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Recycling of Waste Bamboo (Bambusa vulgaris) into Value-Added Platform Chemicals: Bioethanol and Bioethylene

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Abstract

A viable substitute for the urgent ecological and environmental problems in Nigeria associated with traditional crude oil (fossil fuels) is the use of bamboo biomass. The aim of this research is to address these issues by concentrating on the sustainable, abundant, and renewable source of cellulosic content—bamboo. Using the plentiful cellulose found in bamboo, the goal is to produce bio-ethanol, a biofuel recognized for its environmentally beneficial qualities and capacity to reduce greenhouse gas emissions, and bio-ethylene, which is a precursor to various bioplastics. Investing in attaining bamboo-derived platform bio-chemicals would help to mitigate the effects of climate change and reduce environmental pollution while also reducing dependency on finite fossil fuel resources. Physical, chemical, and biological pretreatments were employed to gain access to the cellulose component of the bamboo biomass for further processing. This involved pulverisation, enzymatic hydrolysis, and fermentation procedures used in the process to transform cellulose derived from a species of bamboo, *Bamboo Vulgaris*, into bio-ethanol. NaOH and H_2O_2 were utilised to delignify the lignocellulose, and it was subsequently treated via separate hydrolysis and fermentation (SHF) to attempt optimal depolymerisation of the cellulose structure. *Saccharomyces cerevisiae* was the yeast for the fermentation of the realized glucose because of its efficiency to ferment glucose into bioethanol, before purification by fractional distillation. Finally, catalytic dehydration of the bioethanol was carried out to yield bio-ethylene gas.

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1. Introduction

The over-dependence on crude oil fractions for raw materials used to obtain polymeric resins for the manufacture of popular domestic plastics such as polyethylene (PE) and polypropylene (PP) has led to the deleterious effects of climatic changes and unfavourable impact on livelihoods of those within the vicinity of crude oil explorations (Iriondo, Agirre, Viar, and Requies, 2020; Mthembu, Gupta, and Deenadayalu, 2021; Ilić, Milić, Beluhan, and Dimitrijević-Branković, 2023). *Bambusa vulgaris,* also known as *common bamboo* or *yellow bamboo*, is a species of bamboo that was introduced in Nigeria and other tropical areas of the world in the nineteenth century from South East Asia. Its primary purposes were to utilise it for erosion control, fencing, and the establishment of plantations for the commercialization of its culms (Rojas-Sandoval and Acevedo-Rodríguez, 2022). Today, it is obviously seen in its use for scaffolding in the building industry, aesthetic furnishings and structures in homes and the hospitality business, and also as support structures for creeping plant stems in farms. Bamboo, comprising cellulose, hemicellulose, and lignin, which are its major chemical components, thrives in humid (tropical) climates and can be found forming bushes around rivers; however, excessive moisture does not favour its structural integrity (Kumar et al., 2023). The component material of interest is its cellulose, which is in great abundance to serve as a renewable alternative source to yield value-added platform chemicals such as bioethanol and bio-ethylene for manufacturing industries (Iriondo, Agirre, Viar, & Requies, 2020).

2. Literature Review

The heavy dependence on crude oil exploration, and fears of exhausting this resource (Mthembu, Gupta, and Deenadayalu, 2021), coupled with the consequences of the activities which involve greenhouse gas emissions contributing to adverse climatic change, has been drastic (Iriondo, Agirre, Viar, and Requies, 2020; Mthembu, Gupta, and Deenadayalu, 2021; Ilić, Milić, Beluhan, & Dimitrijević-Branković, 2023). The demands for alleviation have led to the establishment of biorefineries inclining towards the utilization of renewable resources in the form of lignocellulose (Mthembu, Gupta, and Deenadayalu, 2021), a biomass that serves as raw materials for industries that require crude oil fractions (Iriondo, Agirre, Viar, and Requies, 2020), serving as value-added chemicals as precursors for further processing into FMCG products. Plant biomass such as bamboo, among other suitable lignocellulosic plants, has posed to be viable options for processing into biochemical versions of certain value-added chemicals, especially because of its favourable abundance, renewability, sustainability, and distribution (Iriondo, Agirre, Viar, and Requies, 2020; Azeez & Orege, 2018). Bamboo, which is categorised as a second-generation renewable resource (Mendieta et al., 2021), has proven to be a functionally renewable and adaptable material capable of mitigating unfavourable industrial and environmental conditions (Zheng et al., 2023), yielding more biomass content than any other lignocellulosic crop, with the lignocellulosic content constituting 90% of its topsoil structure (Azeez and Orege, 2018). Bambusa vulgaris, which is the most common species of bamboo in Nigeria, thrives in its humid (tropical) climate, which supports its sustainable abundance, hence posing a high growth rate – widely distributed in the land ((Rashid et al., 2023; Abiodun, 2022), with minimal maintenance when compared with other cellulosic plants (Rashid et al., 2023). This species of bamboo has the ability to attain widespread distribution quickly with its rhizomes and culm fragments (Rojas-Sandoval and Acevedo-Rodríguez, 2022).

