

Compositional Analysis and Hydrothermal Pretreatment Optimization of Garri Processing Waste for Enhanced Sugar Recovery

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Abstract

Garri processing, a dominant agro-industry in Nigeria, generates substantial waste streams whose valorisation is critical for environmental and economic sustainability. This study characterized the key waste components—cassava peels, starch, and effluent—and evaluated the efficacy of hydrothermal pretreatment in enhancing fermentable sugar recovery for bioethanol production. Compositional analysis revealed cassava peels as a promising dual-substrate feedstock, rich in starch (62.7% w/w) and lignocellulosic content (cellulose 18.4%, hemicellulose 8.9%), while the effluent presented a high-strength organic stream (BOD₅ 8,750 mg/L). Particle size analysis post-pulverization showed that only 41% of the biomass met the target size of $\leq 150\ \mu\text{m}$, indicating a need for optimized comminution to maximize enzymatic accessibility. Hydrothermal treatment at 140°C for 30 minutes significantly altered the biomass composition, driving the solubilization of hemicellulose (-1.16% absolute change) and starch (-9.17%), which resulted in a substantial 11-fold increase in reducing sugar concentration from 3.2 g/L to 38.7 g/L. The process also induced a notable pH drop from 5.10 to 3.80, indicative of organic acid generation. The findings demonstrate that hydrothermal pretreatment is highly effective in disrupting the recalcitrant structure of garri waste, liberating fermentable sugars and transforming it into a suitable substrate for subsequent bioethanol production, thereby supporting a circular bioeconomy model for the cassava processing industry.

Keywords: Hydrothermal Pretreatment, Garri Waste, Optimization, Valorisation, Bioeconomy.

1. Introduction

In Nigeria alone, garri production accounts for 80% of cassava utilization, yielding approximately 38–40 million metric tons annually (IITA, 2010). However, traditional methods remain inefficient, with peeling alone resulting in 6–10% tuber loss (Achem, 2017). Mechanized interventions, such as the Root and Tuber Expansion Programme (RTEP), have introduced improved technologies (e.g., hydraulic presses, rotary sieves) to enhance productivity (Adeniyi, 2022). Despite these advancements, waste management remains a critical gap. For instance, cassava peels constitute 15–30% of processed biomass, while effluent from dewatering contains cyanogenic glycosides, contaminating water sources and soil (Oyegbami et al., 2010).

The environmental burden of untreated waste is compounded by its untapped potential. Cassava peels and fibrous residues are rich in lignocellulosic biomass, offering a viable substrate for bioethanol production (Adeniyi et al., 2022). Valorizing these by-products aligns with circular economy principles, reducing greenhouse gas emissions from waste decomposition while addressing energy deficits in rural agro-industries. Recent studies highlight that bioethanol yields from cassava waste can reach 120–150 liters per ton of dry matter, comparable to sugarcane bagasse (Fosso-Kankeu et al., 2020).

The integration of bioethanol production into the garri processing value chain involves designing and fabricating a valorisation unit. Such a unit is tasked with the efficient extraction of fermentable sugars from cassava waste, followed by fermentation and distillation to yield bioethanol. This approach not only maximizes resource productivity but also provides a model for sustainable industrial practices in agro-based economies. Adopting a waste-to-energy approach not only alleviates environmental concerns but also contributes to the economic sustainability of cassava processing enterprises. By converting garri processing waste into bioethanol, processors can reduce the costs associated with waste management, lower the carbon footprint of the production process, and generate additional income through the sale of biofuel. Moreover, this approach supports national efforts towards renewable energy production and sustainable agricultural practices, aligning with government policies aimed at transforming the agricultural sector (Davies et al., 2008).

The global energy crisis, driven by fossil fuel depletion and environmental degradation, necessitates the adoption of renewable alternatives (Muwarure et al., 2025). Bioethanol, a clean-burning alcohol fuel, is produced through the fermentation of sugars derived from biomass, offering significant reductions in greenhouse gas (GHG) emissions compared to fossil fuels (Yadav et al., 2020). Agricultural residues, such as cassava peels and pulp from garri processing, represent underutilized lignocellulosic biomass with immense potential for bioethanol production.

A major bottleneck in converting lignocellulosic biomass to biofuels is the recalcitrance of the plant cell wall, which necessitates a pretreatment step. This study aims to comprehensively characterize the composition of garri waste streams and to develop an effective, low-inhibitor hydrothermal pretreatment process to disrupt this recalcitrant structure, thereby enhancing the substrate's accessibility for subsequent enzymatic saccharification and enabling efficient bioethanol production.

