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*RESEARCH ARTICLE*

# Bioconversion of *Bambusa vulgaris* waste into bioethanol and bioethylene for a sustainable green energy economy in Nigeria

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## Abstract

Nigeria's heavy dependence on fossil fuels significantly exacerbates environmental degradation, underscoring the need for ongoing research on sustainable alternatives, such as utilizing *Bambusa vulgaris* (common bamboo) biomass to mitigate carbon emissions and foster a green energy economy. The overall objective of this research was to examine the bioconversion potential of *Bambusa vulgaris* waste into bioethanol and bioethylene towards promoting sustainable green energy solutions in Nigeria. In the context of this research, bioconversion refers to the recycling of waste from bamboo into bioethanol and bioethylene using microbial and enzymatic methods. The sample of pulverized fine particles of *Bambusa vulgaris* culm flour was first treated with sodium hydroxide (NaOH) and hydrogen peroxide ($H_2O_2$) at selected laboratories in Lagos and Ogun States. Thereafter, the Separate Hydrolysis and Fermentation (SHF) and Simultaneous Hydrolysis and Fermentation (SSF) approaches were applied. Saccharomyces cerevisiae yeast was also applied to ferment the resulting glucose into bio-ethanol. The produced bio-ethanol was subsequently purified using the fractional distillation method. Bio-ethylene gas was generated from a catalytic dehydration of the bio-ethanol. The results yielded 65% bio-ethanol from 2,000 grammes (g) of bamboo biomass and 53% bio-ethylene gas from 500 mL of bio-ethanol. In conclusion, the research findings demonstrate the viability of bamboo biomass as a renewable green energy source that is capable of reducing greenhouse gas emissions. Future research should focus on scaling up the process to assess economic feasibility and environmental impact, towards ascertaining the industrial application potential for a more sustainable green energy economy in Nigeria.

**Keywords:** Bamboo, bioconversion, bioethanol, bio-ethylene, *Bambusa vulgaris* bamboo culm flour, Lignocellulosic biomass, enzymatic saccharification, Nigeria

## 1. Introduction

The global transition away from petroleum-based chemical production has intensified due to mounting environmental concerns and the finite nature of fossil fuel reserves. Consequently, the transformation of lignocellulosic waste materials into renewable energy carriers represents a critical strategy for addressing growing energy demands while minimizing environmental degradation (Mthembu *et al*., 2021). This has led researchers to exploring sustainable alternatives, such as bamboo. The heavy reliance on crude oil exploration, coupled with concerns over its depletion (Mthembu *et al*., 2021) and the environmental impacts of greenhouse gas emissions (Iriondo *et al*., 2020; Mthembu *et al*., 2021; Ilic *et al*., 2023), has prompted a shift towards bio-refineries utilizing renewable lingo-cellulosic biomass. This biomass serves as a sustainable alternative to crude oil fractions, providing value-added chemicals and precursors for the production of fast-moving consumer goods (FMCG) (Iriondo *et al*., 2020; Mthembu *et al*., 2021).

Plant biomass, such as bamboo, offers a viable alternative for producing bio-chemicals due to its abundance, renewability, sustainability, and widespread distribution (Iriondo *et al*., 2020; Azeez and Orege, 2018). Bamboo is a second-generation renewable resource (Mendieta *et al*., 2021) that offers a promising solution for mitigating industrial and environmental challenges (Zheng *et al*., 2023). Specifically, *Bambusa vulgaris Schrad. ex J.C. Wendl*. (Gonçalves *et al*., 2023), a species native to South East Asia, was introduced to Nigeria and other tropical regions in the 19th century for erosion control and commercial use (Rojas-Sandoval and Acevedo-Rodríguez, 2022; Damayanto, 2024).

Nigeria still regrettably depends heavily on fossil fuels (Timiyan, 2022). This scenario greatly exacerbates environmental degradation and worsen the impacts of climate change, thereby, underscoring the need to investigate sustainable alternatives (Hilili *et al*., 2024; Kohnert, 2024). A core sustainable alternative invested in this paper is the use of *Bambusa vulgaris* (common Nigerian native bamboo) biomass to mitigate carbon emissions and foster a green energy economy.

