric plasma and PAW require validation beyond laboratory scales. Pilot-scale trials should evaluate throughput, energy efficiency, process repeatability, and functional stability during storage.

5. Conclusion

The digestion resistance of yam flour and starch can be modified through physical, chemical, non-thermal, and complexation methods. Optimized drying conditions, hydrothermal treatments (HMT and annealing), PAW-assisted extrusion, and complexation with polyphenols or protein hydrolysates successfully shift digestion profiles toward higher SDS and RS contents. Process parameters must be precisely controlled, as non-optimized drying or shear conditions can degrade native RS2 without generating retrograded RS3 or complexed RS structures.

Composite noodles and traditional pastes (*Àmàlà*) provide initial proof-of-concept for modified yam flours. However, chemical crosslinking and enzymatic debranching remain under-researched in whole yam flour matrices. Developing commercial low-glycemic yam products will require standardized *in vitro* testing, evaluations on whole-flour systems, and clinical *in vivo* validation.

Declarations

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