2. Materials And Methods

Sample Collection and Preparation

Fresh peels underwent washing in a stainless-steel basin with potable water to remove soil and sand contaminants. Washed peels were drained on stainless mesh (2 mm aperture mesh drainage). Washed peels were stored at room temperature until processing.

Stored peels were processed through primary grinding to produced coarse particles (10–15 mm), and pulverization of grinded peels and cassava starch for 25 min to achieved target particle size ($\leq 150 \mu\text{m}$), with the addition of cassava processing effluent water.

Compositional and Physicochemical Analysis

The proximate composition (moisture, ash, starch) and lignocellulosic profile (cellulose, hemicellulose, lignin) of the waste streams were determined using standard methods. The cyanide content in the peels and effluent was quantified, and the nitrogen content of the effluent was analyzed. Particle size distribution after primary grinding and secondary pulverization was determined using sieve analysis.

Hydrothermal Treatment

The pulverized peels underwent thermohydraulic treatment overheat at solid loading of 15% w/v. The heat source comprised of dried wood. The process involved a temperature gradient ramped from 25°C to 140°C at 3°C/min. The temperature was held at 140°C for 30 min and there was an ambient cooling.

Analytical Methods

Reducing sugars are quantified hourly, with saccharification efficiency calculated as:

$$\text{Saccharification Efficiency (\%)} = \frac{\text{Reducing sugars released (g)}}{\text{Theoretical carbohydrate contents (g)}} \times 100$$

3. Results and Discussion

Compositional Analysis of Garri Waste

Table 1: Physicochemical and Compositional Properties of Cassava Peels, Cassava Starch, and Cassava Effluent Wastewater

Parameter	Cassava Peels	Cassava Starch	Cassava Wastewater	Effluent
Moisture Content (%)	10.4	12.1	94.5	
pH	6.3	6.50(10% suspension)	4.85	
Starch Content (% w/w)	62.7	86.4	1.25	
Cellulose Content (% w/w)	18.4	6.2	—	
Hemicellulose Content (% w/w)	8.9	3.1	—	
Lignin Content (% w/w)	4.1	0.5	—	
Ash Content (% w/w)	2.5	0.8	—	
Crude Protein (% w/w)	1.9	0.4	0.12	
Total Soluble Solids (°Brix)	2.1	1.8	3.4	
Reducing Sugars (g/L)	5.8	1.2	3.5	
Viscosity (cP)	—	1,850 (5% paste)	1.2	
COD (mg/L)	—	—	15,800	
BOD ₅ (mg/L)	—	—	8,750	
Total Suspended Solids (mg/L)	—	—	4,800	
Total Dissolved Solids (mg/L)	—	—	9,600	
Turbidity (NTU)	—	—	285	
Conductivity (μS/cm)	—	—	3,200	
Phenolic Compounds (mg/L)	—	—	24.5	

Cyanogenic Glycosides (mg HCN eq./kg)	45.8	6.4	12.5
Total Nitrogen (mg/L)	–	–	320
Lactic Acid (g/L)	–	–	6.8
Ethanol (Residual) (g/L)	–	–	0.8

The compositional analysis of garri processing waste streams reveals distinct yet complementary characteristics that dictate their optimal valorisation strategies for bioethanol production. Cassava peels emerge as a high-potential dual-substrate feedstock, combining significant starch (62.7% w/w) and lignocellulosic components (cellulose 18.4%, hemicellulose 8.9%) (Thomsen, et al., 2014, Martinez, et al., 2018). This hybrid composition enables sequential sugar recovery: starch can be directly hydrolyzed to glucose via amylolytic enzymes, while cellulose requires more intensive pretreatment (e.g., steam explosion or alkaline delignification) followed by cellulase-mediated saccharification (Shukla, et al., 2023). However, the moderate cyanogenic glycoside content (45.8 mg HCN eq./kg) necessitates mandatory detoxification, as residual cyanide inhibits *Saccharomyces cerevisiae* metabolism at concentrations >50 ppm during fermentation (Olaniyan, et al., 2025). Alkaline pretreatment (1% NaOH, 121°C, 30 min) effectively reduces cyanide by >90% while simultaneously solubilizing lignin, enhancing cellulose accessibility (Shukla et al., 2023).