Dispersal of single culms by water or human activities is capable of forming large clumps of the bamboo, hence its potency to gain coverage and overwhelm areas where they can thrive (Rojas-Sandoval and Acevedo-Rodríguez, 2022). The Raw Materials Research and Development Council (RMRDC) effected a study expressing the bamboo distribution in the country (Abiodun, 2022; Atanda, 2015), with the potential to save billions, if not trillions, of Naira in foreign exchange equivalent, if adequately and sustainably developed for industrial use in the country (Abiodun, 2022). Just as well, John Agbo Ogbodo, founder and director of the Sustainable Trans Environment International Foundation (STEi), proposed several aspects of bamboo cultivation and industrialization in Nigeria (Hornaday, 2022).

Lignocellulosic biomass contains cellulose, hemicellulose, and lignin, which must each be separated and the preferred component singularly treated (Mthembu, Gupta, and Deenadayalu, 2021; Zheng et al., 2023). Cellulose and hemicellulose are hydrocarbon polymers, while lignin is a phenolic polymer, with all three of them constituting 80% of the lignocellulose dry mass (Ilić, Milić, Beluhan, and Dimitrijević-Branković, 2023). Out of the three composing contents, cellulose has the largest percentage, ranging between 30 - 50% (Ilić, Milić, Beluhan, and Dimitrijević-Branković, 2023); however, the cellulose content tends to decrease as bamboo culms age (Azeez and Orege, 2018; Kumar, Ganguly, and Purohit, 2023).

Cellulose, with the chemical formula $(C_6H_{10}O_5)_n$, poses the most abundant naturally occurring polymer on earth, considering the plant coverage. It is a crystalline linear homopolysaccharide polymer (Mthembu, Gupta, & Deenadayalu, 2021; Quiroz-Castañeda and Folch-Mallol, 2013), comprising monomeric molecules of d-***glucose*** connected by β-1,4 glycosidic bonds (Antunes et al., 2021; Quiroz-Castañeda and Folch-Mallol, 2013). In essence, its constituting monomeric repeat unit is glucose. Attaining a generous fermentable glucose release from cellulosic materials requires the most suitable and efficient alkali or acid pre-treatment method to break up the numerous intra-molecular hydrogen bonds and the collective intermolecular van der Waals forces of the cellulose structure ((Mthembu, Gupta, and Deenadayalu, 2021; Kassim et al., 2022). Glucose serves as a precursor to a variety of value-added chemicals, which include ethanol, sorbitol, succinic acid, lactic acid.

The treatments applied to cellulose are physical, chemical, and biological (Iriondo, Agirre, Viar, and Requies, 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, Agirre, Viar, and Requies, 2020), fractional distillation to attain the biochemicals, and then the option of catalytic dehydration to attain bioethylene gas (Mendieta et al., 2021).

