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Advancing the Nutritional and Functional Quality of Cassava Flour through Emerging Pretreatments and Processing Innovations

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Abstract. Cassava flour, a gluten-free staple in tropical diets, faces key challenges related to cyanogenic glycosides, starch digestibility, and variable functionality. This review systematically synthesizes two decades of Scopus literature under the PRISMA framework to evaluate how physical, chemical, biological, and emerging clean-label pretreatments improve its nutritional and functional quality. Findings show that physical and biological methods effectively reduce hydrogen cyanide to Codex-safe limits, while heat–moisture treatment and enzymatic debranching enhance resistant starch formation and lower glycaemic potential. Improvements in water absorption, pasting stability, and microstructure support broader bakery and noodle applications. Emerging technologies including plasma, ozone, and ultrasound offer detoxification and flavour benefits but face cost and scalability constraints. Persistent gaps include cultivar variability, limited analytical consistency, and scarce sensory or storage data. Integrated pretreatment strategies can thus transform cassava flour into a safe, nutritionally improved, and functionally stable ingredient for global gluten-free markets.

1 Introduction

Cassava (*Manihot esculenta* Crantz) is a starchy root crop native to South America and now widely cultivated across tropical and subtropical regions. It serves as a vital calorie source for more than 500 million people, particularly in sub-Saharan Africa, Latin America, and Southeast Asia, owing to its tolerance to poor soils and drought [1]. Cassava flour, produced from dried and milled roots, has emerged as one of the most versatile derivatives of the crop, valued as a gluten-free alternative to wheat. Its increasing use in bakery, noodle, and snack industries aligns with the global growth of gluten-free markets driven by health awareness and dietary preferences.

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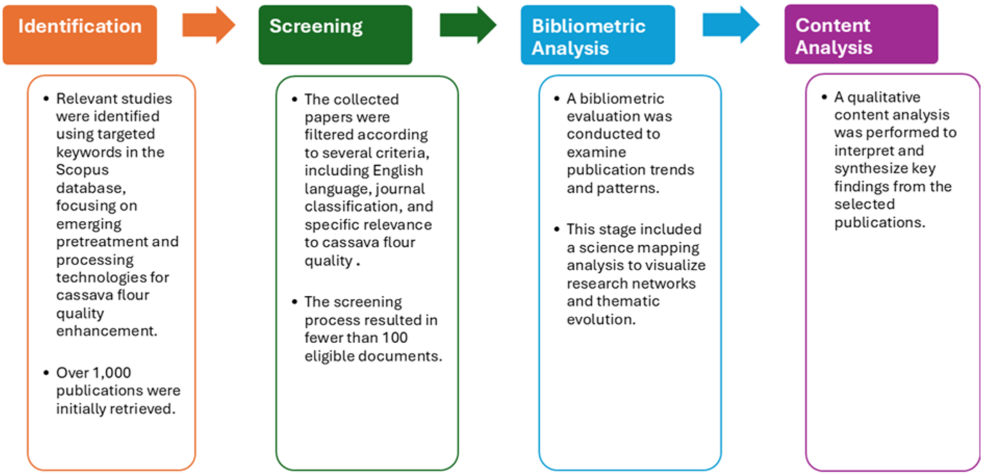
Despite its strategic importance, cassava flour's utilization remains constrained by safety, nutritional, and techno-functional limitations. The presence of cyanogenic glycosides (linamarin and lotaustralin) poses health risks through hydrogen cyanide (HCN) release if processing is inadequate, leading to disorders such as konzo and tropical ataxic neuropathy [2]. Its high starch digestibility contributes to a high glycaemic index (GI), raising concerns for diabetic and obese populations. Nutritionally, cassava flour is deficient in protein and micronutrients such as iron, zinc, and provitamin A [3]. Technologically, the absence of gluten limits dough elasticity and bread quality. Overcoming these constraints requires advanced pretreatment and processing strategies that enhance safety, nutrition, and functionality simultaneously.

Research over the past two decades has diversified toward physical, chemical, biological, and emerging clean-label pretreatments. Physical methods such as blanching, parboiling, heat-moisture treatment (HMT), and annealing modify starch structures and reduce cyanide levels [4]. Chemical modifications, acetylation, hydroxypropylation, and cross-linking, improve stability, promote resistant starch (RS) formation, and optimize pasting behaviour [5]. Biological processes such as lactic fermentation and enzymatic debranching reduce cyanide while enriching protein and antioxidants [6, 7]. Clean-label, non-thermal innovations including high-pressure processing, ultrasound, ozone, and plasma treatments aim to achieve similar benefits without chemical residues [8]. However, outcomes remain inconsistent across studies due to differences in cultivars, conditions, and metrics, revealing the need for standardized methodologies and cross-study comparability.