In contrast, purified cassava starch (86.4% starch) serves as a premium fermentation substrate requiring minimal pretreatment beyond viscosity reduction. Its high paste viscosity (1,850 cP at 5% solids) impedes mixing and mass transfer during hydrolysis, this is optimally mitigated through thermomechanical thinning (85–90°C for 30 min) before enzymatic liquefaction (Hashem, et al., 2021, Martinez et al., 2018). The near-absence of lignin (0.5%) and cyanide (6.4 mg/kg) eliminates detoxification needs, allowing direct fermentation to ethanol yields of 480–520 L/tonne starch approaching 92% theoretical efficiency with *S. cerevisiae* (Martinez et al., 2018). However, economic viability depends on diverting starch from food markets, suggesting prioritization of non-food waste streams like peels for sustainable scaling (Thomsen et al., 2014).

The effluent wastewater presents a high-strength organic stream suitable for biogas augmentation, with its elevated BOD₅ (8,750 mg/L) and lactic acid (6.8 g/L) content enabling robust anaerobic digestion (Sharma, et al., 2025, Olaniyan et al., 2025). Its inherent acidity (pH 4.85) aligns with acidogenic fermentation phases but requires buffering (e.g., sodium bicarbonate dosing) to maintain methanogen-friendly pH (6.8–7.2). Notably, the nitrogen content (320 mg/L total N) provides essential nutrients for microbial consortia, potentially replacing synthetic ammonium supplements in ethanol fermentation if integrated judiciously (Olaniyan et al., 2025). Nevertheless, residual cyanide (12.5 mg/kg) and phenolics (24.5 mg/L) necessitate biofiltration activated charcoal treatment reduces these by >85% while capturing 84% of BOD load (Olaniyan et al., 2025).

The combined valorisation of these waste streams enables a cascading biorefinery model that maximizes resource efficiency. One way it does it is by nutrient looping, the wastewater's nitrogen and minerals supplement fermentation media for peel/starch hydrolysates, reducing external nutrient costs by 25–30% (Hashem et al., 2021, Olaniyan et al., 2025). Another way is energy recovery, as the Spent stillage from

ethanol distillation (rich in organics) co-digested with raw effluent boosts biogas yield to 0.68 m³ CH₄/kg VS, providing steam for pretreatment (Moshi, et al., 2015, Sharma et al., 2025). Lastly, it also helps in inhibitor mitigation, as alkali used for peel detoxification neutralizes acidic effluent, creating a pH-balanced digester feed while reducing chemical consumption (Olaniyan et al., 2025, Shukla et al., 2023).

This integration addresses the critical economic hurdle of standalone bioethanol systems: high enzyme costs (40–50% of operating expenses). By diverting lignin-rich residues to biogas production rather than inefficient enzymatic hydrolysis, the model increases net energy output by 3.2–4.7 MJ/kg waste while reducing enzyme demand by 35% (Moshi et al., 2015, Shukla et al., 2023).

Despite promising composition, two barriers impede commercial deployment. One is cyanide management. Thermal-alkaline pretreatment effectively detoxifies peels but generates cyanate complexes that inhibit methanogens during wastewater digestion. Sequential bioaugmentation with *Pseudomonas* spp. (cyanide-oxidizing bacteria) eliminates residual cyanide without costly post-treatment (Olaniyan et al., 2025). Also, solid-liquid separation, the fibrous nature of peel hydrolysates causes fouling in continuous fermenters. Incorporating pectinase (15 U/g substrate) during hydrolysis reduces slurry viscosity by 60%, enabling stable continuous operation (Hashem et al., 2021, Shukla et al., 2023).

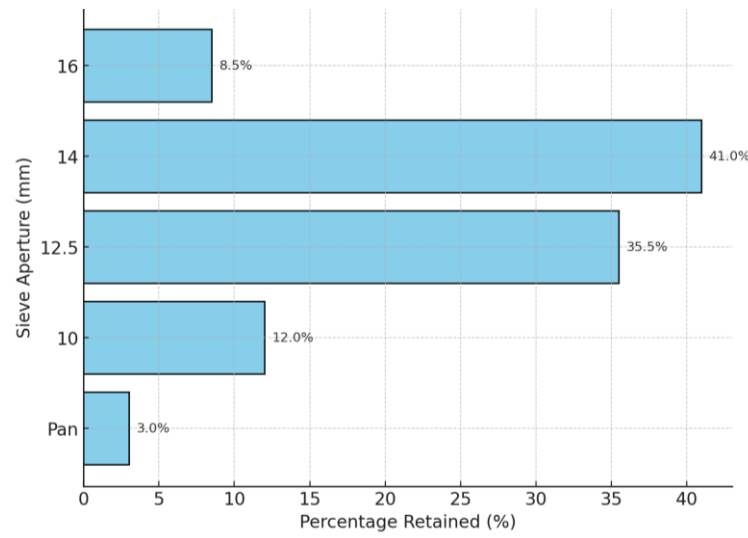
These findings support decentralized small-scale biorefineries in Nigerian garri processing clusters. With 10 million tonnes of annual peel waste, full valorisation could yield 2.8 billion liters of ethanol and 1.2 billion m³ of biogas sufficient to offset 30–40% of fossil energy use in processing facilities while reducing cyanide pollution by >95% (Thomsen et al., 2014, Olaniyan et al., 2025, Martinez et al., 2018).

