
ADVANCING SUSTAINABLE FRUCTOSE SYRUP PRODUCTION FROM SWEET SORGHUM

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ABSTRACT

The increasing demand for high-fructose syrup, coupled with the need to reduce dependence on imported sweeteners and conventional corn-based production systems, has intensified interest in alternative and renewable feedstock. This review studied the potential of sweet sorghum, sustainable feedstock for fructose syrup production, with particular emphasis on clarification technologies, catalytic conversion pathways and process optimization strategies. The physicochemical characteristics of these feedstocks, together with juice extraction, clarification, hydrolysis, glucose isomerization, and purification approaches, are examined. Sweet sorghum demonstrates considerable potential owing to its high fermentable sugar content, relatively low agricultural input requirements, adaptability to semi-arid environments and suitability for decentralized processing. The review further highlights the importance of effective purification, catalyst selection, reaction-condition optimization and integrated processing systems in improving fructose yield, product quality and process efficiency. Consequently, the utilization of this non-conventional feedstock could support value addition, reduce biomass losses and contribute to more sustainable and locally adaptable sweetener production systems.

Keywords: Enzymes; feedstock; fructose; optimization; syrup; valorization

1. INTRODUCTION

Global sweetener industry dwelled on fructose syrup production in food and beverage which is highly cost-effective (Khorshidian *et al.*, 2021; Bulbul *et al.*, 2024). However, conventional corn, sugarcane and sugar beet usage has become a serious problem due to cultivation challenges which necessitate alternative biomass feedstock such as sweet sorghum, (Taylor *et al.*, 2023)

This alternate feedstock is easily cultivated with minimum farming input, care to achieve reasonable outcome (Almodares and Hatamipour, 2011; Velmurugan *et al.*, 2020), waste material like stalk also can be utilized as bagasse in bioenergy production (Appiah-Nkansan *et al.*, 2019).

This review involves the characterization, clarification and purification strategies including the catalytic pathways and process optimization for fructose production from the sweet sorghum.

2. NON-CONVENTIONAL BIOMASS FEEDSTOCKS FOR FRUCTOSE SYRUP PRODUCTION

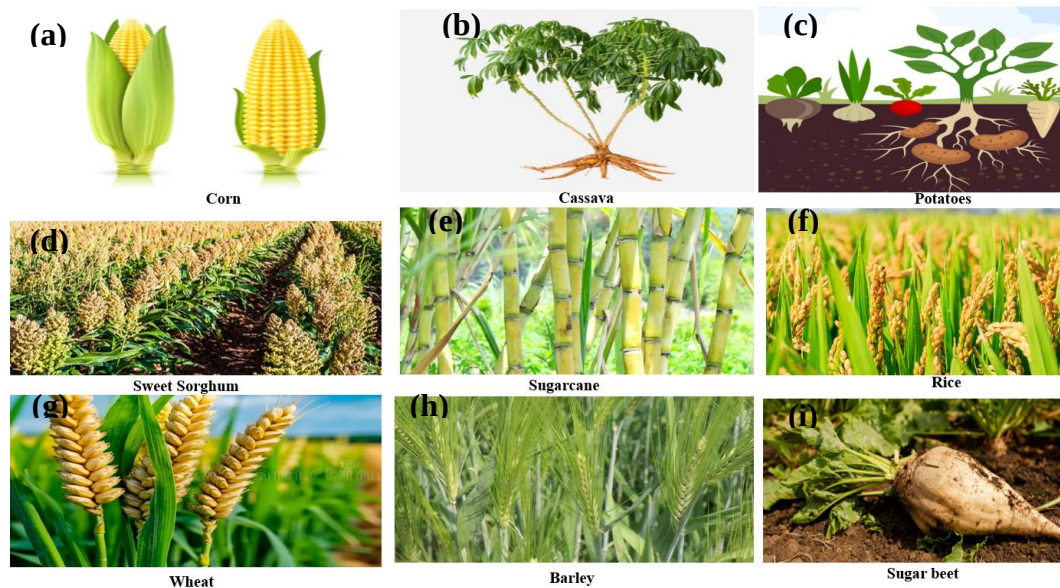


Figure 1: Biomass image of (a) Corn, (b) Cassava, (c) Potatoes, (d) Sweet Sorghum, (e) Sugarcane (f) Rice, (g) Wheat, (h) Barley and (i) Sugar beet for fructose production