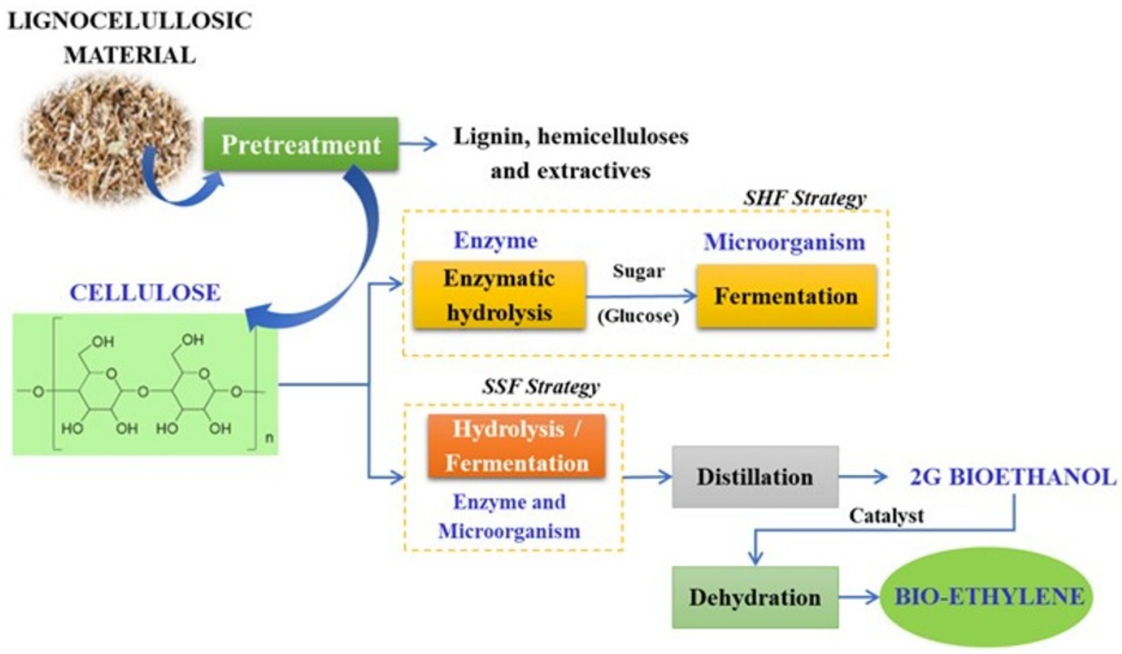

Fig. 1. The pathways for 2G bio-ethylene production by the SHF and SSF strategies (Mendieta et al., 2021)

The production of precursor biochemicals has become an important goal, considering that the petrochemical industry has been necessitated to seek sustainable alternatives (Iriondo, Agirre, Viar, and Requies, 2020; Mendieta et al., 2021). Carbon dioxide emissions can be reduced by approximately 2.5 tonnes per tonne of bio-ethylene produced by replacing fossil fuel-based chemicals with bio-based chemicals (Mendieta et al., 2021; de Jong et al., 2012a). Bamboo has been identified for this purpose because of its relatively higher growth rate, annual biomass yield, and hence the significant amount of glucose content among other sugars that makes it yield 250–380 litres per tonne of bamboo attained from 70 - 85 % of its culm (Azeez and Orege, 2018). The same processes used to obtain bioethanol from other lignocellulosic matter, which include pulverisation, pretreatment, enzymatic hydrolysis, and fermentation, can be applied with bamboo (Azeez and Orege, 2018; Ilić, Milić, Beluhan, and Dimitrijević-Branković, 2023).

2.1. Pulverisation

Lignocellulose is a recalcitrant matter because of the combined physical and chemical properties of the constituting cellulose, hemicellulose, and lignin, which include crystallinity, degree of polymerization, porosity, and accessible surface area, inhibiting enzymatic hydrolysis (Ilić, Milić, Beluhan, and Dimitrijević-Branković, 2023; Quiroz-Castañeda and Folch-Mallol, 2013). To solve this problem, the lignocellulosic biomass would have to be mechanically pulverised into small particles to achieve maximal contact surface area for efficient hydrolysis to affect a high yield of glucose (Ilić, Milić, Beluhan, and Dimitrijević-Branković, 2023).