Generally, bamboo resource is utilised in various applications, including construction, furniture-making, and agriculture, offering potential benefits for the environment and local communities (Ogbodo, 2023a). Recent studies have highlighted the environmental concerns associated with traditional plastics, underscoring the need for sustainable materials like bamboo (Iriondo *et al*., 2020; Mthembu *et al*., 2021; Ilic *et al*., 2023). Bamboo biomass is composed of cellulose, hemicellulose, and lignin as its primary chemical constituents (Kumar *et al*., 2023). Notably, its high cellulose content makes it a promising renewable resource for producing value-added platform chemicals, such as bioethanol and bio-ethylene, which are essential for various manufacturing industries (Iriondo *et al*., 2020).

Bamboo's abundant cellulose content makes it a promising sustainable alternative to traditional sources for producing bioethanol and bioethylene. Cellulose, a crystalline linear homo-polysaccharide polymer with the chemical formula $(C_6H_{10}O_5)n$, is the most abundant naturally occurring polymer on Earth (Mthembu *et al*., 2021; Quiroz-Castañeda and Folch-Mallol, 2013). Composed of d-glucose monomers linked by β-1,4 glycosidic bonds (Antunes *et al*., 2021; Quiroz-Castaneda and Folch-Mallol, 2013), cellulose requires efficient pre-treatment to break its intra-molecular hydrogen bonds and intermolecular van der Waals forces, releasing fermentable glucose (Mthembu *et al*., 2021; Kassim *et al*., 2022). Glucose serves as a precursor to various value-added chemicals, including ethanol, sorbitol, succinic acid, and lactic acid. The treatments applied to cellulose are physical, chemical, and biological (Iriondo *et al*., 2020). This is because physically the component would need to be reduced to sizeable particles, thereby offering sufficient surface area for chemical treatments to dissociate the biomass, biologically by fermentation achieved by either microbe digestive action or fungal enzymatic action (Iriondo *et al*., 2020), fractional distillation to attain the bio-chemicals, and then the option of catalytic dehydration to attain bioethylene gas (Mendieta *et al*., 2021).

Also, bamboo is a high-yielding lignocellulosic biomass, with approximately 90% of its composition consisting of lignocellulose (Azeez and Orege, 2018). This lignocellulosic biomass is primarily made up of cellulose, hemicellulose, and lignin, which account for around 80% of its dry mass and require individual processing (Mthembu *et al*., 2021; Zheng *et al*., 2023). Cellulose is the most abundant component, typically constituting 30-50% of the biomass (Ilic *et al*., 2023), although bamboo's content tends to decrease as bamboo ages (Azeez and Orege, 2018; Kumar *et al*., 2023).

Specifically, Bambusa vulgaris, a species native to South East Asia, was introduced to Nigeria and other tropical regions in the 19th century for erosion control and commercial use (Ogbodo and Odey, 2023; Rojas-Sandoval and Acevedo-Rodríguez, 2022). Bambusa vulgaris, a prevalent species in Nigeria, thrives in the country's humid tropical climate, exhibiting rapid growth and widespread distribution with minimal maintenance requirements (Rashid *et al*., 2023; Abiodun, 2022). The ability of bamboo to spread quickly through rhizomes and culm fragments enables it to form large clumps (Rojas-Sandoval and Acevedo-Rodríguez, 2022). According to the Raw Materials Research and Development Council (RMRDC), bamboo has significant potential for industrial development in Nigeria, which could lead to substantial savings in foreign exchange (Ogbodo, 2023b; Abiodun, 2022).

The overall objective of this research was to bioconversion of waste from *Bambusa vulgaris* into bioethanol and bioethylene towards contributing to attainment of a sustainable green energy economy in Nigeria. In the context of this research, bioconversion refers to the recycling of waste from *Bambusa vulgaris* into bioethanol and bioethylene using microbial and enzymatic methods. In the context of this research, bioconversion refers to the recycling of waste from *Bambusa vulgaris* into bioethanol and bioethylene using microbial and enzymatic methods (Muthukumarappan and Swamy, 2020).

## 2. Literature Review

### *2.1. Bio-ethylene production by the SHF and SSF treatment pathways*

According to Abas *et al*., (2017), Ethylene [also known as ethane ($CH_2$=$CH_2$)] is the first member of the alkene series. It is a colourless gas with a normal boiling point of –103.7 °C and has slight solubility in water and alcohol. Due to the presence of a double bond, ethylene is highly reactive and readily undergoes addition reactions with many chemical reagents. For example, the addition of water to ethylene produces ethanol (Mendieta *et al*., (2021). The simple structure of ethylene, combined with its double bond, makes it an excellent starting molecule for chemical synthesis. It is also a key raw material for producing various grades of polyethylene and other important bulk and base chemicals (Abas *et al*., 2017).