Figure 1 depicted the various images of alternative biomass feedstocks for production of fructose syrup, the potential fructose yield, cost-effectiveness, and environmental influence are reviewed in this section. Corn (Figure 1a) produces the highest fructose yield (50–60%). However, high production costs, intensive water and fertilizer demand, soil degradation are matters of economic and environmental concern. Furthermore, cassava (Figure 1b) representing lower fructose yield (30–40%). Nevertheless, is cost effective, readily available in tropical regions, has low water demand and can grow on poor soils. However, it is competitive in terms of human consumption. In addition, plantain contained lowest fructose yield (20–30%), even though it inexpensive, abundant in the locality, and environmentally friendly.

Similarly, sweet sorghum (Figure 1d) possessed average yield of about 40–50%, it is an example widely cultivated in northern Nigeria; therefore, industrial utilization of this material as an alternate feedstock will improve commercialization, food security and economy of the nation (Yahaya *et al.*, 2020), production of potatoes (Figure 1c) also does not require heavy agricultural duty and input, local availability, non-competitive, affordable, non-sensitivity to a particular region and environmentally friendly (Agbaeze *et al.*, 2020) therefore there is potential and need to commercially sustain the farming of sweet sorghum to high value added product for example fructose syrup production in line with Nigeria's agricultural value chain such as development in technology, innovation and infrastructure under the National Agricultural Technology and Innovation Policy (NATIP) 2022-2027 (Federal Ministry of Agriculture and Rural Development [FMARD], 2022).

3. PROCESSING OF SWEET SORGHUM FOR HIGH-FRUCTOSE SYRUP PRODUCTION

3.1 Raw Material Harvesting and Extraction

Matured sweet sorghum stalks are harvested, defoliated and milled or blind in mechanical roller mill or electric blinder to extract raw juice, cellular debris, suspended solids, insoluble fibers particulates are filtered out (Shirvani *et al.*, 2023), followed by thermal treatment to prevent microbial fermentation and other bacteria, wet-milling operations isolate the starch fraction, yield high purity starch slurry as presented in figure 2 (Zhou *et al.*, 2020).