2.2. Pretreatment

This is imperative to disrupt the lignocellulosic matrix of its three constituting contents where the hemicellulose and lignin are reduced, and the crystalline structure of the cellulose is modified to aid efficient enzymatic hydrolysis (Fuertez-Córdoba, Acosta-Pavas, and Ruiz-Colorado, 2021). Pretreatment with non-polluting and non-corrosive alkali reagents (such as sodium hydroxide (NaOH), calcium hydroxide ($Ca(OH)_2$), sodium carbonate ($NaCO_3$), and ammonia (NH_3)), aids delignification under mild conditions of temperature and pressure with minimal degradation of the glucose, achieving solubilization of mostly the lignin to improve access to the cellulose content

(Fuertez-Córdoba, Acosta-Pavas, and Ruiz-Colorado, 2021). Optimization of this can be achieved by subsequent pretreatment with alkaline hydrogen peroxide (H_2O_2) (Zhang and Wu, 2023).

2.3. Enzymatic Hydrolysis

Enzymatic action is required to hydrolyse the cellulose to achieve de-polymerization of lignocellulose biomass so that fermentation of the resulting glucose by yeast or bacteria into bioethanol will be realized (Bušić et al., 2018). In order to de-polymerise cellulose into glucose, the enzyme cellulase is employed, just as hemicellulases and ligninases depolymerise hemicellulose and lignin, respectively (Ilić, Milić, Beluhan, and Dimitrijević-Branković, 2023). These enzymes are made available by cellulolytic fungi and bacteria that feed on plant cell walls (Quiroz-Castañeda and Folch-Mallol, 2013). During the hydrolysis of cellulose, three major constituting groups of cellulases partake in the process - *endoglucanases* that create free chain ends by degrading areas of low crystallinity in the cellulose fibre to attain free chain ends; *exoglucanases* (*cellobiohydrolases*) that further degrade the molecule by detaching cellobiose units from the free chain ends; and β-glucosidases that finally hydrolyse cellobiose to produce the expected glucose (Bušić et al., 2018).

2.4. Fermentation

Out of all suitable fermentation yeasts, *Saccharomyces cerevisiae* is the most common yeast for the industrial fermentation of glucose because of its capability to efficiently ferment glucose (Mendieta et al., 2021). One of the two common subsequent treatment strategies, separate hydrolysis and fermentation (SHF), and simultaneous hydrolysis and fermentation (SSF), could be adopted (Mendieta et al., 2021). Utilizing the SHF process involves achieving cellulose hydrolysis and glucose fermentation separately, allowing each stage to happen at its optimum conditions with the enzymatic hydrolysis at 50°C, and *Saccharomyces cerevisiae* at 32°C (Dahnum, Tasum, Triwahyuni, Nurdin, and Abimanyu, 2015), while the SSF process requires using just a single reactor for achieving hydrolysis and fermentation simultaneously (Mendieta et al., 2021). The SSF process has proven to be advantageous in terms of efficiency because, upon the release of the monomeric glucose during saccharification, they are immediately fermented into bioethanol by the micro-organisms (Dahnum, Tasum, Triwahyuni, Nurdin, and Abimanyu, 2015), which reduces the chances of unfavourable contamination by microbes (Mendieta et al., 2021). This rapid SSF process renders a higher yield of bioethanol than SHF because low residual sugar relieves inhibition on the cellulase enzyme (Dahnum, Tasum, Triwahyuni, Nurdin, and Abimanyu, 2015).

2.5. Bioethanol Dehydration

Further processing via catalytic dehydration would yield bio-ethylene (Mendieta, Vallejos, Felissia, Chinga-Carrasco, and Area, 2019). Ethylene, as a petrochemical product of great importance, serves as a platform molecule to derive various grades of polyethylene (LDPE, HDPE, LLDPE, etc.), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC), and polystyrene (PS) (Mendieta et al., 2021). This applies just the same with bio-ethylene, which yields the bioplastic versions of the aforementioned ethylene derivative plastics, including bio-polyethylene (bioPE), bio-polyvinyl chloride (bioPVC), bio-polyethylene terephthalate (bioPET), bio-polypropylene (bioPP), bio-polystyrene (bioPS), and others (Mendieta et al., 2021).

3. Methodology

3.1. Procedure

STEP 1: Grinding/Milling

The bamboo was obtained from Alpha et Omega Church of Christ, Aladura, at Mushin, Lagos State, where it was abandoned after its use as scaffolding. It was cut into pieces and then milled into a fine powder, which is the required form for the conversion process.