Biomass conversion to bioethanol employs two key pathways (**Figure 1**): Separate Hydrolysis and Fermentation (SHF) and Simultaneous Hydrolysis and Fermentation (SSF). These approaches facilitate the utilisation of lignocellulosic materials. Notably, bamboo's rapid growth rate and high glucose content make it an attractive feedstock, yielding substantial bioethanol quantities (Azeez and Orege, 2018). The bioethanol production process from bamboo involves standard steps: pulverisation, pretreatment, enzymatic hydrolysis and fermentation.

SHF and SSF as illustrated in Figure 1, are crucial bio-processes for converting bamboo waste into bioethanol and bioethylene. These two processes enable the efficient utilization of lignocellulosic biomass in plant. The Separate hydrolysis and fermentation (SHF) is defined as a two-step process where the hydrolysis of hemicellulose and cellulose occurs separately from fermentation, utilizing fermentative microorganisms (Phwan *et al*., 2018). Phwan *et al*., (2018) further asserts that, the SHF method is considered cost-effective for ethanol production, allowing for ideal conditions tailored for each stage. Basically, SHF involves separate hydrolysis and fermentation steps, allowing for optimal conditions. Simultaneous Hydrolysis and Fermentation (SSF), on the other hand, SSF is a method by which enzymatic hydrolysis and fermentation are performed simultaneously in the same reactor.

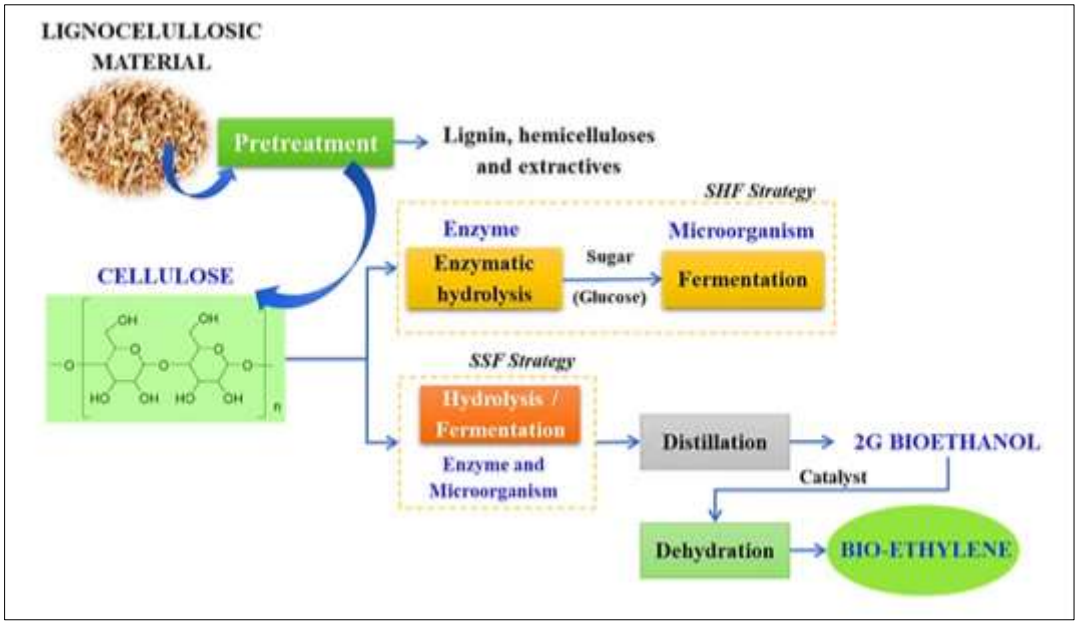


**Figure 1:** Bio-ethylene production using SHF and SSF strategies (Mendieta *et al*., 2021)

Simultaneous Saccharification and Fermentation (SSF), is defined as a method where reducing sugars produced from cellulose hydrolysis are simultaneously fermented to ethanol, which enhances ethanol yields by minimizing product inhibition and eliminating the need for separate reactors for saccharification and fermentation (Haruki and Keiji, 2014).