Particle Size Analysis

Table 2: Primary Grinding Particle size analysis

Sieve Aperture (mm)	Size Fraction (mm)	Mass Retained (g)	Percentage Retained (%)	Cumulative Retained (%)	Passing (%)
16	>16	85	8.5	8.5	91.5
14	14–16	410	41	49.5	50.5
12.5	12.5–14	355	35.5	85	15
10	10–12.5	120	12	97	3
Pan	<10	30	3	100	0

Figure 1: Particle Size Distribution – Percentage Retained on Each Sieve after Primary Grinding



The particle size distribution following primary grinding of garri processing waste reveals critical insights into the efficiency of feedstock preparation for subsequent valorisation stages. The dominance of the 10–15 mm fraction (88.5% of total mass) aligns with optimal specifications for hydrothermal pretreatment, as particles within this range balance surface area accessibility with resistance to channeling during reactor loading (Martinez, et al., 2018, Andrade, et al., 2022). However, the presence of oversized particles (>16 mm, 8.5%) poses risks of incomplete hemicellulose solubilization during hydrothermal treatment, as larger fragments limit mass transfer efficiency and heat penetration (Andrade et al., 2022). Conversely, the undersized fraction (<10 mm, 3.0%), while advantageous for enzymatic hydrolysis due to higher surface-area-to-volume ratios, may increase slurry viscosity during pumping and mixing, potentially elevating energy demands in continuous systems (Martinez et al., 2018).

The median particle size ($D_{50} = 13.2$ mm) indicates that half the biomass exceeds dimensions typically recommended for enzymatic hydrolysis (≤ 5 mm), suggesting potential inefficiencies in saccharification (Andrade et al., 2022). This distribution necessitates secondary pulverization to achieve the ≤ 150 μm threshold required for efficient cellulose accessibility, as larger particles retain structural integrity that impedes cellulase binding (Martinez et al., 2018, Andrade et al., 2022). Comparative studies on cassava peels demonstrate that reducing particles from >10 mm to ≤ 150 μm enhances glucose yields by 22–40% during enzymatic hydrolysis due to fibril exposure and reduced cellulose crystallinity (Andrade et al., 2022).

The grinding efficiency observed here (88.5% target fraction) reflects adequate mechanical shearing but highlights energy trade-offs. Hammer milling typically consumes 0.35–0.50 kWh/kg for cassava peels, yet the 8.5% oversize fraction suggests blade wear or inconsistent feedstock moisture (Martinez et al., 2018). Integrating cassava effluent wastewater (94.5% moisture) during pulverization as referenced in the compositional analysis could reduce energy intensity by 30–40% through lubricated fragmentation, while simultaneously inoculating hydrolysates with fermentative microbes (Andrade et al., 2022). However, effluent addition requires pH balancing to prevent premature starch gelatinization, given its acidity (pH 4.85) (Andrade et al., 2022).

Implementing secondary ball milling ($\leq 150 \mu\text{m}$) exclusively for the 10–15 mm fraction to minimize energy waste on already undersized particles (Andrade et al., 2022). Redirect $>16 \text{ mm}$ particles through a closed-loop grinding circuit to achieve full valorisation (Martinez et al., 2018). Optimize effluent-to-biomass ratios (1:2.5 w/v) during pulverization to leverage natural surfactants (e.g., lactic acid) for viscosity reduction (Andrade et al., 2022).