Fig. 2. *Bamboo culms*

Fig. 3. *Cut-up bamboo culms*

Fig. 4. *Fine-milled bamboo biomass*

STEP 2: Pre-Treatment

The two stages of pretreatment were carried out on the biomass (milled bamboo). The first stage was the alkaline pre-extraction, in which sodium hydroxide (NaOH) was used. 20g of the milled bamboo was soaked in 200ml of 8% (M/V) of NaOH in a 250ml conical flask and was heated at 140℃ on the hot plate. This was set to mix and attain homogeneity with a magnetic stirrer at a speed of 100 rpm for 180 mins. In the second stage, 100 ml of 4% (M/V) of hydrogen peroxide was used for further pre-treatment to gain better access to the cellulose.

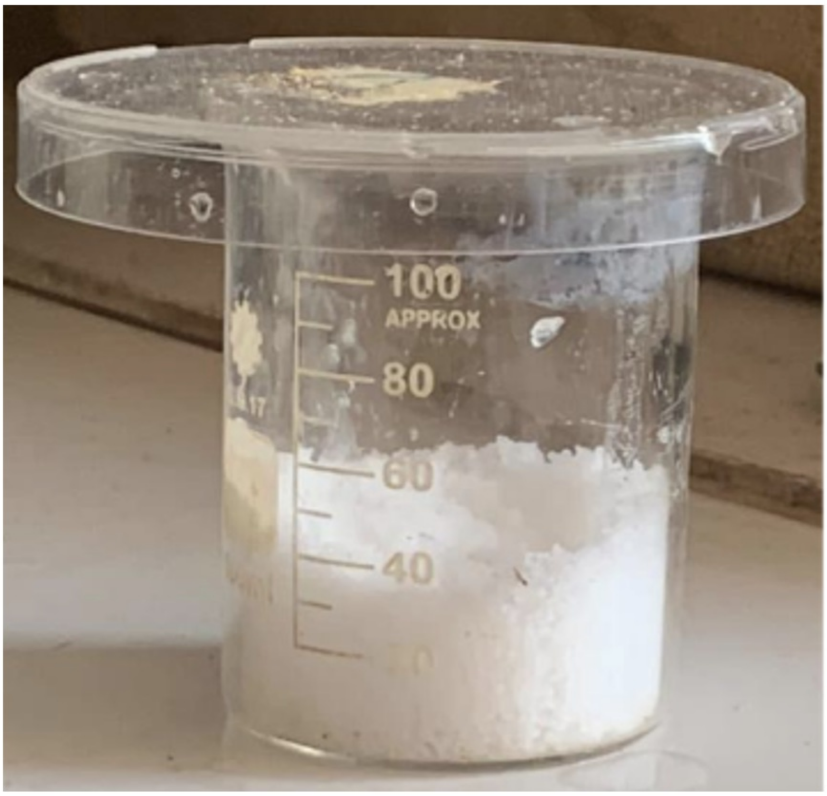

Fig. 5. *Dilute Alkali (NaOH)*

Fig. 6. *Pre-treatment Process*

Fig. 7. *Pre-treated bamboo*

STEP 3: Enzymatic Hydrolysis

The enzyme, cellulase, was added to the pretreated bamboo at 9 FPU/g (fatty acid unit per gram). This was to break the high carbon molecules into smaller ones in order to yield sugar (de-polymerizing the cellulose to glucose).

STEP 4: Fermentation

In this process, the enzyme Saccharomyces cerevisiae (yeast) was added and left for three days to speed up the fermentation process. The enzymes used were provided by the Biotechnology Department of Federal Institutes of Industrial Research, Oshodi, Lagos State, where the whole process was done.

Fig. 8. *Fermented bamboo*

STEP 5: Distillation Process

The fermented liquid was distilled to attain ethanol at the boiling temperature of 78.2°C. The concentrated ethanol was obtained as steam and then condensed.