Haruki and Keiji, (2014) further asserts that, SSF typically involves microorganisms such as *Trichoderma reesei* and *Saccharomyces cerevisiae*. *Trichoderma reesei* (https://www.sciencedirect.com/topics/pharmacology-toxicology-and-pharmaceutical-science/trichoderma-reesei) is a filamentous fungus known for producing cellulases and other lignocellulose-degrading enzymes, and is widely utilized as a heterologous chassis for enzyme production due to its high protein synthesis capabilities. On the other-hand, Saccharomyces cerevisiae (https://www.sciencedirect.com/topics/neuroscience/saccharomyces-cerevisiae) is a principal yeast used in biotechnology globally, known for its unique physiology and significant roles in food fermentations, industrial processes, and fundamental research.

Simultaneous Saccharification and Fermentation (SSF) is a viable process option for producing ethanol Bio-ethylene from lignocellulose in bamboo based sources (Zakaria and Pa, 2023; Kumar *et al*., 2023). By combining enzymatic hydrolysis and fermentation, SSF offers advantages such as reduced end-product inhibition and lower investment costs. However, finding optimal conditions (temperature and pH) for both processes and recycling yeast and enzymes pose challenges. To mitigate such scenarios, SSF is often operated at temperatures below 37°C with low yeast concentrations and high solid loadings (Zakaria and Pa, 2023). Furthermore, bamboo waste can be converted into bioethanol and bioethylene through SSF and Separate Hydrolysis and Fermentation (SHF), with pulverisation being a crucial preprocessing step.

*2.2. Pulverisation*

Pulverisation plays a crucial role in reducing particle size and enhancing enzyme accessibility. These bio-processes offer promising approaches for sustainable biofuel production. This approach (Ilic *et al*., 2023; Quiroz-Castaneda) can improve hydrolysis efficiency and glucose yields and enable the production of biofuels and bio-chemicals using lignocellulose. Lignocellulose is recalcitrant due to its complex physical and chemical properties,

including crystallinity, degree of polymerization, porosity and accessible surface area, which hinder enzymatic hydrolysis (Quiroz-Castaneda and Folch-Mallol, 2013).

To overcome this recalcitrance, lignocellulosic biomass is often mechanically pulverized into smaller particles, increasing the contact surface area for efficient hydrolysis and higher glucose yields (Ilic *et al*., 2023). The increased surface area achieved through pulverisation sets the stage for effective enzymatic hydrolysis by facilitating more efficient pretreatment.

### *2.3. Pretreatment in Bamboo-based Bioethanol and Bioethylene Production*

Alkali-based pretreatments, like sodium hydroxide, have shown promise in breaking down lignin and hemicellulose (Zhang and Wu, 2023). Thus, optimizing pretreatment methods, such as alkali or ultra-high-pressure explosion, is crucial for enhancing enzymatic accessibility and subsequent ethanol purification. Effective pretreatment disrupts the lignocellulosic matrix, reducing hemicellulose and lignin content, and modifying cellulose structure for efficient hydrolysis (Kuttiraja *et al*., 2013; Fuertez-Córdoba *et al*., 2021). Raina *et al*., (2024) and Devi *et al*., (2022) research both underscore the significance of pretreatments in improving sugar yields and ethanol production. By optimizing pretreatment, bamboo bioethanol and bioethylene productions can become more efficient and cost-effective. Specifically, bamboo-to-bioethanol production through biorefinery involves a multi-step process: pretreatment to break down lignocellulose, fermentation to produce bioethanol and enzymatic hydrolysis to convert cellulose and hemicellulose into sugars.

### *2.4. Enzymatic Hydrolysis in bioconversion*

Enzymatic hydrolysis breaks down lignocellulosic biomass into fermentable glucose. Cellulases, hemicellulases, and ligninases work together to depolymerize cellulose, hemicellulose, and lignin. The process involves three key cellulase groups: endoglucanases, exoglucanases, and β-glucosidases, which sequentially convert cellulose to glucose. In other words, enzymatic hydrolysis is necessary to break down cellulose and achieve depolymerization of lignocellulosic biomass thereby, enabling fermentation of the resulting glucose into bioethanol (Busic *et al*., 2018).

