

Wet Waste / Green Waste to Compressed Biogas: Waste to Wealth Project

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ABSTRACT

The growth rate and the yield of biomass of the napier grass (*Pennisetum purpureum*) has made it a promising biomass feedstock in the production of biogas. What limits its use as bioenergy, however, is its lignocellulosic composition, especially that it contains a high level of lignin. Mechanical, thermal as well as alkaline methods have been investigated to improve pretreatment methods in improving the biogas production through increasing the digestibility of Napier grass. The most important advances have been made through alkaline pretreatment specifically with the use of sodium hydroxide (NaOH) which has enhanced methane output up to 70%. Also, co-digestion in other organic waste materials such as piggery manure and food waste has also been established to increase biogas productions more since the carbon to nitrogen ratio is improved and a synergy in the microbes is enhanced. The effect of harvesting age and growth conditions on the biogas yield has also been studied and it has been established that Napier grass that is harvested when it is at its prime maturity yields the best methane quantity. Enhanced methane production is also related to the fact that the integration of higher-order technologies like two-stage anaerobic digestion and microbial consortia are also featured. Even though these strategies are effective, the challenges in energy demand of pretreatment, and the requirement of further optimization on large-scale use actions are still present. Future studies need to concentrate on energy usage reduction, implementing better pretreatment procedures and on new ways of utilizing enzymes and biological means to maximize biogas produce out of Napier grass.

Keywords: Napier grass, biogas production, pretreatment techniques, methane yield, co-digestion.

How to cite this article: Lokhande A, More A, Kale K. Wet Waste / Green Waste to Compressed Biogas: Waste to Wealth Project. *Int J Drug Deliv Technol.* 2026;16(48s): 1501-1519. DOI: 10.25258/ijddt.16.48s.146

Introduction

With the current world energy consumption, there is a growing concern to utilize renewable sources of energy to substitute the reliance on exhaustible fossil fuels that have been contributing to the degradation of the environment and climatic change. Fossil energy sources such as coal, oil and natural gas are nonrenewable sources that require millions of years to develop and thus cannot be used in the long run. The depletion of fossil fuels and the rising awareness of the negative impact of the greenhouse gas emissions have contributed to the rising popularity of renewable energy sources. Among the most promising renewable resources in overcoming the energy crisis is bioenergy since it provides a sustainable solution to both the production of energy and environmental conservation[1]. One of the renewable energy resources is biomass that is made of plants, animals, and wastes. It is possible to transform biomass into various sources of useful energy that include heat, electricity, biofuels, and biogas. Such conversion may be done in a number of ways, including direct combustion, gasification, pyrolysis, and anaerobic digestion. All the approaches have various benefits based on the biomass feedstock, the target end-use, and the technology available. Among such techniques, anaerobic digestion has become a more acceptable option of converting

organic waste, including wet and green waste, into useful biogas[2].

The green waste, especially the organic waste of plants and leaves and agricultural waste can be used to produce bio gas. *Pennisetum purpureum* (Napier grass) is a fast-growing perennial grass that has received considerable attention as an optimum feedstock in the production of bio-gases because of its high yield, high rate of growth and low resource demands. Napier grass is also renowned in terms of flexibility since it is capable of surviving in all types of climates and developing on low water supply and marginal land. This renders it a cost effective and eco-friendly biomass source of generating renewable energy. Also, Napier grass does not occupy the same space as food crops, which is why it is a viable choice in terms of producing sustainable energy sources[3]. Napier grass is especially useful in areas in which there is limited arable land or other crops are not as suitable to be grown. It can be harvested repeatedly throughout the year which offers a constant and dependable supply of biomass to be used in the production of energy. Besides, it is a vital component in land management, soil conservation, and erosion management, which increases its ecological value even more. Napier grass biomass can be digested anaerobically, i.e. in the presence of microorganisms that decompose organic matter without oxygen, to create biogas,

which is mostly made of methane (CH₄) and carbon dioxide (CO₂). This biogas can be further purified and compressed to produce Compressed Biogas (CBG) that is a renewable and clean fuel[4].

An anaerobic digestion is the biological process that breaks down the organic matter without any oxygen. In the process, complex organic molecules like carbohydrates, proteins and lipids are broken down into simple molecules. This process takes place through four consecutive steps namely hydrolysis, acidogenesis, acetogenesis as well as Methanogenesis. Complex organic polymers are divided into monomers such as sugars, fatty acids and amino acids in the hydrolysis process. During acidogenesis phase, these monomers are further fermented into volatile fatty acid (VFAs). The VFAs are changed into acetogenesis to produce acetic acid, carbon dioxide, and hydrogen. And lastly, in methanogenesis step, acetic acid and hydrogen are converted to methane by methanogenic microorganisms which form the largest constituent of biogas. The rate at which anaerobic digestion process is conducted is influenced by a number of factors such as the nature of the feedstock, temperature, pH, availability of nutrient and the microbial community that is involved. With Napier grass, cellulose and hemicellulose make a high percentage which is an excellent source of fermentable material to produce methane. The lignin content in the biomass however complicates the process of breaking it down and this can decrease the overall

efficiency of the production of biogas. To manage this problem, pretreatment will be used to enhance the digestibility of lignocellulosic biomass such as Napier grass[5].

Recent developments in biogas production technologies have been based on the enhancement of efficiency and scale of the anaerobic digestion process. The development of pretreatment methods of lignocellulosic biomass to improve the breakdown of lignocellulosic biomass, e.g. Napier grass, has been one of the critical areas of research. These pretreatment methods are: physical (e.g., steam explosion), chemical (e.g., acid hydrolysis), biological (e.g., enzymatic treatments), and a sort of a combination of the methods. Such processes can minimize the lignin level, raise the porosity of the biomass, and make fermentable sugars more accessible to the anaerobic digestion process, thus optimizing efficiency of the entire process of biomass conversion to biofuels. Also, co-digestion, which is taking more than one substrate in anaerobic digestion, has become quite popular in an effort to enhance the production of biogas. Napier grass can be paired with other organic solids like animal waste, food waste, or agricultural solids to achieve the optimal ratio of carbon to nitrogen, which in turn would result in an increase in biogas generation. Co-digestion is also used to alleviate some of the difficulties of digestion on use of single feedstock like high concentration ammonia and low PH, both of which can suppress the active growth of microorganisms in the digestion process[6].