To address this fragmentation, systematic and PRISMA-guided syntheses have been proposed to consolidate evidence across detoxification, digestibility modulation, and RS enhancement. Such frameworks clarify which interventions consistently yield safe and functional cassava flour while identifying optimal processing trains for scalability. Within this context, the present review systematically analyses two decades of cassava-flour pretreatment research, categorizing physical, chemical, biological, and clean-label technologies to evaluate their comparative effectiveness. It hypothesizes that hybrid pretreatment strategies can deliver synergistic gains in safety, resistant starch, and techno-functional properties beyond those of single methods. As one of the first PRISMA-based syntheses integrating conventional and emerging approaches, this work provides a comprehensive framework for transforming cassava flour into a safe, nutritious, and competitive ingredient for modern food systems, particularly in resource-limited contexts.

2 Methodology

The methodological framework followed a systematic and transparent approach to synthesize evidence on cassava flour pretreatments and processing innovations. A structured review protocol was developed following the PRISMA 2020 guidelines to ensure rigor, reproducibility, and minimal bias in evidence synthesis. Literature was retrieved from the Scopus database, which comprehensively indexes agricultural, food science, and biochemical studies. Search strings combined Boolean operators and truncation across terms such as "cassava," "emerging pretreatments," "processing innovations," and "food application," limited to peer-reviewed studies published between 2005 and 2025. Titles, abstracts, and full texts were screened using predefined inclusion criteria emphasizing cassava flour, explicit pretreatment methods, and empirical outcomes related to detoxification, digestibility, or techno-functional quality. The methodology for data collection is depicted in Fig 1.



- Relevant studies were identified using targeted keywords in the Scopus database, focusing on emerging pretreatment and processing technologies for cassava flour quality enhancement.
- Over 1,000 publications were initially retrieved.

- The collected papers were filtered according to several criteria, including English language, journal classification, and specific relevance to cassava flour quality .
- The screening process resulted in fewer than 100 eligible documents.

- A bibliometric evaluation was conducted to examine publication trends and patterns.
- This stage included a science mapping analysis to visualize research networks and thematic evolution.

- A qualitative content analysis was performed to interpret and synthesize key findings from the selected publications.

Fig. 1. Research methodologies.

Eligible studies were extracted and coded into four analytical categories: detoxification (focused on Codex HCN thresholds), starch digestibility and resistant starch formation, techno-functional properties, and product-relevant attributes. Narrative synthesis and comparative tabulation were used to integrate and validate findings, highlighting mechanistic links such as cyanide hydrolysis during fermentation or crystalline perfection during annealing. Variations in cultivars, analytical techniques, and process parameters were examined to identify heterogeneity and stress the need for standardized HCN and glycaemic assays.

3 Recent Trends and Bibliometric Perspective

Over the past two decades, research on cassava flour pretreatments has evolved from regional studies on safety to globally integrated investigations into nutrition, functionality, and sustainability. Publication growth accelerated after the mid-2000s, reflecting cassava’s dual identity as a staple and a functional food ingredient. While early studies emphasized soaking, fermentation, and sun drying for detoxification. The research landscape has expanded beyond Africa and Southeast Asia to include contributions from Europe, China, and Latin America, integrating novel clean-label technologies such as high-pressure processing, ultrasound, and plasma [8]. Fig. 2 presents an overview of publication trends on emerging pretreatment and processing technologies aimed at enhancing cassava flour quality, derived from the Scopus database. It illustrates the annual number of publications (Fig. 2a) and the distribution of document types (Fig. 2b), providing key insights into the evolution and research emphasis within this domain.