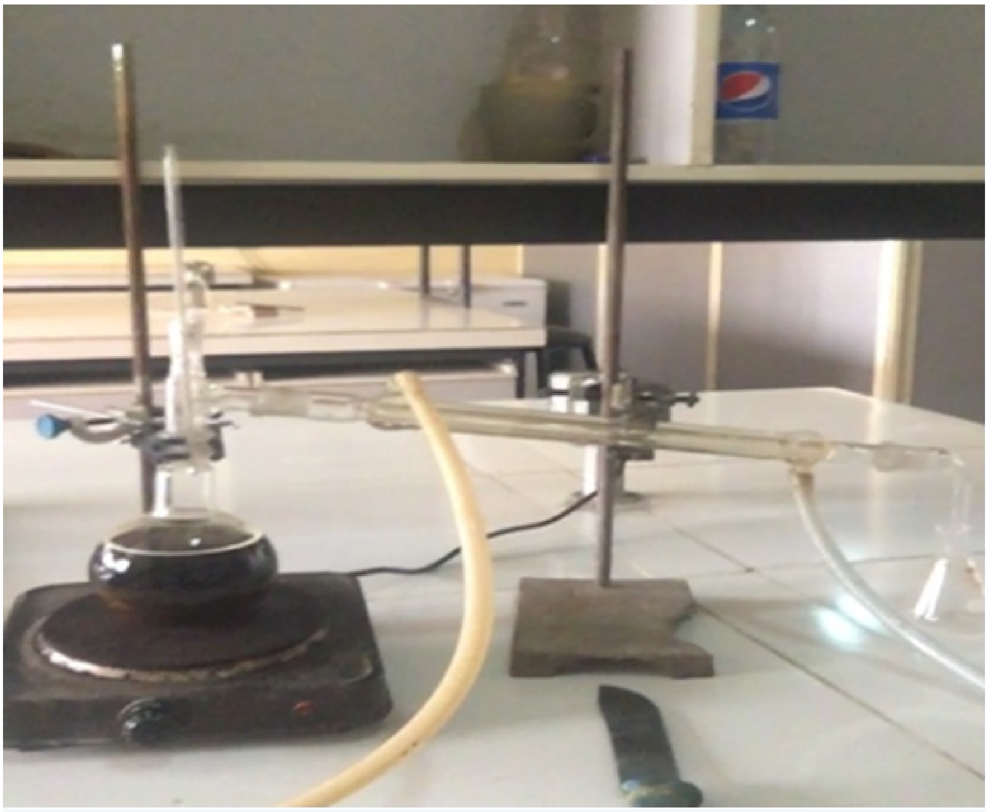

Fig. 9. *Fractional distillation process*

Fig. 10. *Distilled bio-ethanol*

Yield: 800ml of bio-ethanol was produced from 2kg of bamboo.

Percentage Yield of bio-ethanol: Bio-ethanol produced was 65% of the bamboo mass (2kg).

STEP 6: Dehydration Process to Yield Bio-Ethylene

The bio-ethanol from the bamboo waste was poured into a conical flask, then it was placed on a tripod stand, a filter paper containing aluminum oxide (Al_2O_3) was placed on the conical flask, then two burettes were connected together, then to a pipe rod connected to the refrigerant coolant (cylinder).

The bio-ethanol was then subjected to heat; the catalyst present helped to speed up the reaction. As the bio-ethanol began to boil, the vapour began to pass through the burette, which contained silica gel (drier) that helped in drying up all the water so as to collect the expected bio-ethylene gas through a pipe rod into the cylinder.

Fig. 11. *Cylinder of collected Bio-ethylene gas*

Yield: 0.21 kg of bio-ethylene gas was obtained from 500 ml of bio-ethanol.

Percentage yield of bio-ethylene gas: Bio-ethylene gas produced was 53% from 500 ml of bio-ethanol.

4. Results and Discussion

4.1. Results

4.1.1. Comparison Between Bio-Ethanol and Conventional Ethanol

Table 1. Test Values for Bio-ethanol

S/N	TEST	VALUE	UNIT
1	Flash Point	16.72	°C
2	Auto Ignition Temperature	480.0	°C
3	Ignition Temperature	372.0	°C
4	Boiling point	78.20	°C
5	Specific Gravity	0.79	
6	Vapour pressure	13.05	mmHg

Table 2. Test Values for Conventional Ethanol

S/N	TEST	VALUE	UNIT
1	Flash Point	13	°C
2	Auto Ignition Temperature	440.0	°C
3	Ignition Temperature	365	°C
4	Boiling Point	78.37	°C
5	Specific Gravity	0.789	
6	Vapor Pressure	59.0	mmHg

4.1.2. Flash Point Test

The flash point of bio-ethanol indicates the lower temperature at which it releases sufficient vapor to form an ignitable mixture in the air. This is particularly crucial for safety in handling, storage, and transportation to prevent accidental fires or explosions.