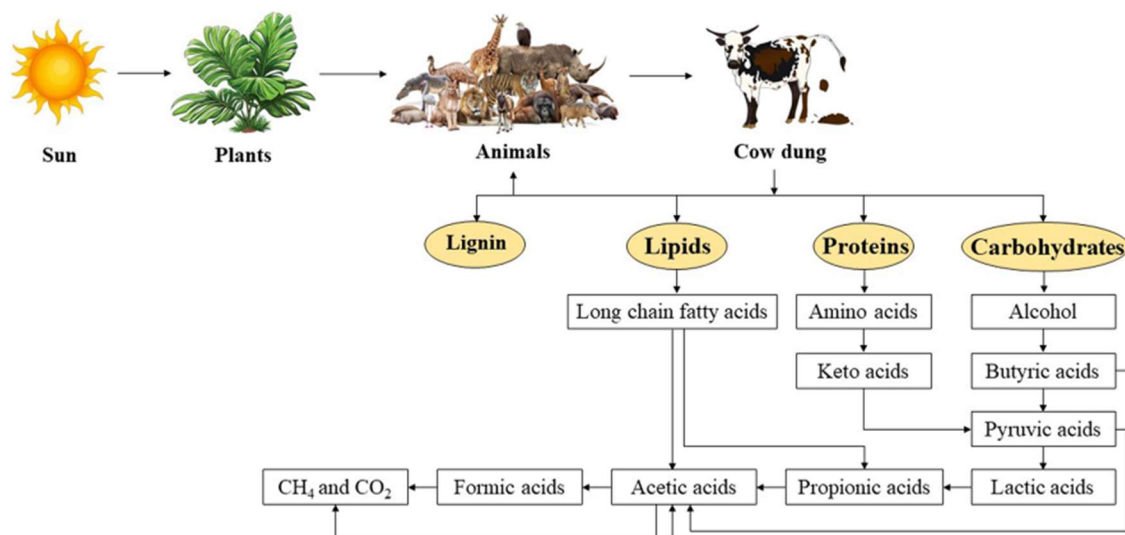


Fig. 1. Biogas Production Scheme

The process of transforming Napier grass into biogas has various advantages to the environment such as reducing greenhouse gas emission and inhibited waste build-up. Biogas being a renewable source of energy can substitute fossil fuel, thus minimizing carbon emission. Furthermore, the anaerobic digestion process is useful in the process of managing organic waste, including agricultural residues, food waste, and sewage, which would otherwise decay in landfills and produce methane, which is a strong greenhouse gas. This waste is made to go through Napier

grass to produce biogas, so it does not go to landfills, which affects the ecological environment less significantly[7]. In terms of economics, the production of biogas using Napier grass has a number of benefits, such as it may provide employment opportunities to individuals in rural areas, a higher income to the customers, and enhance energy security. Planting Napier grass as a mono-energy crop would also generate a source of extra revenue to the farmers, particularly those in regions where agricultural output is minimal. Moreover, the production of

biogas can be used to generate energy independence through the local and renewable source of fuel that can be used to generate electricity, heat and transportation. With the ever increasing energy prices globally, the biogas is a cheaper energy source that is also environmentally friendly when compared to traditional energy sources.

Biogas that are produced using Napier grass is a good direction to sustainable energy production and biogas utilization. Through the conversion of green waste like Napier grass to compressed biogas, this process will be in line with the waste-to-wealth principle where organic waste can be converted to useful energy as biogas. Among the benefits of the use of napier grass are its quickness of growth, low resource needs, ecological qualities, including land control, and erosion prevention, among others,[8]. The use of technology in the process of anaerobic digestion and pretreatment techniques has also made biogas production systems more efficient and scalable, and Napier grass is becoming an even better option in producing renewable energy. In the future, it is important to note that further research and development work on biogas production technologies, such as co-digestion, pretreatment methods, and optimization of processes will become important to reach the potential of Napier grass as a bioenergy source to the maximum. The mass production of Napier grass-derived biogas can help greatly in the reduction of the reliance of fossil fuels and climate change because of the large-scale production, and the sustainable use of agriculture can be promoted with the use of the global energy requirements of the population today;[9]. Napier grass-based biogas production has the potential to help make the future more sustainable with the continued progress in technology and the rising awareness of the benefits of the technology.

Napier Grass

Napier Grass (Napier Grass) is a fast growing, perennial grass, which is highly resilient and produces significant amounts of biomass used in bioenergy production and thus a favored candidate. This grass is indigenous to tropical Africa and this explains its great importance to areas with poor climatic conditions like in some of the parts of Asia, Africa, and also in Latin America. Napier grass thrives and grows quickly, usually up to 6 meters tall, and its leaves are 30 to 90 cm in length and 3 cm in breadth which is amongst the strongest leaves and widest up to 3 cm wide n.pag.-[10]. The plant is particularly reputable because of its capacity to grow in high-temperature regions, high sunlight areas as well as in areas with low water supply. This has seen it become a perfect option in use in bioenergy projects of reducing greenhouse gas emission as well as alleviating the effect of climatic change[11]. Napier Grass can provide a great deal in terms of biomass; this is one of the factors that give it a huge edge over competing grasses. It is capable of yielding 30-40 metric tons of dry matter per hectare per year on average, and some areas are even yielding up to 85 tons per hectare DOI: 10.9734/CJAST/2018/45224. This has seen it emerge as one of the most productive bioenergy crops that has done better compared to other common crops like switch grass and sugarcane. The characteristics of the rapid cycle of growth with

several harvests (often three or four times a year) has an effective source of biomass that can be employed in the generation of biofuels (e.g. in the manufacture of compressed biogas (CBG)). Subsequently, Napier Grass has become extremely important to complete the process of waste-to-wealth, meaning that organic waste is transformed to useful biofuels that would assist in accessing clean energy sources sustainably.

Napier Grass has also been exhibiting exceptional tolerance to a vast diversity of geographical and environmental conditions, which can further increase the potential use of this grass in bioenergy production. The grain is native to tropical Africa but has invaded other areas of the world such as Southeast Asia, South America and some regions of Oceania. Its ability to grow in a wide range of habitats, including tropical climates to subtropical climates, demonstrates its adaptability and possible use on a large scale of cultivation[12]. The ability of the plant to be tolerant to various types of soil, extreme temperatures, and available water makes it a good trial candidate in areas which are inappropriate to use conventional agriculture such as marginal and degraded lands[13]. Specifically, the laboratory experiments in the Rio de Janeiro region in the north have assessed different genotypes of Napier Grass to determine their effectiveness in bio-energy venture. The study determined that there were high yielding varieties like Mercker 86 Mexico, Gramafante among others which did extremely well in both the productivity and their adaptive limits, a fact that proved the ability of genetic selection to maximize biomass production as a source of energy. Besides being highly productive in terms of dry matter, such varieties are also characterized by their excellent resilience to pests and diseases, which makes them more reliable as a sustainable source of biomass to power conversion[14]. Further, the flexibility of Napier Grass to various planting densities and soils can be maximized to enhance the efficiency of nitrogen use (NUE) as well as reduce the use of chemical fertilizers to increase its sustainability in bioenergy systems[15].