According to Gonzalez-Gonzalez and Miranda- Lopez (2022), cellulase enzymes depolymerize cellulose into glucose, while hemicellulases and ligninases target hemicellulose and lignin, respectively. These enzymes are produced by cellulolytic fungi and bacteria that degrade plant cell walls (Quiroz-Castaneda and Folch-Mallol, 2013). The hydrolysis process involves three key groups of cellulases: endoglucanases, which create free chain ends by targeting low-crystallinity areas; exoglucanases (cellobiohydrolases), which detach cellobiose units from these ends; and β-glucosidases, which convert cellobiose to glucose (*Gonzalez-Gonzalez and Miranda- Lopez*, 2022). The next step to enzymatic hydrolysis in pretreatment process is fermentation.

### *2.5. Fermentation*

Saccharomyces cerevisiae is the most commonly used yeast for industrial glucose fermentation due to its efficient conversion capabilities. Two primary strategies (Valles *et al*., 2020), Separate Hydrolysis and Fermentation (SHF) and Simultaneous Saccharification and Fermentation (SSF), can be employed, with SSF proving advantageous due to its efficiency, higher bioethanol yields, and reduced contamination risks, as glucose is immediately fermented into bioethanol, relieving cellulase inhibition (Althuri *et al*., (2017). This bioethanol can then be further processed through dehydration.

*2.6. Bioethanol Dehydration*

Bio-ethylene can be produced from bioethanol through catalytic dehydration (Singh and Rangaiah, 2017). As a crucial petrochemical building block, ethylene is used to derive various polyethylene plastics, including (Platzer, 1983; Zhang *et al*., 2004): Low-Density Polyethylene (LDPE), High-Density Polyethylene (HDPE), and Linear Low-Density Polyethylene (LLDPE). Other derivatives are polyethylene terephthalate – PET (Joseph *et al*., 2024) as well as polypropylene – (PP), polyvinyl chloride (PVC) and polystyrene (PS) (Siracusa, and Blanco, 2020). Similarly, Siracusa, and Blanco, (2020) further expressed that bio-ethylene can be converted into bioplastics such as bio-polyethylene (bioPE), bio-polyvinyl chloride (bioPVC), bio-polyethylene terephthalate (bioPET), bio-polypropylene (bioPP), and bio-polystyrene (bioPS), offering alternatives to traditional plastics.

## 3. Materials and Methods

*3.1. Study site*

The four-week experiments were carried out in two Biotechnology Laboratories in Southwest Nigeria: the Ramatech Global Solar Institute, Sango Ota, Ogun State and Federal Institute of Industrial Research in Oshodi (FIIRO), Lagos State. FIIRO is situated on latitude 6.5465°N and longitude 3.3512°E (Google Earth: https://share.google/3aJytgGeXpE0DHVDz).

*3.2. Description of pretreatment*

Sundry bamboo culms (Bambusa vulgaris) were sourced from The Eternal Sacred Order of The Alpha Et Omega Church of Christ, Aladura, situated at #22, Ifelodun Street, off Sadiku, Ilasamaja, Mushin, Lagos State, Southwest Nigeria. The bamboo, previously used as scaffolding, was abandoned and subsequently repurposed for this study. The dried culms were sliced with cutlass and later crushed, mechanically (Figure 2a). The resulting product was ground further in a mortar and pestle into fine particles tagged in this experiment as '*Bambusa vulgaris* bamboo culm flour' (**Figure 2b**). The essence of this grinding was to ensure an increase in the surface area for pretreatment and enzymatic attack during the experiment. The ground *Bambusa vulgaris* bamboo culm flour was later sieve to produce finer particles in order to ensure uniformity and optimal reaction conditions. Overall, a total of two thousand (2,000) grammes (i.e. 2.0 Kg) of the *Bambusa vulgaris* bamboo culm flour (bamboo biomass) was utilized in this research. Digital weighing scale was used to measure the samples throughout this research. This research utilised three main chemicals, as follows: sodium hydroxide (NaOH) for delignification (Bosenbecker *et al*., 2024; Li *et al*., 2012), hydrogen peroxide ($H_2O_2$) as a bleaching agent (Loor, 2022), and cellulase as a biocatalyst for enzymatic hydrolysis (da Silva, 2024).