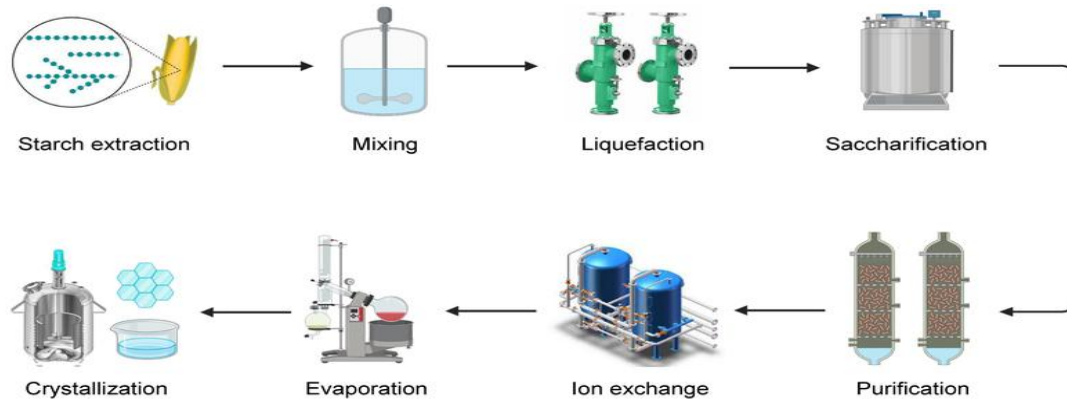


Figure 2: General Process Flowchart for Fructose Syrup Production

3.1 Purification Methods

Conversion of non-conventional biomass into high-quality fructose syrups requires adequate purification to remove impurities such as suspended solids, colloids, proteins, phenolic compounds, minerals, pigments and microbial contaminants. These impurities can inhibit the catalytic activity of enzymatic reaction which could affect product quality (Harlen & Ristiarini, 2023; Zhao *et al.*, 2022). Therefore, this section discusses the various clarification methods depicted in Table 2. For example, Chemical clarification applying calcium hydroxide and alum rapidly clarifies extracted juice via neutralisation and precipitation with effective cost. However, chemical residues and environmental impacts existence is considered as a challenge (Bourguerra *et al.*, 2024; Kameneva *et al.*, 2021). Furthermore, mechanical clarification such as membrane filtration, chromatography, and ion exchange limits chemical consumption and highly efficient. Despite this, it has high energy demand and equipment wear (Almodares & Hatamipour, 2011; Zhou *et al.*, 2020). In addition, natural clays such as bentonite are a cheap, available and active adsorbent for pigments and proteins removal. Nevertheless, it affects juice quality (nutrient) when used in excess, also cause environmental challenges in terms of waste management (Teetor *et al.* 2011; Rajvanshi *et al.* 2020). Similarly, according to Amaral-Fonseca *et al.* (2021), Moringa *et al.* (2021) plant-based clarification is done by deploying natural clarification agents, for example moringa oleifera seed extract, okro mucilage, and guar gum are locally source, cost effective, non-toxic, and environmentally friendly options, that eliminate impurities via binding or trapping the undesired juice extracts.

Table 1: Comparison of Traditional and Natural Clarification Methods

Clarification method	Material	Mechanism	Advantage	Disadvantage	Reference
Chemical	Calcium Hydroxide (KOH).	Neutralizes acid and promotes precipitation.	Cost-effective, fast, established technology	Chemical residues, environmental impact, health risks	Bourguerra <i>et al.</i> (2024), Kameneva <i>et al.</i> (2021)
	Aluminium sulfate (Alum).	Forms aluminium hydroxide to bind particles			
Mechanical	Membrane.	Filters particles and extraction residues.	High efficiency, scalable, less chemical use	High energy consumption, equipment wear	Wibisono <i>et al.</i> (2023), Kameneva <i>et al.</i> (2021), Zhao <i>et al.</i> (2022)
	Chromatography. Ion exchange.	Adsorbs pigment, colour. Binding base on charge Interactions.			
Natural Clay	Bentonite	Adsorbs impurities such as pigments, and protein.	Low-cost, effective at removing pigments and proteins	Excess clay can affect nutrient content, waste management issues	Teetor <i>et al.</i> (2011), Rajvanshi <i>et al.</i> (2020)
Plant Based	Moringa Oleifera Seed Extract.	Bind pigments, proteins, and Solids.	Sustainable, non-toxic, biodegradable	Variability in raw material quality, scalability issues	Saïed <i>et al.</i> (2020), Amaral-Fonseca <i>et al.</i> (2021), Moringa <i>et al.</i> (2021)
	Okro Mucilage.	Bind particulate matter.			
	Guar Gum.	Forms gel-like network, traps biocompatible.			

4. CATALYTIC REACTION PATHWAYS

The popular industrial production of fructose syrup relies on three (3) stages of enzymatic pathway that breaks down biomass feedstock to glucose prior to reversible isomerisation to produce fructose.

4.1 Enzymatic reactions.

4.1.1 Liquefaction (Starch to Dextrins) entailed the use of catalyst like thermostable α -amylase which cleaves α -1,4-glucosidic bonds randomly at pH 5.8–6.5, temperature 95°C–105°C, requires Ca^{2+} ions for enzyme stability. This reduces viscosity and yields shorter-chain maltodextrins (Li *et al.*, 2017; Frey *et al.*, 2020).