Napier Grass has more environmental advantages than its use as a high bioenergy crop. Napier Grass has a great carbon binding capacity in that it sequesters large quantities of carbon dioxide in the air due to its rapid growth rate and high production of biomass. Napier Grass is said to absorb up to 40 tons of CO₂ per hectare hence an effective tool in fighting climate change and lowering greenhouse gas emissions[16]. Such ability both to take in carbon and help offset the effects of global warming as well as to make Napier Grass an indispensable element of sustainable agricultural processes geared towards improving the soil fertility of the ground as well as help lower the levels of the carbon dioxide concentration found in the air [17]In addition, Napier Grass has also demonstrated remarkable excellence in intake of nitrogen and as a result, it can be utilized as an instrument in enhancing the soil quality. Its capacity to fix nitrogen in the soil is 10 times greater than the chemical fertilizers and this makes the use of synthetic fertilizers less harmful on the environment. This feature is specifically valuable in bioenergy projects in which the goals are to reduce their environmental imprint[18]. Through Napier Grass bioenergy

systems, farmers and energy generation companies can not only produce renewable energy but also increase soil fertility and also make the agricultural practice sustainable. This grass is used in waste-to-wealth applications, including the adaptation of organic waste into compressed biogas, which are in line with the more general objectives of sustainability and environmental preservation[19].

Napier Grass is a feedstock option that has garnered a lot of attention in the recent years as a source of biofuels; specifically a compressed biogas (CBG). Napier Grass is a good source of biofuels due to its high cellulosic composition that is an excellent raw material to be used in manufacturing biofuels through anaerobic digestion, where the biofuel is produced by digesting the materials available to us in a process studied by microorganisms. With a calorific value of Napier Grass ranging between 14 and 19 MJ/kg, the dry biomass has the potential to generate plenty of heat energy just like the standard fossil fuels and yet with a significantly lesser carbon footprint. Besides the production of biofuels, the lignocellulosic biomass content of Napier Grass has potential in other sustainability processes including paper making and bioplastics due to its rich lignocellulosic biomass lining. This is because the grass has a fast rate of growth, which means that it is suitable in highly biomass producing energy generation systems that need sustained, regular supply of organic matter. This is why the introduction of Napier Grass as a component in waste-to-wealth initiatives, e.g., changing organic waste to compressed biogas, can be a viable and cost-efficient answer to the energy requirements in the world community[20]. Napier Grass supplies a direction to a more sustainable future by lessening the use of fossil fuels and encouraging the utilization of renewable energy sources.

NAPIER GRASS AS A SUBSTRATE

Through the international search of renewable energy the development of bio energy sources has risen with research developing biogas as a viable source of sustainable energy. Methane, which is its main ingredient, is biogas that is produced through anaerobic digestion of organic substances, i.e. wet waste and green waste[21]. Napier grass (*Pennisetum purpureum*) among other types of feedstocks that are utilized in biogas production has attracted attention because of the elevated lignocellulosic material present in it and its capability to undergo anaerobic digestion. Being a perennial, strong and with high volume of biomass, this type of grass is an important constituent in the processes of developing biogas systems of energy. The article discusses Napier grass as a potential feedstock in the compressed biogas production due to its attributes, culture, and its role in the waste-to-wealth initiative[22].

Napier grass is a lignocellulosic biomass which is known to contain high percentage of biomass hence making it an option to biogas production. Lignocellulosic biomass is composed of three major components namely lignin, cellulose, and hemicellulose that form a major contribution to the biogas yields. When these constituents are left to undergo anaerobic digestion, they break

down to simple sugars, which are further fermented by the microbes to generate methane.

Napier grass has a variable lignin content which has a lower lignin content that is better than bioenergy applications as it is more easily digested as indicated in Figure 3 (Reproduced with permission via[23] copyrights Elsevier BV, 2025). They suggest that the cellulose concentration of Napier grass is 22 to 84.56 which plays a critical role in glucose production during the biogas process. Biogas production is further augmented by the composition of hemicellulose whose gross product is added to sugar production. Napier grass has a structural composition that makes it an extremely good substrate base of anaerobic digestion to produce methane; therefore, a great feedstock to use in biogas plants. The picture in Figure 2 displays Napier grass and its characteristic structure and development capacities, which make it an appropriate choice to produce biogas[24]. The Napier grass has a production rate of about 150 Mt /acre/year, which depends on the geographical location as well as management practices[25]. The high yield also makes it an effective source of biomass to be used in the unit of biogas production particularly in tropical and subtropical areas where the grass grows well.

Environmental factors that play an important role in determining the growth properties and biomass of Napier grass include the climate, soil type, altitude and the management practices. Napier grass is a grass that grows in tropical and subtropical regions and temperatures of between 25 °C and 35 °C, and annual rainfall amount of between 750 to 2500 mm. The grass should have fertile, well-drained soils with the pH level of 5.5-7.5. Photosynthesis is speeded up by high solar radiations and this directly affects the production of biomass by the grass[26]. The growth rate of Napier grass in those areas or regions with lower temperatures may be inhibited in the shaded areas. Nevertheless, it is a hardy crop that can endure drought and rebound sooner than rain, thus a perfect crop in a variety of climatic conditions is one that can withstand drought and recover soon after the rainfall[27]. Areas such as tropical Africa and Southeast Asia enjoy good favorable climatic conditions hence resulting into high yields of biomass. Conversely, regions with dry or infertile soils, like some regions of South Asia need improvement in management measures, including irrigation and fertilization to get maximum productivity. These are major practices that are imperative in ensuring maximum harvesting of Napier grass that is of vital importance to provide constant supply of biomass to be used in biogas.

The biogas potential of Napier grass is very much dependent on how this grass is managed such as the frequency of harvesting it. Evidence has shown that the time of harvesting greatly affects the makeup of the grass which consequently affects suitability of the grass to anaerobic digestion. The lignin, cellulose and hemicellulose fiber content is variable on various days of harvesting and timing the harvest in such a way that biogas production is maximized is feasible. https://lucris.lub.lu.se/ws/files/30364253/Thesis_Chao_Li_150_dpi.pdf.