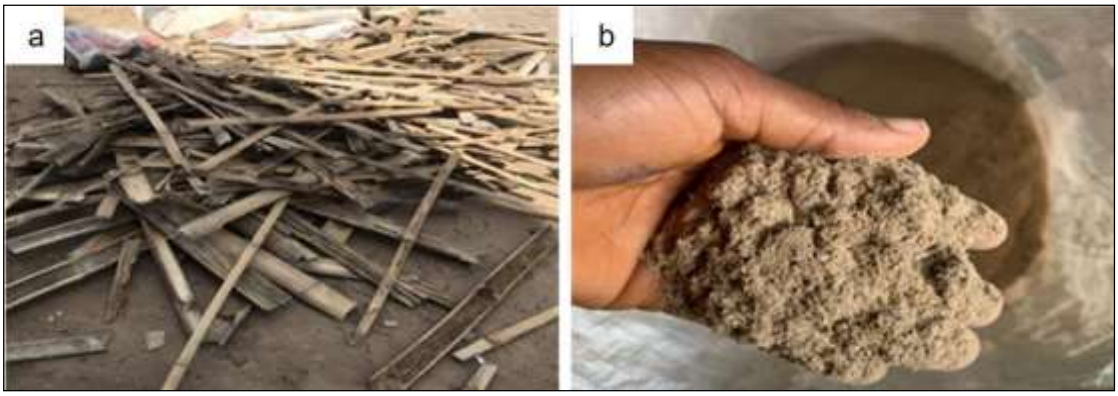


**Figure 2:** Sliced *B. vulgaris* culms (a) and finely-milled particles of *B. vulgaris* culm flour (b)

### 3.3. Methodology

#### 3.3.1. Isolation of cellulose from the Bambusa vulgaris bamboo culm flour

The finely milled bamboo particles were converted into pulp using the Kraft method. According to ScienceDirect (2023), the Kraft process is a widely used pulping technique that breaks down lignin in an alkaline solution, typically using sodium sulfide and sodium hydroxide at high temperatures. This process facilitates lignin depolymerization, releasing phenolic hydroxyl groups and dissolving lignin in the solution. In this research, a two-stage pretreatment process was applied to the bamboo biomass. Initially, 20 grammes (20 g) of milled bamboo particles were soaked in 200 millilitres (200 ml) of an 8% (mass per volume, M/V) sodium hydroxide (NaOH) solution in a 250 millilitres (250 ml) conical flask and left for 48 hours. Figure 3 (a-e) presents the outputs of methodology followed in this research. Afterwards, the solid residue was washed with distilled water to remove residual chemicals. The mixture was heated to 140°C on a hot plate for 2 hours and stirred using a magnetic stirrer at 100 revolutions per minute (100 rpm) for 180 minutes to ensure homogeneity. The second stage was to further pretreat the *Bambusa vulgaris* bamboo culm flour with 100 millilitres (100 ml) of a 4% (M/V) hydrogen peroxide solution to improve access to the cellulose. Prior to enzymatic hydrolysis, the washed, pretreated bamboo flour was dried overnight at 60°C (Kuila *et al*., 2011).

#### 3.3.2. Enzymatic Hydrolysis of treated Bambusa vulgaris bamboo culm flour

The procedure described in Kuila et al., (2011) was adapted in this study. The pretreated sample of *Bambusa vulgaris* culms residue was placed in a flask containing 18 ml of 0.1 mol/l of phosphate buffer with a pH 6.5 (John, 1993) and 2 ml of cellulase enzyme at nine (9) FPU/g (fatty acid unit per gram). According to ScienceDirect (2008), centrifugation is defined as a technique used to separate solid particles dispersed in a liquid medium by rotating the sample rapidly, utilizing centrifugal force to segregate components based on their density differences. In this study, the sample was centrifuged at 2,000 RPM (Revolutions Per Minute) for three hundred (300) seconds and sample aliquots were taken periodically. The formula (Kuila *et al*., 2011), "Saccharification (%) = 100 × [Reducing sugar concentration obtained / Potential sugar concentration in the pretreated substrate]" was applied. This formula is a standard way to calculate the degree of hydrolysis of a pretreated biomass during enzymatic hydrolysis. This calculation quantifies how effectively the cellulose and hemicellulose in the substrate have been broken down into smaller, fermentable sugar molecules (reducing sugars).This was to break the high-carbon molecules into smaller ones in order to yield sugar (de-polymerizing the cellulose to glucose) as expressed by Deshmukh and Pathan, (2024) and Wang *et al*., (2024a). Akita and Matsushika, (2024) expresses that, a successful pretreatment has to a large extent removed the hemicellulose, leaving the cellulose available for hydrolysis. Since the most commonly used microorganisms for ethanol production solely utilize sugar monomers, the cellulose needs to be hydrolyzed, which in an SSF occurs concomitantly with the fermentation.