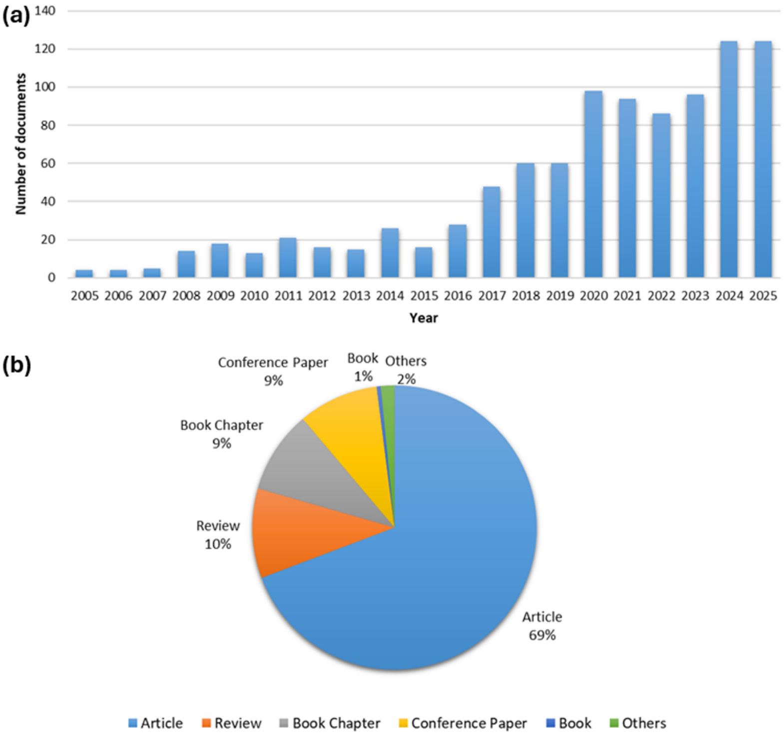


Fig. 2. Annual publication trends on emerging pretreatment and processing technologies for improving cassava flour quality, based on Scopus data: (a) number of documents published per year, and (b) distribution by article type.

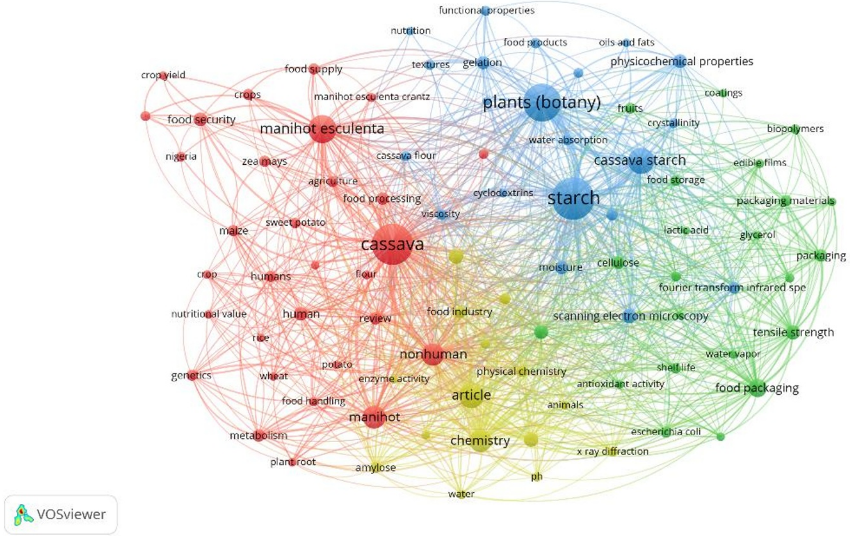


Fig. 3. Keyword co-occurrence map illustrating research themes related to emerging pretreatment and processing technologies for enhancing cassava flour quality.

Fig. 3 displays a keyword co-occurrence map that visually illustrates the interrelationships among research themes related to emerging pretreatment and processing technologies aimed at improving cassava flour quality. The keyword co-occurrence network reveals four thematic clusters, representing research streams in cassava agronomy and production, starch chemistry and processing mechanisms, physicochemical and botanical studies of starch, and material or packaging applications of modified starch, illustrating the interdisciplinary breadth of cassava–starch research. Early work targeted cyanide reduction below Codex Alimentarius limits [2], followed by efforts to enhance resistant starch and modulate glycaemic response. Current studies focus on harmonizing detoxification, nutritional improvement, and techno-functional performance through sustainable, non-thermal methods. Despite progress, methodological fragmentation persists, emphasizing the need for standardized analytical frameworks to ensure process–outcome concordance and reproducibility across diverse cassava cultivars and product applications [3]. Equations should be centred and should be numbered with the number on the right-hand side.