Table 1. Chemical Composition of Napier Grass in Literature

Harvesting Days	Lignin (%)	Cellulose (%)	Hemicellulose (%)	Total Carbon (C) (%)	Total Nitrogen (N) (%)	C/N Ratio	References
-	32.04	34.25	17.36	49.93	2.02	24.72	[28]
-	30.23	29.48	17.32	45.36	0.78	58.15	[29]
30–45	10–33	25–43	15–53	49.93	2.05	24.35	[30]
45	11.08	84.56	4.36	11.37	0.44	25.84	[31]
45	30.40	36.34	34.12	44.19	2.00	22.10	[32]
-	21.67	32.26	19.73	-	-	-	[33]
10	2.26	17.64	-	-	-	-	[34]
10	2	5	-	-	-	-	[35]
-	24	22	24	-	-	-	[36]
-	21.6	47.1	31.2	-	-	-	[37]
60	8.27	36.81	26.16	24.3	2.67	9.10	[38]
-	43.9	2	21.95	-	-	-	[39]
-	44.2	2	22.1	-	-	-	[40]
-	44	1.9	23.16	-	-	-	[41]

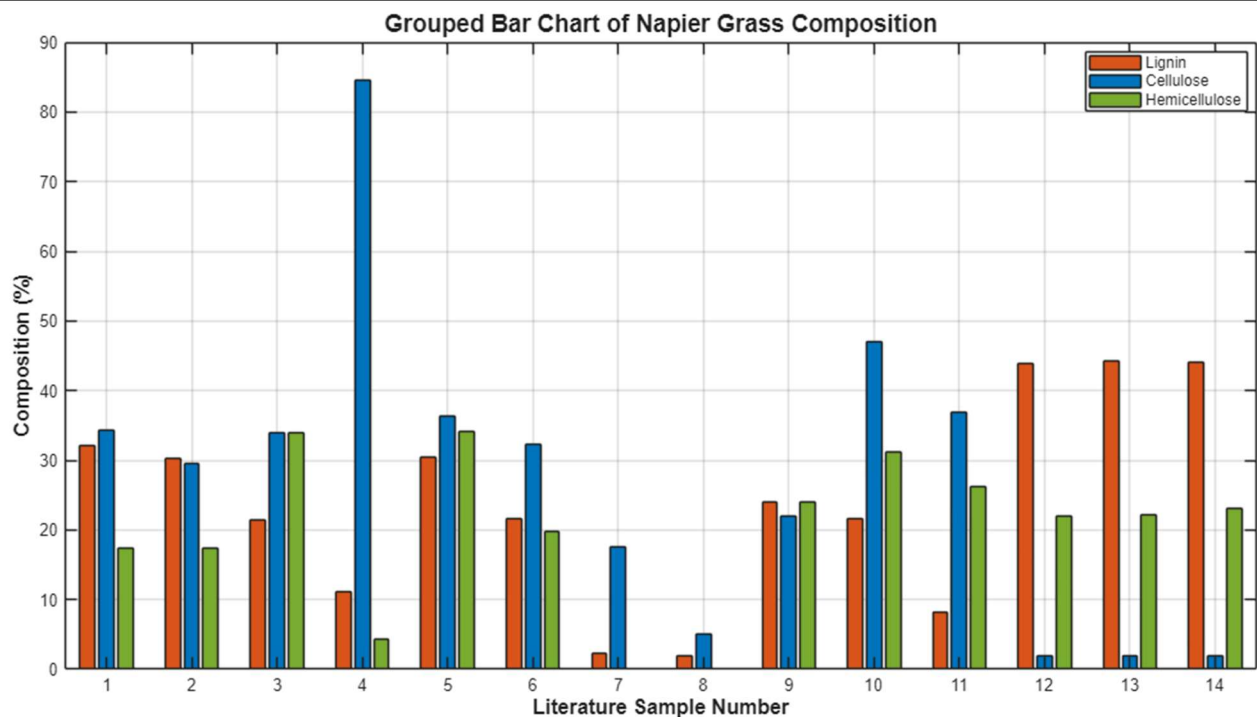


Fig. 2. Chemical Composition of Napier Grass in Literature

As an example, harvesting the Napier grass in 30-45 days will enable a balance of these parts that will result in greater production of digestible constituents of biogas. Lignin and lignocellulosic content are also a crucial factor in dictating the digestibility and greatly the efficiency of methane generation[42]. Table one reveals the lignocellulosic biomass composition at various days of harvesting with range of lignin (8.27 to 32.04%), cellulose (22 to 84.56), hemicellulose (4.36 to 34.12) and total carbon (10-49.93), nitrogen (0.44-2.6 An

important parameter that determines the rate of decomposition during anaerobic digestion is the C/N ratio which ranges between 9.10 and 58.15. A good C/N ratio guarantees the generation of methane in the most optimum way as it aids in the optimum activities of the microbes during the digestion process. The study sheds light on the role of a proper harvesting season in terms of the biggest biogas output, as the relationship between the Napier grass composition and its favorable use in biogas is direct.

