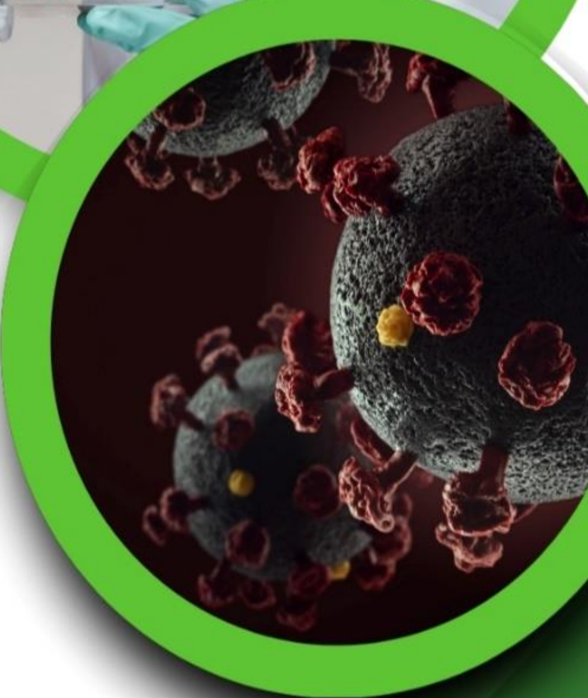

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Sustainable Bioconversion of Cassava: Enzymatic and Biorefinery Developments

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Abstract

The need for renewable and sustainable energy sources has increased due to the world's growing energy consumption and environmental issues surrounding fossil fuels. A viable substitute that offers biodegradability, reduced greenhouse gas emissions, and compatibility with current fuel infrastructure is bioethanol. The high-starch, high-yield crop cassava (*Manihot esculenta*) is ideal for producing bioethanol because it can be grown in poor soils, requires little input, and is consistently available throughout the year. Using amylase and glucoamylase, cassava starch is efficiently hydrolyzed to produce fermentable sugars, which are then fermented into ethanol by vigorous strains of *Saccharomyces cerevisiae*. Modern developments in simultaneous saccharification and fermentation (SSF), high-solid fermentation, and process optimization have greatly increased ethanol yields and process economics. In addition to bioethanol, cassava biomass can be converted into other valuable biochemicals, such as single-cell proteins, organic acids, and bioplastics, improving the biorefineries' economic feasibility and sustainability. Economic and environmental analyzes show that the manufacture of bioethanol from cassava can boost local energy security, encourage rural development, and lower greenhouse gas emissions. Notwithstanding these successes, issues including infrastructural investment, feedstock variability, and enzyme cost still exist. Opportunities include the creation of new fermentation technologies, genetically modified yeast strains, and integrated biorefineries, all of which can optimize resource use and diversify product portfolios. To address the world's renewable energy needs and promote the bioeconomy, this paper highlights recent developments and provides ideas for utilizing cassava as a sustainable feedstock.

Keywords: Cassava bioethanol, Enzymatic hydrolysis, Saccharomyces cerevisiae, Biorefinery

1. Introduction

The global need for energy is continually increasing due to population increase, industrialization, and urbanization. The widespread use of fossil fuels like coal, oil, and natural gas has also had detrimental effects on the ecosystem, including the steady depletion of nonrenewable resources, greenhouse gas emissions, and climate change (IEA, 2021). The hunt for ecologically acceptable and sustainable energy options has been more intense as a result. Because of its high energy density, biodegradability, and compatibility with the current fuel infrastructure, bioethanol has become a promising alternative among renewable energy sources [1].

The manufacture of bioethanol from renewable biomass is essential for lowering reliance on fossil fuels and minimizing pollution in the environment. An important starchy root crop that is extensively grown in tropical and subtropical climates is cassava (*Manihot esculenta*), sometimes referred to as tapioca. Particularly in underdeveloped nations, it has attracted a lot of interest as a sustainable feedstock for the manufacturing of bioethanol [2]. Rapid growth, minimal input needs, a high starch content (up to 85% dry weight), and tolerance to marginal soils unsuitable for other staple crops are only a few of cassava's many benefits [3,4,5]. Because of these qualities, cassava is a useful natural resource for the production of renewable energy.

In contrast to traditional fermentation techniques, high-solid fermentation (HSF) is a new biotechnological technique that enhances substrate utilization, boosts product concentration, and uses less water [7]. HSF methods are more effective and financially feasible for commercial applications because the substrate (such as tapioca starch hydroxylate) ferments at high solid loading (>15–20% w/v). Compared to lignocellulosic biomass, tapioca starch hydrolyses have fewer inhibitory chemicals and a simple sugar content following enzymatic hydrolysis, making them especially well-suited for fermentation [5].