#### 3.3.3. Fermentation of the treated Bambusa vulgaris bamboo culm flour

This study analysed *Bambusa vulgaris* flour for reducing sugars using Saccharomyces cerevisiae. The process involved preparing a supernatant from the flour through enzymatic treatment, followed by yeast fermentation to quantify fermentable sugars. The yeast converts sugars like glucose, fructose, and maltose into ethanol and other products, allowing for the measurement of reducing sugars in the flour extract (da Silva *et al*., 2024; Kuila et al., 2011). The fermentation process lasted three days, during which yeast enzymes facilitated the conversion of sugars into ethanol (Wang *et al*., 2024b). In the end, a "mash – i.e. fermented liquid", containing ethanol from bamboo flour, was prepared.

*3.3.4. Distillation of Ethanol from Fermented Bambusa vulgaris Mash*

Adapting the methods described by Tse *et al*., (2021) and Stanzer *et al*., (2023), the fermented liquid was heated in a still, causing the ethanol to vapourise at 78.2°C, while water remained in liquid form at its higher boiling point of 100°C. The ethanol vapour then rose into a condenser, where it was cooled and converted back into a liquid. Finally, the distilled liquid, known as the distillate (**Figure 3e**), was collected in a receiving flask and tested for percentage ethanol concentration.


**Figure 3:** (a) mixture of *B. vulgaris* bamboo culm flour + sodium hydroxide (NaOH) solution; (b) *B. vulgaris* residue of enzymatic hydrolysis; ( c) Mash – the fermented liquid - containing ethanol from bamboo flour; prepared/stored in a container

*3.3.5. Production of Bio-ethylene from ethanol dehydration in this research*

The researchers reported that their methodology was adapted from Nanjing Tech University (2007). They noted that bio-ethylene, with a boiling point of -103.7°C, is a gas at room temperature. The process involved preparing ethylene through a biomass route, where ethanol from biomass fermentation undergoes catalytic dehydration to produce ethylene. In the experiment, bio-ethanol from bamboo waste was heated in a conical flask with an aluminum oxide ($Al_2O_3$) catalyst to facilitate the reaction. The vapour passed through a burette containing silica gel, which dried the vapour, and then into a cylinder where the bio-ethylene gas was collected. The process involved distillation and catalytic dehydration of ethanol (5-45% concentration) to produce crude ethylene, which was then cooled, separated, washed, dried, and refined to yield ethylene gas. Finally, the percentage yield of bio-ethylene gas was calculated.

## 4. Results and Discussion

*4.1. Results*

The recycling of waste bamboo (Bambusa vulgaris) into value-added platform chemicals yielded promising results. The experiment produced 1,301 g [i.e. 65.05 percent (%) yield] of bio-ethanol from 2,000 grams (g) of bamboo biomass. Subsequently, 800 ml (approximately 632 g, at a density of 0.79 g/ml for bio-ethanol) of bio-ethanol was converted to bio-ethylene through catalytic dehydration. The bio-ethylene yield was calculated based on the mass of bio-ethanol input, and the resulting yield was 53% (209.35 g being an equivalent of 262.5 litres (L), at a density of 1.178 kg/m$^3$ for bio-ethylene at standard conditions). The standard reaction conditions for bio-ethanol production involved fermentation at 30°C for 48 hours, while bio-ethylene production occurred at 372.00°C with an aluminum oxide ($Al_2O_3$) catalyst. A mass balance of the process revealed that approximately 65% of the bamboo biomass was converted to bio-ethanol, and 53% of the bio-ethanol was subsequently converted to bio-ethylene. That is, parameters for the Mass Balance are as follows:

i. Bamboo biomass input: 2,000 g
ii. Bio-ethanol produced: 1,301 g (65.05% yield)
iii. Bio-ethanol input for bio-ethylene production: 632 g
iv. Bio-ethylene produced: 335 g (53% yield)

Also, from the application of the formula: "Saccharification (%) = 100 × [Reducing sugar concentration obtained / Potential sugar concentration in the pretreated substrate]" the saccharification procedure yielded a saccharification percentage of 65.05%, indicating that approximately 65.05% of the potential sugars in the pretreated bamboo biomass were converted into reducing sugars. This result suggests efficient enzymatic hydrolysis of the biomass, which is crucial for subsequent bio-ethanol production.