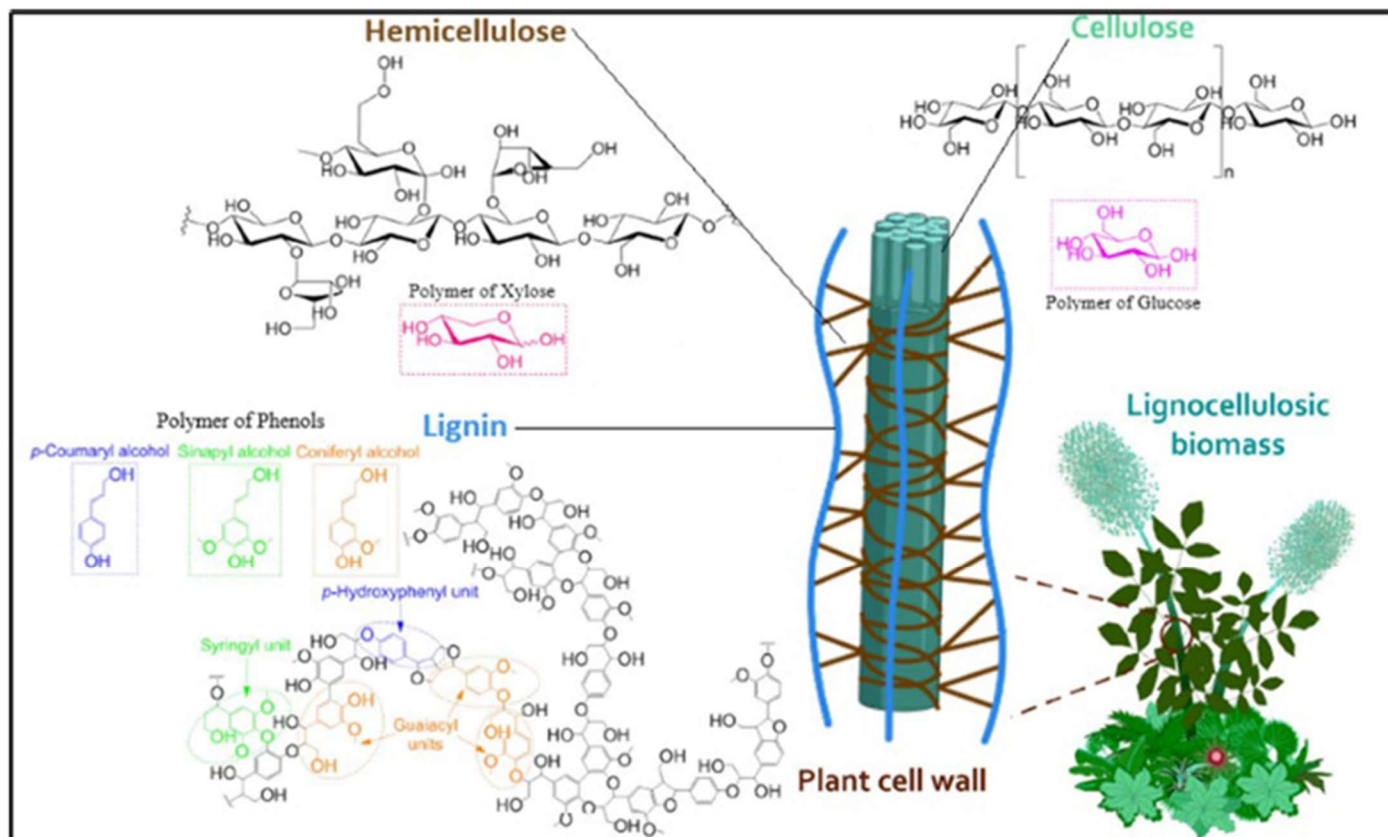


Fig. 3. Structure of Lignocellulosic Biomass (Reproduced with permission from [43]copyright Elsevier BV

Napier grass stands as a great waste-to-wealth technology resource, especially when it comes to biogas generation.1064. The grass can be planted on the lands which might not accommodate the usual food crops and therefore, marginal lands can be used in a sustainable manner. Moreover, the high biomass production and rapid growth rate of Napier grass enable it to be an ideal candidate in a large scale biogas production systems[44]. Use of Napier grass in biogas plants does not only aid in the production of renewable energy, but also serves to decrease the reliance on fossil fuels, which is known to have a negative impact on the environment regarding the use of the traditional energy sources. Furthermore, the Napier grass is very good in sequestration of carbon. It is a growing perennial, in the course of its growth cycle, it captures carbon dioxide in the atmosphere, which helps combat climate change by its attenuation. Using Napier grass in biogas production will minimize the carbon footprint of the entire energy production

process thus it is a sustainable fuel source in renewable energy production. In addition, the resultant of anaerobic digestion can be utilized as a high-nutrient fertilizer, which will further encourage the development of sustainable agricultural methods[45].

Napier grass also has a big potential as a feedstock in the production of compressed biogas in waste to wealth project. It is a perfect choice as a biogas plant due to its high content of lignocellulosic material, drought resistance and its adaptation to tropical and subtropical climates[46]. The cellulose, hemicellulose and lignin composition of the grass makes it to decompose efficiently anaerobically producing methane. Moreover, its production helps sustain agriculture and capture carbon and avoid reliance on fossil fuel. Napier grass is a renewable biomass resource that is very vital in global praise to clean and sustainable energy. It will make emphasis on waste-to-wealth programs that contribute to waste-management and

renewable energy generation goals in the world, so it will be a key component in the search to a sustainable future[47].

RELATED WORK

Thermal and Chemical Pretreatment in Biogas Production

An interesting measure to address the issue of waste processing and produce renewable energy through anaerobic digestion (AD) of organic waste is the conversion of organic waste into biogas[48]. Some feedstocks are however difficult to use like Napier grass which has an intricate structure especially high lignin content that is not degraded by microbes. Some pretreatment methods have been devised to overcome these problems and help biogas to produce more output. Among them, thermal and chemical pretreatment methods were proven to contribute significantly to the digestibility enhancement of the lignocellulosic biomass to become more susceptible to anaerobic digestion. This section examines the performance of thermal and chemical pretreatment processes, the way they can be applied to both municipal solid waste (MSW) and biomass feeds, such as Napier grass. High temperature and chemical pretreatment methods are combined, during which it is subjected to heat and chemical conditions, resulting in the degradation of the complex lignocellulosic structure of the biomass[49]. The major aim of such pretreatment techniques is to increase the availability of cellulose and hemicellulose which are the most significant elements of biomass by lessening the recalcitrant lignin. It has been demonstrated that, when such a combination is used to pretreat biomass such as Napier grass, much higher yields of methane are obtained and this increased the overall efficiency of the biogas production process.

Another approach that has not yet been established effectively, though has presented promising results, is the application of microwave-assisted chemical pretreatment in enhancing the biogas produced by biomass. According to studies, microwave exposure combined with pretreatment with hydrogen peroxide proved to have a significant effect on the biodegradability of organic waste and consequently resulted in increased production of methane (Shahriari et al.[50]. In the same way, Akhbar et al. <https://doi.org/10.5772/62728> found that the rate of lignin removal was increased when chemical treatments were used, including the addition of hydrogen peroxide during the pretreatment using microwaves. Besides increasing the digestibility of the biomass during this chemical pretreatment it also increased the amount of methane that was produced during anaerobic digestion. Microwave-assisted chemical pretreatment process employs microwaves to heat the biomass in a short time, that is, lignin softens and becomes more exposed to the enzymes in the microorganisms making them more accessible. Hydrogen peroxide is added to further break down the lignin thereby exposing the cellulose and hemicellulose to digestion by microbes. It has been found that this pretreatment process can reduce the lignin content of the Napier grass by up to 72 and this is the main factor causing the increase in the biogas yields[51]. These findings indicate the possibility of microwave-assisted

chemical pretreatment in the optimization of producing biogas using lignocellulosic biomass.