By stimulating the breakdown of α-1,4-glycosidic bonds in starch molecules, amylase plays a crucial role in the hydrolysis of starch into fermentable sugars, producing glucose and maltose [6]. The yeast *Saccharomyces cerevisiae*, which is extensively employed in commercial bioethanol production because of its high ethanol output, resistance to osmotic stress, and well-characterized genetics, transforms the fermentable carbohydrates into ethanol after enzymatic hydrolysis [8].

The high-solid fermentation of tapioca starch hydrolyses using amylase and *Saccharomyces cerevisiae* is thoroughly covered in this paper, with an emphasis on process optimization, technical difficulties, and future prospects. According to the study, using cassava as a sustainable and financially viable feedstock for the manufacture of bioethanol has the potential to support global environmental sustainability initiatives and the mix of renewable energy sources.

2. Cassava as a Source of Biofuel

The high starch content, cheap cultivation costs, and tolerance to marginal soils of cassava have led to its growing recognition as a sustainable feedstock for the manufacture of bioethanol. Over 300 million tons of cassava are produced each year, making it the fourth most significant carbohydrate crop in the world after maize, rice, and wheat [3,9]. Because it can grow in low-fertility soils where other crops cannot, cassava is a great option for renewable energy applications. It flourishes in tropical and subtropical locations [4].

Since 20–40% of cassava's dry weight is starch, it may be readily converted to fermentable sugars without the need for harsh chemical pretreatments [9]. In contrast, complex polymers found in lignocellulosic biomass necessitate more energy-intensive pretreatment techniques [7]. Furthermore, cassava supports the ongoing synthesis of bioethanol by offering a somewhat consistent supply of starch throughout the year [10].

The manufacture of cassava bioethanol is economically advantageous due to its low agricultural input costs and straightforward processing methods, especially in underdeveloped nations. According to Adekunle et al. [11], smallholder farmers profit from selling cassava not just as food but also for energy generation, which creates new business options and enhances rural lives. Incorporating cassava biorefineries into regional agricultural systems also helps to reduce waste by using Agassi and peels for biotechnological uses [12].

Comparing cassava bioethanol to fossil fuels, life cycle assessment (LCA) studies demonstrate that using sustainable farming techniques can result in considerable reductions in greenhouse gas emissions [3]. Additionally, cassava's sustainability profile can be enhanced by crop rotation and integrated pest control. Nonetheless, issues including water usage, changes in land use, and fuel vs. food problems need to be carefully considered [10,14].

3. Hydrolysis of Cassava Starch

In order to produce bioethanol, cassava starch must hydrolyze, which transforms polysaccharides into fermentable sugars. Amylose and amylopectin, the main components of starch, must be broken down by enzymes to produce glucose, the fermentable sugar that *Saccharomyces cerevisiae* uses [8].

Liquefaction and saccharification are the two primary steps in the enzymatic hydrolysis process. Under high temperatures (50–70°C) and ideal pH (5.5–6.5), α-amylase breaks down α-1,4 glycosidic linkages in the starch during the liquefaction step, turning it into dextrins. This lowers the viscosity of the starch slurry and facilitates process handling [5,6]. The saccharification process is then finished by glucoamylase, which hydrolyzes dextrins into glucose monomers at gentler circumstances (about 50°C, pH 4.5–5.5) to avoid microbial contamination [7].

High-solid enzymatic hydrolysis, when solid loadings surpass 15% (w/v), is the focus of recent developments. Although this method lowers water consumption and enhances sugar concentration, it also increases slurry viscosity, which restricts mass transfer and enzyme accessibility [5,7].

An important obstacle for industrial applications is still the cost of enzymes. To increase the cost-effectiveness of hydrolysis, methods including enzyme recycling, on-site enzyme manufacturing, and the creation of strong enzyme combinations are being investigated [6]. To further boost efficiency, researchers are also looking at genetically modified α-amylase and glucoamylase with wider operational ranges [8].

Enzymatic hydrolysis is still preferred due to its selectivity and low environmental effect; however, other pretreatment techniques, such as mild acid hydrolysis or ultrasonication, can increase starch accessibility [14].

4. Fermentation of Hydrolysates

A crucial stage in the synthesis of bioethanol is the fermentation of hydrolysates, in which microorganisms transform fermentable sugars derived from cassava starch into ethanol. Because of its high ethanol output and ability to withstand process stressors, *Saccharomyces cerevisiae* is employed extensively [7]. Furfural and hydroxymethylfurfural, two fermentation inhibitors that adversely impact microbial activity and ethanol output, may be present in the hydrolysates [7]. In order to get around this, scientists like Singh et al. [6] have concentrated on creating genetically altered yeast strains that are more resistant to inhibitors, allowing for the effective generation of ethanol from difficult substrates.

The temperature, pH, and nutrient content during the fermentation process all have a significant impact on the amount of ethanol produced. Gallegos et al. [10] optimized these parameters using a response surface approach, which led to increased production and ethanol concentration. Moreover, the capacity of high-solid fermentation (HSF) techniques to raise the concentration of sugar and ethanol while lowering water consumption and process expenses has made them popular [5]. Although there are obstacles, including inadequate mixing and substrate inhibition at high solid loadings, HSF is a viable approach for producing ethanol on an industrial scale[6].