4 Types of Pretreatments and Processing Innovations

4.1 Physical Pretreatments

Physical pretreatments are among the most established methods for improving cassava flour quality and safety, relying solely on controlled heat and moisture manipulation rather than chemical reagents. Techniques such as blanching, parboiling, HMT, and annealing modify starch structures while detoxifying cyanogenic glycosides (CGs). Blanching, for example, employs short exposure to hot water or steam to hydrolyse cyanogenic compounds and volatilize HCN, effectively lowering cyanide levels below the Codex Alimentarius threshold of 10 mg/kg [2]. However, blanching may cause nutrient leaching, highlighting the need to balance detoxification efficiency with nutrient retention. Table 1 provides an overview of how different pretreatment categories (physical, chemical, biological, and clean label) compare in terms of their effectiveness and scalability for cassava flour processing.

Table 1. Comparative effectiveness and scalability of physical, chemical, biological, and clean-label pretreatment methods for cassava flour processing

Method	Effectiveness	Scalability
Physical	Enhances digestibility and enzyme access; improves structural and thermal properties [1]	Scalable in extrusion/microwave; gamma irradiation limited by infrastructure
Chemical	Improves drying kinetics, whiteness, stability; functional modifications enhance processing tolerance [5]	Highly scalable, but involves hazardous chemicals and waste management
Biological	Reduces cyanide, boosts protein and antioxidants, improves fermentation quality [6]	Scalable in food and fuel sectors, requires controlled fermentation/enzyme use
Clean-Label	Natural processes reduce cyanide, add antioxidants, avoid synthetic additives [8]	Growing scalability, requires investment in modern technologies

Parboiling involves soaking and steaming prior to milling, partially gelatinizing starch granules to improve enzymatic hydrolysis but often decreasing RS while increasing rapidly digestible starch [4]. Although this process enhances textural stability and reduces amylose leaching, favourable for bakery and noodle applications, it may raise the glycaemic index, revealing a nutritional trade-off between digestibility and functional performance. HMT and annealing represent advanced hydrothermal modifications that restructure starch granules below the gelatinization point. HMT, performed under restricted moisture (15–30%), reorganizes crystalline and amorphous domains, increasing RS, thermal stability, and lowering enzymatic digestibility. Conversely, annealing under excess moisture reinforces crystalline order and double helices, improving thermal resistance and narrowing gelatinization range [5]. Despite these benefits, outcomes remain highly dependent on cultivar characteristics and precise moisture–temperature control, necessitating standardized process reporting to enhance reproducibility and optimize flour quality.

4.2 Chemical Pretreatments

Chemical modification of cassava flour is a targeted route to tune swelling, pasting, freeze–thaw stability, and shear/thermal tolerance for diverse food systems. Acetylation decreases intermolecular hydrogen bonding and enzymatic accessibility, which can shift digestibility toward higher RS fractions and improve freeze–thaw stability, albeit often with reduced peak viscosity and gelatinization temperatures that must be product-tuned [5]. Hydroxypropylation disrupts starch–starch interactions, raising cold-water solubility and paste clarity and improving freeze–thaw stability, attributes valuable for instant, bakery, and confectionery formats. In contrast, cross-linking reinforces granules via di-ester bridges, markedly enhancing resistance to heat, acid, and shear and stabilizing viscosity during extrusion/noodle processing; pilot-scale reactive-extrusion studies confirm its industrial feasibility [5]. Citric-acid esterification (starch citrate) can also raise thermal stability and RS formation, supporting lower glycaemic responses, though performance depends on degree of substitution and process conditions [9].

On detoxification, chemical pretreatments (acidulants, sulphites) aid cyanide removal by promoting enzymatic hydrolysis and leaching during subsequent wet steps; integrated pretreatment–drying workflows show improved flour functionality while targeting safety limits [1]. In practice, processors must meet Codex guidance/maximum levels for cyanide in cassava products using validated processing controls, with simple wetting/spreading steps providing proven risk reduction at scale [2]. Industrially, chemical modifications deliver robust, reproducible functionality and RS-related nutritional benefits, yet face scrutiny regarding reagent residues, labelling, and sustainability; this underscores the need for standardized reporting of degree of substitution/cross-linking, validated HCN analytics, and alignment with clean-label trends [9].

4.3 Biological Pretreatments

Biological pretreatments harness microbial metabolism and enzyme specificity to detoxify cassava, improve nutritional attributes, and tailor techno-functional performance. Lactic fermentations decrease cyanogenic glycosides through linamarase-mediated hydrolysis with HCN volatilization, while often enriching protein and flavour complexity [6]. Mixed cultures of lactic bacteria and yeasts also modulate pasting and viscoelastic behaviour, enabling higher wheat-flour substitution in breads without unacceptable losses in quality. Enzymatic debranching with pullulanase or isoamylase cleaves α-1,6 linkages in amylopectin, producing more linear chains that recrystallize upon cooling, mechanisms known to elevate resistant starch and lower in-vitro digestibility [6].