Thermal and Mechanical Pretreatment for Napier Grass

Along with the chemical pretreatment, thermal and mechanical treatments are also popular in order to enhance the efficiency of the anaerobic digestion process. In thermal pretreatment, the biomass is subjected to temperatures that are high and thus serve to decompose complex organic materials and make them available to microorganisms. The process of mechanical pretreatment, however, dissolves down the particle size of the biomass enhancing areas where it is exposed to the microbial attack. When used together, these pretreatment processes have been demonstrated to effectively boost the production of biogas when using such feedstocks as Napier grass. Wett et al. [52] have employed the impact of mechanical and thermal pretreatment on sludge, and they found that the mixture could enhance biogas yield by 75. It was observed that there was high enhancement in the biogas yield when the biomass was subjected to the process known as mechanical pretreatment which entailed exerting pressure at 1921bar and temperatures of 160180. Moreover, the research established that the situational combination of such pretreatment techniques lowered the dewatering capabilities of the sludge decreasing the disposal expenses by 25 percent. This makes it possible to point out the twofold advantages of the thermal and mechanical pretreatment, namely, the high yield of biogas and low costs of processing[53].

In the case of Napier grass, thermal treatment, including hydrothermal processing (HTP) or microwave-assisted hydrolysis with mechanical pretreatment, e.g. chopping, has been reported to produce significant improvements in solids content at fairly low volatile levels in the solids product - The major organic matter that microorganisms use to produce biogas is volatile solids, and thus the less undigested solids one has, the more effective biogas production would be. It has also been demonstrated that pretreatment techniques such as microwave-assisted hydrolysis could lead to a reduction in volatile solids, by up to 50 percent and subsequently increase methane yields[54]. Also, mechanical breaking down of the size of the particle size adds to the surface area accessible to microbial digestion, which also augments biogas generation.

Combined approaches in bettering the biogas output have been explored and proven in numerous studies that have demonstrated the advantages of thermal, chemical and mechanical treatments used simultaneously[55]. The chemical pretreatment followed by the thermal treatment such as boiling or hydrothermal has demonstrated spectacular results when used together with sodium hydroxide (NaOH) in enhancing the methane yield in Napier grass. Table 2 shows that NaOH (0.6–2%) chemical pretreatments degrade lignin by up to 24.11 to enhance methane yields of up to 45.6170 per cent. This applies more especially with such feedstocks as Napier grass which contain large amounts of lignin that hinder the digestion of cellulose and hemicellulose. More efficient biogas production is achieved by thermal treatment (boiling or hydrothermal treatment at 175 o C)

that can disaggregate the complex lignocellulosic structures and increase the accessibility of cellulose. In certain instances, these processes have been known to raise production of methane by as much as 35 per cent. More so, these pretreatments can also be combined with mechanical treatments such as chopping to enhance biogas production even more, as smaller particles of the biomass are susceptible to biogas-producing microorganisms (Soyez et al., 2017, p. 2012).

Microbial consortia applied in biological pretreatment is also important in enhancing Napier grass and other lignocellulosic biomass digestibility. The research has indicated that lignin and hemicellulose have been treated with microbes resulting in high yields of biogas. Indicatively, biological treatments have been demonstrated to elevate yields of biogas by 247-279ml/gm of

volatile solids (VS). In the production of biogas, the chemical, mechanical and biological pretreatments together provide the best improvements in yield of methane and feedstock digestibility and hence is the best method of producing biogas. Although the combined thermal, chemical, and mechanical pretreatment approaches have proved to have a tremendous potential in boosting the biogas production, there are a number of issues and concerns that should be considered to streamline the process[56]. Among the difficulties is the non-uniformity of such feedstocks as Napier grass that may depend on the localities and climate conditions. Chemical composition of the Napier grass with its lignin and cellulose contents can also be varied depending on the climate and region it is planted. This variability may lead to the discrepancy in the effectiveness of methods of pretreatment and the final yield of biogas.

Table 2. Comparison of Some of The Pretreatment Techniques on Napier Grass in Literature

Pretreatment Process	Feedstock	Composition (after Pretreatment)	Results (Gas Production)	Variation	References
Physical	25:25:100 (cow dung: grass: water)	Volatile solid reduction up to 50%	524.3 Lit	31.37% methane content	[57]
	Hydrolysate Napier Grass	Lignin content reduced from 32.04% to 22.9%, Cellulose content reduced from 34.25% to 29.9%, Hemicellulose content reduced from 17.36% to 13.0%	299.69 ml CH ₄ /L	2.11 times higher methane yield	[58]
	Slaughterhouse Wastewater	-	220 ml/day	45.61% increase in methane yield	[59]
Chemical	Napier Grass	Lignin content 24.11%, Cellulose content 40.05%, Hemicellulose content 26.23%	0.158 m ³ CH ₄ /kg TS	45.61% increase in methane yield	[60]
	Anaerobic Sludge Inoculum	Total Solid 93.87%, Volatile Solids 83.50%, Total Organic Carbon 43.80%	179.38 L/kg VS	9.33% increase in biogas yield	[61]
	Microorganism	Total Solid 99867 mg/lit, Volatile Solids 81700 mg/lit	850 ml/kg VS	64% methane content	[62]
Thermal	Napier Grass	Total Solid 31.60%, Volatile Solids 93.70%, Ash Content 2.00%	155.91 L/kg VS	4.9% decrease in biogas yield	[63]
	Napier Grass	Total Solid 79983 mg/lit, Volatile Solids 69917 mg/lit	248.20 ml CH ₄ /gm VS	35% higher methane yield	[63]
Biological	Napier Grass	Volatile Solids 96.90%, Cellulose 48.50%, Hemicellulose 11.3%, Lignin 14.7%	259 ml/gm VS	39% increase in methane yield	[64], [65]
	Napier Grass	Lignin degradation 37.50%, Cellulose degradation 19.90%, Hemicellulose degradation 29.9%	279 ml/gm VS	49% increase in methane yield	[66], [67]

	Napier Grass	Lignin degradation 35.50%, Cellulose degradation 22.0%, Hemicellulose degradation 40.0%	247 ml/gm VS	32% increase in methane yield	[68], [69]
	Napier Grass	Lignin degradation 31.50%, Cellulose degradation 17.70%, Hemicellulose degradation 38.80%	247 ml/gm VS	32% increase in methane yield	[70], [71]