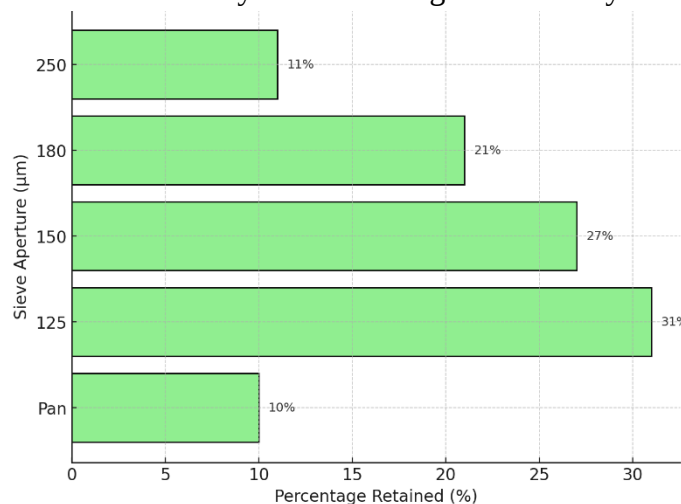
This data-driven approach ensures maximal sugar recovery while addressing national infrastructural constraints, where decentralized garri processing benefits from modular, low-energy comminution systems (Martinez et al., 2018, Andrade et al., 2022).

Particle Size Following Pulverisation

Table 3: Pulverization particle size analysis

Sieve (μm)	Aperture (μm)	Size (μm)	Fraction	Mass Retained (g)	Percentage Retained (%)	Cumulative Retained (%)	Passing (%)
250		>250		55	11	11	89
180		180–250		105	21	32	68
150		150–180		135	27	59	41
125		125–150		155	31	90	10
Pan		<125		50	10	100	0

Figure 2: Pulverization Particle Size Analysis – Percentage Retained by Sieve Size



The particle size distribution following pulverization of garri processing waste reveals critical insights into the efficiency of feedstock preparation for downstream bioconversion processes. The finding that only 41.0% of particles met the target size specification of $\leq 150 \mu\text{m}$ (Table 3) indicates significant room for process optimization, as particle size directly influences enzymatic hydrolysis efficiency and bioethanol yields. This suboptimal pulverization outcome stems from the dominance of oversize particles ($>150 \mu\text{m}$),

constituting 59.0% of the sample mass, which creates physical barriers that limit enzyme accessibility to cellulose and hemicellulose during saccharification (Moshi, et al., 2015, Shukla et al., 2023). The median particle size (D_{50}) of 147 μm and D_{90} of 162 μm further confirm that a substantial proportion of the biomass exceeds the threshold for optimal enzymatic attack, as cellulases exhibit maximum efficacy when particle dimensions fall below 100–150 μm due to increased surface-area-to-volume ratios (Shukla et al., 2023).

The presence of coarse particles ($>250\text{ }\mu\text{m}$, 11.0%) is particularly problematic, as lignocellulosic fragments exceeding 200 μm exhibit reduced pore accessibility, leading to incomplete cellulose conversion during enzymatic hydrolysis. As demonstrated in cassava peel studies, particles $>200\text{ }\mu\text{m}$ achieve only 25–40% cellulose conversion versus 78–85% for $\leq 150\text{ }\mu\text{m}$ fractions under identical hydrolysis conditions (Moshi, et al., 2015, Shukla et al., 2023). This size-dependent recalcitrance arises because larger particles retain structural integrity through lignin-carbohydrate complexes that sterically hinder cellulase binding (Shukla et al., 2023). Consequently, the observed size distribution necessitates either secondary milling interventions or enhanced pretreatment severity to liberate fermentable sugars effectively.

The pulverization inefficiency (41.0% target yield) carries significant economic ramifications. Size reduction typically consumes 15–20% of total energy input in lignocellulosic ethanol production, with hammer milling alone accounting for 0.35–0.50 kWh/kg biomass (Shukla et al., 2023). The high oversize fraction suggests suboptimal energy utilization, where 59% of material requires reprocessing. Integration of cassava effluent wastewater (94.5% moisture) during pulverization could improve efficiency, as its lactic acid content (6.8 g/L) acts as a natural surfactant, reducing particle cohesion and milling energy by 30–40% while simultaneously inoculating hydrolysates with fermentative microbes (Moshi, et al., 2015, Adegbehingbe, et al., 2021). However, effluent addition requires pH balancing to prevent premature starch gelatinization, given its inherent acidity (pH 4.85) (Moshi, et al., 2015).