Compared with purely thermal routes, biological processing proceeds at lower temperatures, preserving heat-labile nutrients and generating desirable aroma/volatile profiles. Nonetheless, outcomes vary with strain selection, enzyme dosage, and pH–temperature regimes; moreover, reporting of HCN and glycaemic indices is heterogeneous, hampering cross-study comparison despite Codex guidance for cassava flour (10 mg HCN/kg) [2]. Standardized analytical methods and product-relevant testing are needed to strengthen industrial translatability. Table 2 summarizes the relative effectiveness of different pretreatment methods in lowering HCN levels in cassava processing.

Table 2. Comparative efficiency of physical, chemical, and biological pretreatments for HCN reduction in cassava processing.

Method	HCN Reduction	Time Required	Meets Codex flour threshold	Reference
Soaking + Drying	61–90%	24–96 h	yes	[1]
Ultrasonic Pretreatment	40%	10 min	No	[10]
Nonthermal Plasma	30-40%	15 min	No	[8]
Sodium Bicarbonate	33%	Variable	No	[11]
LAB Fermentation	50-97%	24-48 h	yes	[12]

4.4 Emerging Clean-Label Technologies

Clean-label technologies are redefining cassava flour processing by improving safety, functionality, and sustainability without relying on synthetic additives. High-pressure processing (HPP) modifies starch–protein matrices and enzyme sensitivity, enhancing digestibility and reducing the glycaemic potential of cassava starch, though sometimes decreasing RS content. Ultrasound-assisted pretreatment accelerates cyanide detoxification through cavitation, which facilitates β-glucosidase activation and enhances microstructural homogeneity. A 10-minute ultrasound treatment at 45 °C reduced free HCN by approximately 40% and cyanogenic glycosides by 25% [10]. Additionally, ultrasound and freeze–thaw combinations have been shown to improve pasting stability, solubility, and retrogradation-based RS3 formation. Table 3 provides a comparative overview of clean label versus conventional pretreatment approaches employed in cassava processing.

Table 3. The overview of clean label versus conventional pretreatment approaches employed in cassava processing.

Aspect	Clean-Label Technologies	Conventional Pretreatments
Energy Efficiency	Lower energy use (HPP, plasma, ultrasound)	Higher energy use (thermal, chemical)

Scalability	High (HPP in commercial use; plasma scaling)	High for thermal; limited for chemical
Environmental Impact	Lower (no synthetic chemicals, less waste)	Higher (chemical residues, waste generation)
Product Quality	Nutrients and functionality preserved	Risk of degradation of sensitive compounds

Oxidative clean-label methods such as ozone and plasma generate reactive oxygen and nitrogen species that degrade cyanogenic compounds and maintain starch crystallinity. Ozone has been reported to oxidize cyanide efficiently in cassava starch processing streams, while atmospheric plasma reduces free HCN in dry cassava flour under first-order kinetics without thermal degradation [8]. These approaches preserve colour, flavour, and nutritional attributes, positioning them as viable nonthermal detoxification options.

From an industrial perspective, such technologies align with consumer demand for minimally processed, additive-free foods. However, scale-up challenges persist, mainly related to equipment costs, process uniformity, and limited sensory or shelf-life data. Future studies should focus on techno-economic assessments, pilot-scale applications, and hybrid processes that combine ultrasound, ozone, or plasma with drying or cooling cycles to maximize detoxification and resistant starch recovery while ensuring clean-label compliance.

5 Applications and Effectiveness

Cassava flour plays a pivotal role in food security, nutrition, and technological innovation. Over the past two decades, research on pretreatments has focused on two main objectives: detoxifying cyanogenic glycosides to meet Codex safety thresholds and enhancing resistant starch fractions for improved nutritional functionality. Physical and biological methods such as soaking, blanching, and fermentation remain the most effective detoxification strategies, often reducing cyanide by over 80% and achieving safe thresholds [6]. Blanching above 26 °C combined with controlled drying consistently lowers cyanide levels, while fermentation methods like those used in gari or mocaf also improve sensory attributes. Chemical treatments, such as citric acid and sodium metabisulfite, aid whiteness and drying kinetics but often require integration with physical or biological steps to ensure full detoxification [5]. Emerging technologies such as ultrasound and non-thermal plasma show promise for nutrient-preserving detoxification, though scalability remains a challenge [8].