### *4.2. Discussion*

The results of this research as discussed in this paper demonstrate the feasibility of recycling waste bamboo (*Bambusa vulgaris*) into value-added platform chemicals, specifically bio-ethanol and bio-ethylene. The high yield of bio-ethanol (65.05%) from bamboo biomass is consistent with previous studies on lignocellulosic biomass conversion (Wang *et al*., 2024a; Kuila *et al*., 2011). Furthermore, the conversion of bio-ethanol to bio-ethylene with a yield of 53% highlights the possibility of producing petrochemical substitutes from renewable biomass, as also reported by other researchers (da Silva *et al*., 2024; Bosenbecker *et al*., 2024). The mass balance analysis reveals that approximately 65% of the bamboo biomass is converted to bio-ethanol, indicating efficient utilization of the feedstock. However, the bio-ethylene yield is lower, suggesting potential areas for process optimization, such as improving catalyst performance or reaction conditions (Raizada and Sarin, 2024). Comparison between Bio-Ethanol and Conventional Ethanol is present in **Table 1**.

**Table 1.** Comparison between Bio-Ethanol and Conventional Ethanol (Gou *et al*., 2024)

| Test | Test Value [In this study] | Conventional Value |
|---|---|---|
| Flash Point | 16.72°C | 13.00°C |
| Auto Ignition Temperature | 480.00°C | 440.00°C |
| Ignition Temperature | 372.00°C | 365.00°C |
| Boiling point | 78.20°C | 78.37°C |
| Specific Gravity | 0.79 | 0.79 |
| Vapour pressure | 13.05 mmHg | 59.00 mmHg |

Consequently, the high saccharification percentage obtained in this study suggests that the pretreatment method used was effective in breaking down the biomass structure, making the cellulose and hemicellulose more accessible to enzymatic hydrolysis (Enjamuri and Darbha, 2024; Wang *et al*., 2024b). Furthermore, the consistency between the saccharification percentage and bio-ethanol yield indicates that the enzymatic hydrolysis step was efficient in converting the released sugars into fermentable sugars in agreement with (Gou *et al*., 2024; Valles *et al*., 2020). The findings of this study have implications for the optimization of bioethanol production from bamboo biomass, as it highlights the importance of optimizing pretreatment and enzymatic hydrolysis conditions to achieve high saccharification yields. Overall, this study demonstrates the potential of waste bamboo as a valuable resource for the production of bio-based chemicals, and further research is warranted to explore scaling up this process and optimizing reaction conditions for improved yields and efficiency.

## 5. Conclusion and Recommendation

### *5.1. Conclusion*

This article successfully demonstrates the conversion of waste bamboo (Bambusa vulgaris) into valuable bio-based chemicals, including bio-ethanol and bio-ethylene, with yields of 65.05% and 53%, respectively. By leveraging bamboo biomass as a sustainable feedstock, this approach offers a promising alternative to fossil fuels and contributes to mitigating climate change. The findings presented in this article have significant implications for the development of circular economy principles and sustainable production pathways, particularly in Nigeria.

*5.2. Recommendation*

Future studies should therefore, investigate scaling up production, optimizing pretreatment and enzymatic hydrolysis conditions, evaluating catalyst performance, and assessing the environmental and economic feasibility of this process. A detailed life cycle assessment and economic analysis would provide valuable insights into the sustainability and viability of producing bio-ethanol and bio-ethylene from bamboo biomass.

**Conflicts of Interest:** All authors have read and agreed to the published version of the manuscript. The authors declare no conflicts of interest.

**Author Contributions:** Conceptualization (Ugo, U. K. /Ogbodo, J.A.), Methodology (Ugo, U. K./ Ajekwene, K. K.), Data analysis and interpretation (Ugo, U. K./ Ogbodo, J.A.), Writing the original manuscript/draft preparation (Ugo, U. K./ Ogbodo, J.A.), Writing the review and editing (Ogbodo, J.A.), Supervision (Ajekwene, K. K./Icheta-onye, S.I.), Project administration (Ugo, U. K.).

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