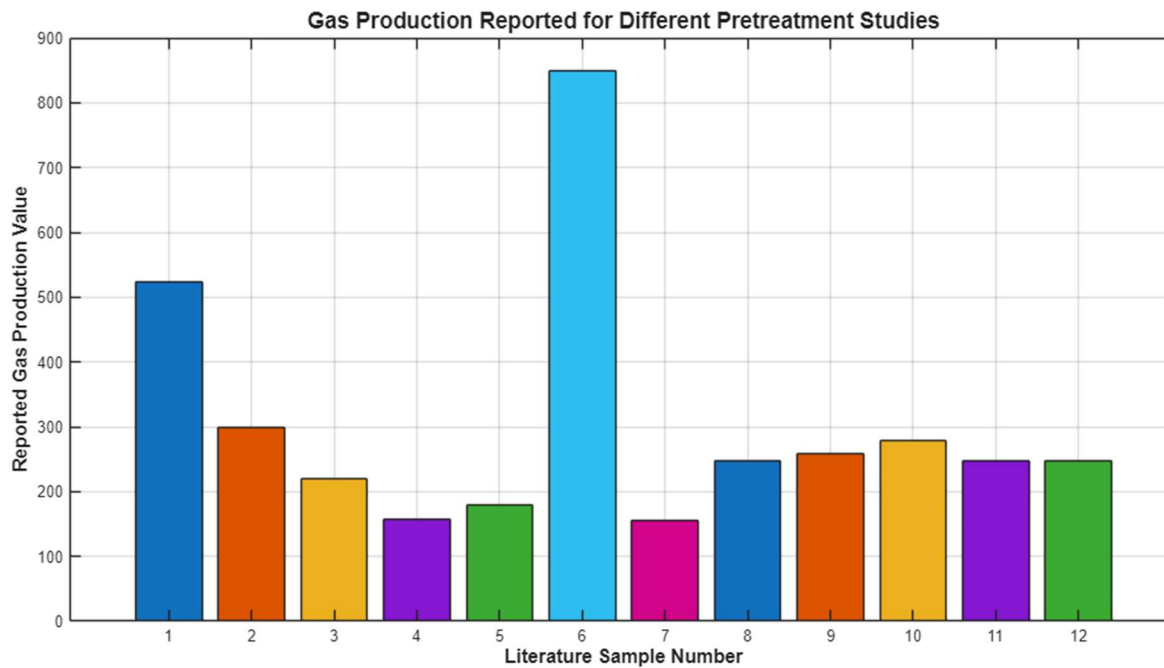


Fig. 4. Comparison of Some of The Pretreatment Techniques on Napier Grass in Literature

Future studies on the effects of regional and climatic differences on the composition of Napier grass and other feedstocks should be conducted to overcome these challenges, such as en8053403 (2018). The knowledge on how various environmental factors affect biomass composition will be used to optimize pretreatment processes in certain regions. In addition, a more effective and uniform biogas production in various regions may be affected by the development of universal pretreatment procedures considering these regional differences, which may yield a more effective and uniform product, referred to as biogas[72]. The other factor is the possibility of scaling the pretreatment process of large-scale production of biogas. Although small-scale studies have provided encouraging results in the lab, little has been done to verify the feasibility of these processes on a large scale and whether they are cost effective or not. More studies are required to determine the economic viability of the applications of these pretreatment methods on a commercial scale, specifically waste-to-wealth applications that would convert municipal solid waste and agricultural residues to renewable energy[73].

Past Studies

Pennisetum purpureum, or Napier grass has been identified as a high potential feedstock in the production of biogas, as it grows at a fast rate and possesses high biomass potential. Different

researches have been done on how various pretreatment methods can be used to improve the output of methane during anaerobic digestion. The promising results of using alkaline pretreatment especially NaOH have been demonstrated to enhance methane generation by as much as 70 percent as a result of complex lignin/hemicellulose dissolution, thereby facilitating cellulose availability to microbial hydrolysis (Warade et al., 2025). Hydrothermal processing at 175 o C has also led to increased yield of methane by 35 percent thus highlighting the power of heat in disrupting biomass structure (Johannes et al., 2024). The microbial consortiums, such as MC1 and WSD-5, have been shown to increase the biogas yield by 31 to 49 percent maximally through the degradation of lignocellulosic components (Warade et al., 2025). Napier grass has also been experimented on as co-digestion with other organic substances including cow dung to increase overall biogas levels, but there can be a variation in the level of methane based on substrate mix (Mukwane et al., 2025). These results highlight the importance of using a combination of different pretreatment options to maximize the biogas yield of Napier grass and thus it can be evaluated as a viable and sustainable source of bioenergy (Yusuf et al., 2025).

Napier grass is a fast growing feedstock and has a high biomass production; it can be utilized in production of biogas which will make a significant contribution to renewable energy sector. The

two-stage anaerobic digestion (AD) system of producing biogas and biohydrogen using Napier grass has undergone research where it has been found that the system has marked positive advancements in the production of methane as opposed to the single-stage systems. In a study, Pomdaeng et al. (2022) discovered that two-stage AD system, that involved biohydrogen production in the first stage, and biomethane in the second stage, generated 367 mL of CH₄/g volatile solids, a 30% rise in energy recovery compared to uni-stage systems. In addition, Kubde and Gulhane (2023) also investigated different pretreatment options, including enzymatic hydrolysis and sonication, noting that sulfuric acid pretreatment at 120 °C produced the highest yields of sugars (85.5% glucose and xylose) in Napier grass. Also, Kumar et al. (2020) added that the conversion of biomass into syngas and bio-oil via pyrolysis and gasification is ideal to augment energy production since these materials can be converted into electricity. Another concept that encourages the bioligent use of biochemicals as a sustainable circular bioeconomy involves biochemical biorefinery, which has been pursued by Igbokwe et al. (2022), who have highlighted the potential of Napier grass and other lignocellulosic biomasses to biofuels and biochemicals. Finally, Saravanan et al. (2024) provide the correlation of the necessity of biorefineries and the need to use biomass to promote the development of sustainable bioenergy production.

Napier grass has been used to produce biogas which have been significantly improved using different pretreatment methods. Dahunsi et al. (2019) found an increase of 65% in yield of methane using alkaline hydrogen peroxide pretreatment when biomass was not treated. The research by Wilawan et al. (2014) investigated co-digestion of *Pennisetum purpureum* cv. The chicken manure Pakchong1 grass at the optimal carbon-to-dividend (C/N) ratio and with an organic loading rate (OLR) to form a steady-state yield of a methane yield of 0.27 L CH₄/kg VS at optimal C/N ratio of 20. Other studies by Aleme and colleagues (2024) highlighted the potential of Napier grass varieties to produce biomass because in some cases the variety of Napier grass such as Bako 1 produced up to 20.93 t/ha of dry matter. The results of the study conducted by Jameel et al. (2024) showed that pretreatment is important to maximize the production of biogas using agricultural residues such as paw paw peels as in the study a 26.5 percent of increase in the production of methane was achieved after pretreatment took place. In the same way, environmental benefits of biogas systems are also described by Jameel et al. (2024), such as serious decreases in greenhouse gas emissions and energy that can be produced. These results indicate that pretreatment and co-digestion are necessary to maximize biogas production of Napier grass.