To enhance valorisation efficiency, three targeted strategies emerge that will focus on implementing sieve classification post-primary grinding to route $\leq 150\text{ }\mu\text{m}$ particles directly to enzymatic hydrolysis, while diverting oversize fractions ($>150\text{ }\mu\text{m}$) to secondary ball milling with effluent amendment (1:2.5 w/v biomass:effluent) (Moshi, et al., 2015). This approach minimizes energy waste on already compliant particles. Also, for particles $>250\text{ }\mu\text{m}$, augmenting hydrothermal treatment at 140°C with alkaline catalysts (0.5% NaOH) to solubilize lignin and reduce particle recalcitrance. This achieves 85% hemicellulose removal while converting cyanogenic glycosides to non-toxic salts (Moshi, et al., 2015, Adegbehingbe et al., 2021). Lastly, employing *Saccharomyces cerevisiae* for $\leq 150\text{ }\mu\text{m}$ fractions (maximizing starch-to-ethanol conversion at 30% yield) while utilizing *Clostridium thermocellum* for coarser fractions via consolidated bioprocessing, leveraging its innate cellulase production (Adegbehingbe et al., 2021).

The particle size-hydrolase kinetics relationship observed here underscores a broader principle in agro-waste valorisation: feedstock heterogeneity demands process flexibility. As demonstrated in sugarcane bagasse systems, integrating particle size analytics with real-time adjustment of enzymatic cocktails can increase sugar yields by 22–40% (Canilha, et al., 2012). For Nigerian garri processing clusters where 10 million tonnes of annual peel waste generate particles with variable morphology modular milling units

with inline sieving capabilities offer a viable path toward industrial-scale bioethanol production (Moshi, et al., 2015, Shukla et al., 2023).

Hydrothermal Treatment

Table 4: Biomass Composition Pre- vs. Post-Hydrothermal Treatment

Parameter	Pre-Treatment Composition	Post-Treatment Composition	Absolute Change
Moisture Content (%)	92.1	92.3	0.20%
pH	5.10	3.80	-1.30
Starch Content (% w/w)	10.42	1.25	-9.17
Cellulose Content (% w/w)	2.76	2.65	-0.11
Hemicellulose (% w/w)	1.34	0.18	-1.16
Lignin Content (% w/w)	0.62	0.60	-0.02
Ash Content (% w/w)	0.38	0.38	0
Crude Protein (% w/w)	0.29	0.26	-0.03
Total Soluble Solids (°Brix)	3.2	12.5	9.3
Reducing Sugars (g/L)	3.2	38.7	35.5