4.1.3. Auto Ignition Temperature Test

This is the temperature at which bio-ethanol self-ignites without any external source of ignition, such as a spark or flame. The aim of this test is to determine the minimum temperature at which bio-ethanol can self-ignite. This is also crucial for safety during transportation and storage to prevent catastrophes.

4.1.4. Ignition Temperature Test

This temperature indicates the minimum amount of heat energy required to initiate combustion of bio-ethanol. This value is essential for fire safety protocols and the design of equipment and processes involving bio-ethanol to prevent spontaneous ignition.

4.1.5. Boiling Point Test

It is essential for distillation processes used in ethanol production and purification, as well as for understanding its behavior under different temperature conditions.

4.1.6. Specific Gravity Test

It is essential for quality control, blending with other substances, and is used to evaluate the concentration of ethanol in solutions, such as in fuel blends or alcoholic beverages.

4.1.7. Vapor Pressure Test

Vapour pressure shows the tendency of bio-ethanol molecules to escape into the vapour phase at a given temperature. The comparatively lower vapour pressure of the bio-ethanol implies it has a lower volatility than conventional ethanol, and reduced potential for inhalation upon exposure, and flammability. This is imperative for storage, handling, and workplace safety.

4.2. Discussion

Bio-ethanol has a slightly higher flash point compared to ethanol, indicating that bio-ethanol is less volatile and less likely to ignite at lower temperatures because of water content and other impurities such as organic acids, aldehydes, esters, and higher alcohols resulting from the fermentation process. The purification and refining processes involved in conventional ethanol production tend to yield a lower flash point compared to that of bio-ethanol.

In general, bio-ethanol usually has a slightly lower specific gravity than regular ethanol. This is because bio-ethanol is often produced from renewable resources such as corn, sugar cane, or other biomass sources that may have a different composition than the raw material used in conventional ethanol production. Conventional ethanol, which is typically obtained from fossil fuels through processes such as ethylene hydration, may have a slightly higher specific gravity than bio-ethanol due to differences in production methods and raw material sources. Bio-ethanol and ethanol do have similar boiling points, and this is attributed to their identical chemical properties. Test equipment for bio-ethylene was not available for characterization of the yielded gas collected from the dehydration process, hence the lack of test results for the suspected bio-ethylene gas.

5. Conclusion and Recommendations

In conclusion, the production of bio-ethanol and bio-ethylene gas from the waste bamboo biomass was achieved utilizing an enzymatic hydrolysis and fermentation process. Bio-ethanol produced was 65% of the bamboo mass (2kg), while bio-ethylene was 53% of the bio-ethanol derived from the same source (500ml). This shows that its promising yield is economically viable. The results show that biofuels are less volatile compared to conventional fuels (fossil fuels), indicating that they can be stored under low temperatures without igniting. The cultivation and processing of *Bambusa vulgaris* expresses a low carbon footprint, doing well to alleviate adverse effects of climate change, making this an eco-friendly biorefinery value chain.

Possible improvements in the yield and cost effectiveness could be attained by modifying and optimizing the pretreatment processes, purification techniques, and also by providing precision test equipment for characterization tests and quality control of both biochemicals. This is especially because of the lack of test equipment or set-up to characterize the suspected bio-ethylene gas which was yielded. Funding pilot bio-refineries and full-scale bio-refineries that will encompass these improvements will eventually involve continuity in terms of polymerization processes to convert the bio-ethylene to yield polyethylene and other bioplastic resins to ease the over-dependence on imports and the deleterious activities of the petrochemical industry. The underutilised bamboo in Nigeria shows prospects for a positively impactful industry and would require involvement from the government and the private sectors to invest in research and development to realize a substantial reduction of GHG emissions, hence the climate change solutions and import alleviation it would bring about.

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