5. Process Engineering and Optimization

In order to increase ethanol yield and lower production costs, process engineering optimization focuses on combining hydrolysis and fermentation processes into an effective system. One such cutting-edge technique is Simultaneous Saccharification and Fermentation (SSF), which reduces equipment costs and processing time by combining enzymatic hydrolysis and fermentation in a single stage [6]. Edama et al. [15] showed that SSF improves ethanol production by reducing sugar inhibition during hydrolysis, which boosts process efficiency.

Additionally, process optimization entails adjusting crucial variables, including fermentation duration, enzyme dosage, and solid loading. Optimized fed-batch fermentation, in which substrate is given gradually, has been demonstrated by Chavalparit and Ongwandee [16] to assist in maintaining ideal sugar content and yeast viability. To reduce enzyme expenses and enhance operational stability, strategies for enzyme recycling and immobilization are also being investigated [5].

Economic feasibility and resource use are enhanced by the integration of biorefinery technologies, which generate ethanol, lactic acid, and biogas from the same biomass [10]. When compared to conventional single-product processes, integrated techniques dramatically reduce greenhouse gas emissions, according to life cycle assessments (LCA) conducted by Pereira et al. [11].

6. Beyond Bioethanol: Value-Added Biochemicals

In addition to ethanol, value-added biochemicals such as organic acids, bioplastics, and animal feed may be made from cassava hydrolysates. Lactic acid is a precursor for biodegradable polymers, which is why lactic acid generation from cassava hydrolysates has drawn interest [10]. Similar to this, single-cell proteins made from leftover cassava have been investigated for use as animal feed in an effort to increase product portfolio diversity and decrease waste [11].

These co-products' production supports the circular economy concept, which turns waste streams into commodities with market value, making cassava-based biorefineries more viable from an economic standpoint [12]. The biorefinery strategy will probably continue to be the most viable and successful option for using cassava biomass as research advances.

7. Environmental and Economic Perspectives

When sustainable techniques are used, the manufacture of bioethanol from cassava has several environmental advantages, including a decreased dependency on fossil fuels and a reduction in greenhouse gas emissions [2]. Cassava ethanol has a positive carbon footprint, according to life cycle studies by the International Energy Agency [3], particularly when combined with integrated waste management and energy recovery systems.

Through the creation of jobs and local energy sources, cassava bioethanol initiatives support rural development economically. However, obstacles including the necessity for a large capital investment and the instability of feedstock prices prevent broad implementation [9]. The future expansion of the cassava bioethanol business will be greatly aided by government subsidies, legislative frameworks, and technical advancements [8].

8. Challenges and Future Aspects

There are still a number of obstacles to scaling up the production of bioethanol from cassava. During hydrolysis and fermentation, mixing and mass transfer are made more difficult by high viscosity at high solid concentrations [6]. Furthermore, the high cost of enzymes continues to motivate research into genetically modified strains with increased activity and enzyme recycling [5]. It is anticipated that future developments in integrated biorefinery models, such as multi-product extraction and sophisticated yeast strains, would increase process effectiveness and financial sustainability [10].

To sum up, further investigation into integrated value chains, fermentation techniques, and high-efficiency enzyme systems is necessary to get beyond current obstacles and realize cassava's full potential as a sustainable biofuel source.

9. Conclusion

The manufacture of bioethanol from cassava is a sustainable way to satisfy the need for renewable energy. While diversification into biochemicals improves economic viability, advancements in hydrolysis, fermentation, and process engineering have increased efficiency. To fully realize cassava's potential in the bioeconomy, more research funding, governmental support, and innovation are needed to overcome current obstacles.

Acknowledgement

We would like to express our sincere gratitude to Rapture Biotech, Bengaluru and Garden City University, Bengaluru, for their encouragement, guidance, and support, and for providing us with the foundation to successfully complete this work.

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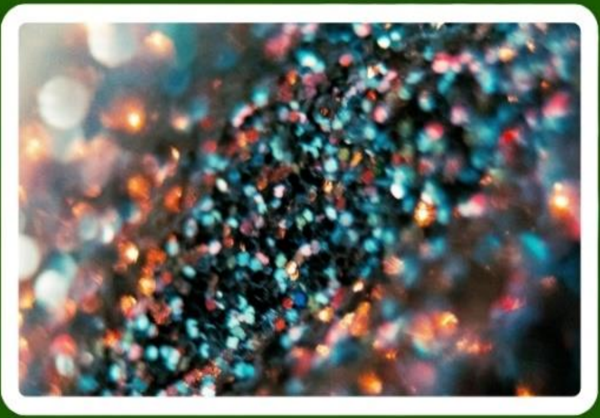

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