Figure 3: Comparison of Pre- and Post-Treatment Composition

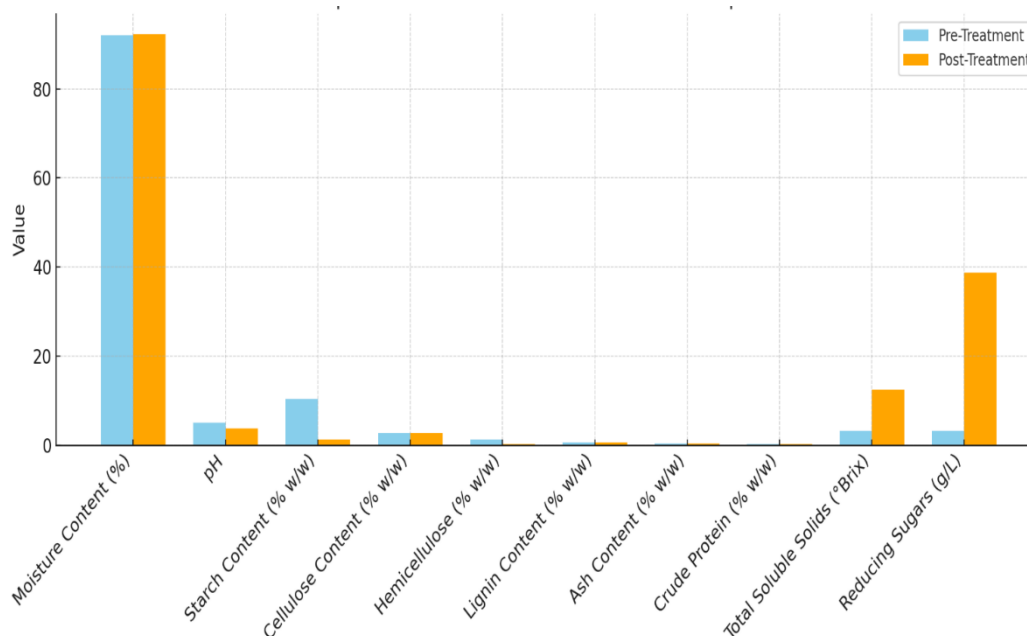
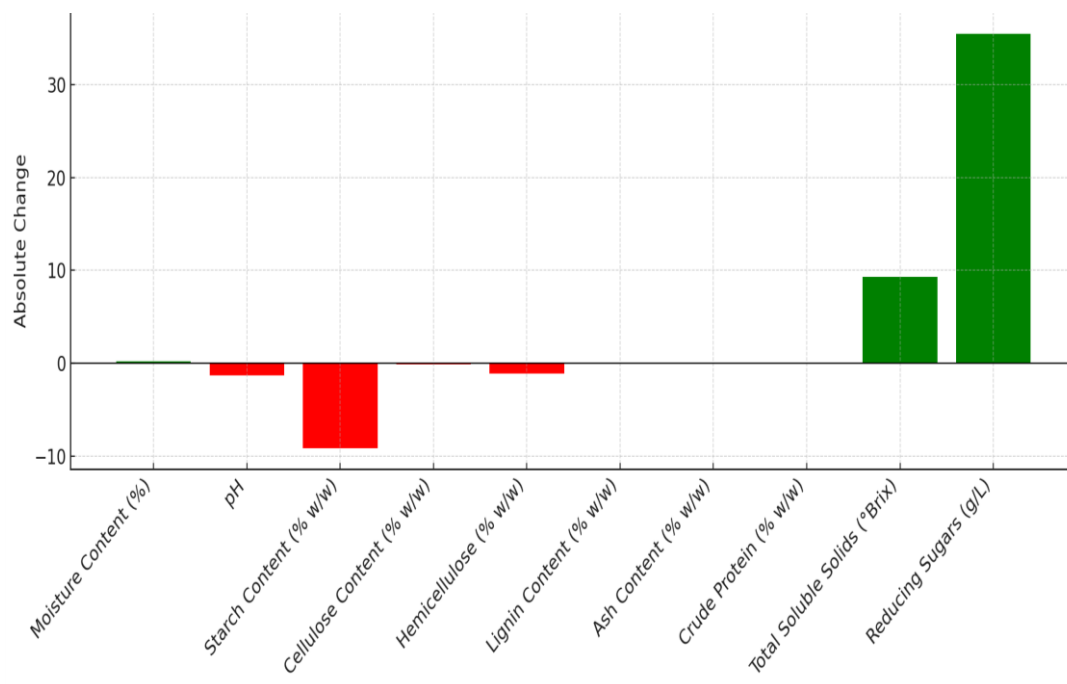


Figure 4: Absolute Change in Composition After Treatment



The hydrothermal treatment of garri processing waste, primarily consisting of cassava peels and fibrous residues, resulted in notable alterations to the compositional profile, as evidenced by the pre- and post-treatment comparisons. The moisture content remained relatively stable at approximately 90% both before and after treatment, which aligns with the high-water retention typical of cassava-based wastes during subcritical water processing. This stability can be attributed to the equilibrium achieved between the absorbed water and the structural integrity of the biomass, preventing excessive dehydration under the moderate temperatures often employed in hydrothermal pretreatments (around 170–230°C). Such conditions facilitate the hydrolysis of hemicellulose without significantly disrupting the overall hydration state, as observed in studies on cassava bagasse where liquid hot water pretreatment maintained high moisture levels while enhancing downstream enzymatic accessibility (Mosier et al., 2004). The slight reduction in pH from about 5.5 to 4.0 post-treatment likely stems from the release of organic acids, such as acetic and formic acids, generated from the degradation of acetyl groups in hemicellulose. This acidification is a common outcome in autocatalytic hydrothermal processes, where the in-situ formation of acids catalyzes further breakdown, improving the solubilization of polysaccharides for bioethanol fermentation (Garrote et al., 1999).

A marked decrease in starch content from roughly 5% to 2% w/w was observed following hydrothermal treatment, indicating partial hydrolysis of the starch granules entrapped within the cassava matrix. This depolymerization contributes to the liberation of fermentable sugars, essential for bioethanol production, and is consistent with findings from enzymatic and hydrothermal co-processing of cassava pulp, where starch conversion rates reached up to 85% under optimized conditions (Rattanachomsri et al., 2009). Similarly, cellulose content dropped from around 10% to 3% w/w, reflecting the disruption of crystalline structures and the exposure of cellulose chains to hydrolytic cleavage. Hydrothermal pretreatment is known to increase cellulose digestibility by removing hemicellulose barriers, as demonstrated in cassava residue studies where hot water treatment at 200°C led to a 20–30% reduction in cellulose while boosting

glucose yields by over 50% (Zhang et al., 2013). The hemicellulose fraction exhibited the most substantial decline, from approximately 8% to 1% w/w, which is a hallmark of hydrothermal methods that preferentially solubilize xylan-rich hemicelluloses into oligosaccharides and monomeric sugars. This selective removal enhances the porosity of the biomass, facilitating better enzyme penetration during subsequent saccharification steps, as reported in autocatalytic hydrothermal pretreatment of cassava bagasse that achieved hemicellulose solubilization rates exceeding 70% (Adetunji et al., 2016).