In parallel, pretreatments increasingly aim to enhance RS and slowly digestible starch (SDS) contents. Such modifications contribute to lower glycaemic indices and improved colonic health. Nevertheless, outcomes vary due to cultivar-specific starch structures and inconsistent processing parameters [3]. Some treatments like parboiling reduce RS content, while acetylation boosts RS but faces clean-label regulatory challenges. Standardized analytical frameworks for RS, SDS, and digestibility are needed to harmonize these findings across studies.

Functionally, pretreatments enhance techno-functional traits such as water absorption, pasting stability, and microstructural uniformity, properties critical for bakery and noodle industries [4]. Composite blends with wheat or legume flours and enzymatic fermentation further improve elasticity, texture, and sensory appeal [6]. These advances link food safety, nutrition, and functionality, reinforcing cassava flour's role in gluten-free innovation and sustainable food systems, while supporting local economies and circular bioeconomy pathways. Table 4 presents functional modification techniques and additive strategies aimed at improving the quality and nutritional attributes of cassava-based bakery and noodle products.

Table 4. Functional modifications and additive strategies to enhance the quality and nutritional performance of cassava-based bakery and noodle products.

Application	Modification	Benefits	Reference
Muffins/Biscuits	Composite flours, WPC, rice bran, finger millet	Higher protein, dietary fibre, lower starch digestibility	[7]
Bread	Pre-gelatinization, frozen storage	Elastic properties, proper inflation after thawing	[13]
Wet Noodles	Composite flour	Comparable to wheat noodles, improved texture and shelf life	[14]
Dry Noodles	Pre-gelatinized flour, xanthan gum, pea protein isolate	Optimized hardness, tensile strength, consumer acceptance	[15]

6 Future Perspective

The integration of pretreatment technologies for cassava flour processing presents both promising opportunities and systemic challenges that hinder widespread adoption. Cultivar variability remains a primary constraint, as differences in starch fine structure, endogenous enzyme activity, and matrix composition strongly influence detoxification kinetics and RS formation. Certain cultivars tolerate postharvest deterioration better and exhibit enhanced starch rearrangements under hydrothermal conditions, while others perform poorly, complicating standardization and necessitating cultivar-specific optimization. Analytical inconsistencies further limit comparability, as HCN quantification varies across studies despite the Codex threshold [2], and non-harmonized starch digestibility assays impede meta-analytic synthesis.

Balancing nutrition, functionality, and clean-label demands represents another trade-off. While blanching, fermentation, and chemical modifications enhance functional attributes such as water absorption and texture, their effects on glycaemic response remain inconsistent [4]. Emerging methods, plasma, ozone, and high-pressure processing, offer sustainable, additive-free options but require costly, sophisticated setups [8]. Moreover, limited data on sensory acceptance and shelf-life under tropical storage conditions restrict real-world validation. Advancing cassava flour innovation demands standardized analytical protocols, cultivar-specific process design, and comprehensive field-level trials to reconcile safety, nutrition, and scalability.

7 Conclusion

This review has synthesized two decades of research on pretreatments and processing innovations for cassava flour, focusing on their effects on detoxification, resistant starch enhancement, techno-functional performance, and industrial relevance. Evidence shows that physical and biological methods consistently reduce hydrogen cyanide to Codex-compliant levels, while heat–moisture treatment and enzymatic debranching are the most reliable strategies for resistant starch accrual and glycaemic modulation. Functional improvements such as higher water absorption, enhanced pasting stability, and refined microstructures underpin the growing adoption of cassava flour in bakery and noodle systems. However, variability in glycaemic outcomes, cultivar-dependent responses, and methodological heterogeneity in hydrogen cyanide and digestibility assays highlight critical challenges.

The study underscores the importance of integrated process design, where hybrid approaches can leverage complementary strengths of fermentation, oxidative treatments, and hydrothermal modifications. Industrial translation will require cultivar-specific optimization, standardized analytics, and validation of sensory and storage performance under real-world conditions. By consolidating fragmented evidence into mechanistic insights and practical pathways, this review advances the body of knowledge on cassava flour processing and positions it as a sustainable, multifunctional ingredient in global gluten-free food systems. Future research should expand on life-cycle assessments, consumer studies, and hybrid processing validation to ensure scalability and predictability across diverse contexts.

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