4.1.2 Saccharification (Dextrins to Glucose), is the process in which a catalyst such as glucoamylase (enzyme) hydrolysis α -1,4 and α -1,6 linkages sequentially from the non-reducing ends, typically under the following conditions pH 4.0 - 4.5, temperature 60°C- 62°C and employed Glucoamylase to yield a high-purity glucose hydrolysate (D-glucose) (Frey *et al.*, 2020; Chen *et al.*, 2022; Gromada *et al.*, 2008)

4.1.3. Isomerization (Glucose to Fructose), this reaction converts aldose sugar (glucose) to its ketose isomer (fructose) at pH 7.5-8.2, temperature 55°C-60°C with the facilitation of Immobilized Glucose Isomerase/Xylose Isomerase. However, the reaction typically has an equilibrium challenge

with roughly 42 % fructose, 52% glucose, and 6% other sugars (known as HFCS-42) (Amaral-Fonseca *et al.* 2021; Taibi *et al.* 2023)

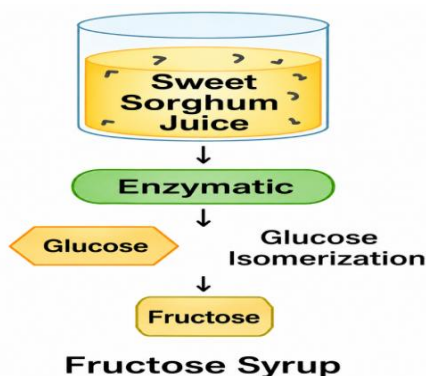


Figure 3: Enzymatic Hydrolysis and Glucose Isomerization for Fructose Syrup Production

4.2 Chemical and Chemocatalytic Reactions.

To bypass the slow reaction kinetics and high costs of enzymes, researchers considered chemocatalysts to convert glucose or directly transform biomass into fructose which involve the following methods.

4.2.1 Homogeneous Base Catalysis such as Sodium hydroxide (NaOH), calcium hydroxide (Ca(OH)₂), or soluble amines is employed, limitation involves high byproduct formation (psicose, mannose) (Chen *et al.*, 2022; Frey *et al.*, 2020; Li *et al.*, 2017)

4.2.2 Heterogeneous Lewis Acid Catalysis for example, Lewis acid center (like Sn⁴⁺) coordinates with the carbonyl oxygen of glucose, facilitating an intramolecular 1,2-hydride shift to form fructose leading to highly selective, water operation and easy catalyst recoverability (Moliner *et al.*, 2010; Frey *et al.*, 2020)

4.2.3 Bronsted Base Solid Catalysts promotion of isomerization via proton abstraction at C2 position using catalysts such as hydrotalcites, basic resins or functionalized silica (Wang *et al.*, 2022; Frey *et al.*, 2020)

5. PROCESS OPTIMIZATION FOR FRUCTOSE SYRUP PRODUCTION

The optimization of catalytic reaction conditions are pH, temperature, concentration, catalytic loading for high percentage yield, stability, quality and economic viability (Dai *et al.*, 2020; Ma *et al.*, 2022). However, optimization faces drawbacks from feedstock variability, impurity, seasonal availability and scale constraints.

In optimization, conditions such as temperature and pH play a critical path in affecting the glucose isomerase, degradation, reaction rates which are determined by the microbial source (Dai *et al.*, 2020; Ma *et al.*, 2022). The catalyst loading and concentration specifically influences the mass transfer during the reaction depends on enzymatic (hydrolysate) conditions (Okpalanma *et al.*, 2024; Debora *et al.*, 2024).

6. CONCLUSION

The non-conventional use of biomass feedstock such as sweet sorghum, cassava, sweet potato and especially waste food leads to waste valorization, circular economy, reduce greenhouse gas emissions, and above all less cost effective. The sweet sorghum demonstrated the potential of catalytic pathway for high percentage yield, purity with high stability. Membrane technologies, enzyme immobilization and the catalyst loading improved the fructose production efficiency and the quality.

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