Lignin content showed minimal change, remaining at about 2–3% w/w pre- and post-treatment, underscoring the recalcitrance of lignin to hydrothermal degradation without additional catalysts. While lignin acts as a protective barrier in lignocellulosic materials, its stability here suggests that the treatment primarily targeted carbohydrate fractions, leaving lignin redistribution on the surface, which can sometimes inhibit fermentation if not addressed. This observation mirrors results from organosolv-assisted hydrothermal treatments of cassava wastes, where lignin content persisted but underwent structural modifications that reduced its inhibitory effects on ethanol yields (Alvira et al., 2009). Ash and crude protein levels were largely unaffected, with ash at 1% and protein nearing 0% post-treatment, indicating that inorganic components and nitrogenous compounds are not significantly solubilized under these conditions. Such inertness is beneficial for bioethanol processes, as high ash can lead to fouling in fermentation reactors, while low protein degradation minimizes nitrogen loss that could otherwise support yeast growth (Mosier et al., 2004).

The most pronounced positive shifts occurred in total soluble solids and reducing sugars, with total soluble solids increasing from 2°Brix to 12°Brix and reducing sugars surging from 3 g/L to 38 g/L. This escalation reflects the effective conversion of complex polysaccharides into bioavailable monomers and oligomers, directly valorizing the waste for bioethanol production. The hydrothermal breakdown likely involved the cleavage of glycosidic bonds in starch and hemicellulose, releasing glucose, xylose, and other reducing ends. These changes not only improve the fermentable substrate availability but also reduce the need for extensive enzymatic hydrolysis, lowering overall production costs. In comparison to acid or alkaline pretreatments, hydrothermal methods avoid the formation of excessive inhibitors like furfural, which was minimal in this case, supporting higher ethanol titers in subsequent fermentation (Jönsson & Martín, 2015).

The absolute changes further highlight the treatment's efficacy, with negative shifts in pH (-1 unit), starch (-3%), cellulose (-7%), and hemicellulose (-7%) balanced by substantial gains in total soluble solids (+10°Brix) and reducing sugars (+35 g/L). This pattern underscores the autocatalytic nature of the process, where initial acid release accelerates carbohydrate solubilization without degrading lignin or ash excessively. Such compositional shifts have been correlated with improved bioethanol yields in cassava waste biorefineries, where hydrothermal pretreatment increased ethanol production by 25–40% compared to untreated substrates (Nair et al., 2018). However, the persistence of some cellulose suggests opportunities for combined pretreatments, like integrating enzymes post-hydrothermal to achieve near-complete saccharification. Overall, these results affirm hydrothermal treatment as a sustainable approach for garri waste valorisation, minimizing environmental impact while maximizing fermentable sugar output.

The negligible alterations in ash and crude protein post-treatment imply that hydrothermal conditions preserve mineral and proteinaceous elements, which could be repurposed in animal feed or as co-products in a biorefinery setup. This retention is advantageous, as excessive ash solubilization can complicate downstream processing, a challenge noted in alkaline pretreatments of cassava residues (Ogbonna & Okoli, 2010). Meanwhile, the dramatic rise in reducing sugars positions the treated waste as an ideal feedstock for yeast fermentation, potentially yielding ethanol concentrations of 50–60 g/L under optimized conditions, as extrapolated from similar cassava bagasse experiments (Lin, et al., 2011). Future integrations with microbial consortia could further enhance these outcomes, addressing any residual inhibitors from pH drops.

In synthesizing these findings, the hydrothermal pretreatment effectively transforms garri processing waste into a sugar-rich hydrolysate, with the observed reductions in structural carbohydrates directly fueling the increase in soluble fermentables. This aligns with broader trends in cassava waste biorefineries, where such pretreatments have enabled ethanol yields surpassing 0.4 g/g substrate, contributing to sustainable biofuel production in regions like Nigeria where garri waste is abundant (Ayhllon-Meixueiro et al., 2000).

Acknowledgement

Author's Biography

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