It has been investigated by different studies that Napier grass (*Pennisetum purpureum*) and other biomass materials have a potential to produce biogas by using different anaerobic digestion (AD) and co-digestion processes. In co-digestion of untreated Napier grass and industrial hydrolyzed food waste, Kriswantoro et al (2024) state that BG production increased significantly with 1, 161.33 mL/g VS added at the end of 60 days of digestion with 67.29% methane. Equally, Jonathan et al.

(2025) investigated the influence of various proportions of feedstock in co-digestion whereby a combination of Napier grass and cow dung in 1:1 ratios yielded the best yield of 54.6 percent methane. Napier grass pretreated with alkali solutions in another study by Antunes et al. (2021) exhibited increased xylitol and ethanol production, proving Napier grass as a sustainable biomass feedstock to be used in the biorefinery process. In addition, Singh et al. (2023) reviewed the position and issues of compressed biogas (CBG) plants in India, and found that agricultural waste, such as Napier grass, has potential as the feedstock of CBG. Finally, Reza et al. (2020) employed the thermogravimetric analysis (TGA) and Fourier transform infrared spectroscopy (FTIR) to display the structural composition of Napier grass, which is a potential bioenergy feedstock. According to these studies, co-digestion and pretreatment have been important in the enhancement of the biogas yield that is produced using Napier grass.

The promising biomass feedstock, Napier grass (*Pennisetum purpureum*) has been thoroughly researched with regard to biogas production based on its high biomass production and quick growth. A number of studies have been dedicated to the optimization of biogas production out of Napier grass using different pretreatment processes and the co-digestion procedures. In a study on co-digestion of Napier grass and industrial hydrolyzed food waste, Kriswanto et al. (2022) found the two stage process of anaerobic digestion produced a 30 percent greater yield of methane when the system used compared to the single-stage system, with a methane concentration of 67.29. On the same note, Akcakaya et al. (2022) pointed at the importance of alkaline pretreatment procedures, specifically NaOH, which was effective in the elimination of lignin and enhancement of methane yielding in Napier grass. Wainaina et al. (2019) also considered two-stage bioreactor system to biogas, which demonstrated dramatically more production of biohydrogen and biomethane of Napier grass with a particularly significant increase of methane production up to 367.00 mL CH₄/g VS. Another study by Wu et al. (2022) concentrated on the advantages of co-digesting Napier grass with food waste that resulted in the increase in biogas yields and the enhancement of the methanogenesis. Gundupalli et al. (2023) also noted the effect of pretreatment, which indicated that the use of alkaline treatment contributed significantly to the use of biomass in the production of methane by decomposing the cellulose and lignin levels in Napier grass. All these findings indicate that pretreatment and co-digestion strategies are significant in maximizing the production of biogas by Napier grass.

Napier grass (*Pennisetum purpureum*) has received a lot of attention over its potential in biogas production whereby some studies highlight its befitting use as a feedstock owing to this high biomass yield and lignocellulosic content. Sawadee and Pisutpaisal (2014) report that Napier grass is suitable in biogas production, particularly when the plant concentrations are optimized. Their experiment concluded that the best percentage methane content and rate of production was at a solid concentration of 5% implying that Napier grass is an economical

and sustainable alternative of producing renewable energy using biogas. The paper highlighted the economic feasibility of Napier grass as a feedstock, which has a strong benefit to cost ratio, which makes it a promising energy source. Besides that, Janejadkarn & Chavalparit (2013) investigated the improvement of biogas production in hybrid Napier grass because of its lignocellulosic-based character. They discovered that Napier grass is capable of generating high yields of methane when it is employed as a co-substrate on other organic materials such as food waste thus proving its use as an energy crop in producing bio-gases. In the same way, Mbachu et al. (2021) explored the co-digestion of Napier grass with other organic feeds, especially food waste and found out that there was a marked boost in the production of methane. Their experiment found that the co-digestion self under 1:1 ratio between Napier grass and food waste enhanced the production of methane by 28.4. Moreover, Masse et al. (2010) too examined the impact of various ages of harvesting on the production of bio-gas using Napier grass and established that the production of Methane differed widely, and the maximum production was observed when the grass was cut after it had attained a maturity of 45 days. All these studies indicate that Napier grass is potentially an excellent feedstock in biogas production, and different systems such as co-digestion, optimization of harvesting age and solid content are significant factors in improving methane production.

When analyzing the biogas production potential, especially of Napier grass (*Pennisetum purpureum*) and its co-digestion with piggery manure (PM), some important studies will provide information on optimization of the methane production as well as the efficiency of various pretreatment procedures. The article by Ojediran et al. (2021) focuses on the benefits of mixing Napier grass with piggery manure in order to boost the production of biogas, where the pretreatment methods of mechanical, thermal, and alkaline treatment display that the digestibility and the methane production are greatly enhanced by pretreatment processes. The results showed that the co-digestion process especially when under mesophilic conditions caused a significant enhancement in biogas production, with the pretreated Napier grass and PM mixture getting 409.5 m³ CH₄/kg VS, whereas the untreated mixtures got 184.1 m³ CH₄/kg VS.

In a separate research paper by Dahunsi et al. (2021), the concept of co-digestion of Napier grass and piggery manure was examined under varied pre-treatment conditions. The findings suggested that the mechanical and alkaline pretreatments had great effects on enhancing biogas yields and the highest yield was observed in a two-stage anaerobic digestion system. Moreover, Ojediran et al. (2020) pointed out the environmental advantages of Napier grass, commonly considered a weed, as energy source in biogas production due to the high amount of cellulose it contains. In addition, Sawasdee and Pisutpaisal (2022) compared the yield of the biogas using Napier grass as a substrate and its co-digestion with food waste found that the yield of biogas increased with the addition of the other substrates to overcome the negative impact of the high lignin contents in the grass. This article by Haegele et al. (1994) had further

information of the canopy architecture of Napier grass and could correlate the effective use of light and growth with large biomass production, which is directly reliant on the suitability of the grass as a source of renewable energy. All these studies confirm that Napier grass when co-digested with piggery manure and undergoing proper pretreatment methods presents a potential and a viable feedstock to biogas production.

Energy Conversion Pathways of Napier Grass

An excellent example of a biomass resource that can be converted into other forms of energy using the different conversion routes is Napier grass, which has been shown to grow at an exceptional rate and has enormous biomass output. These are ecofriendly and sustainable avenues of utilizing biomass, which can be used to achieve the increased global demand of renewable energy. Direct combustion, gasification, pyrolysis, and bioconversion are the conversion technologies, which each present different benefits toward Napier grass, and it can be flexible in the production of energy. This text explains all the different energy conversion technology applied to Napier grass, their advantages, difficulties and scalability possibility.

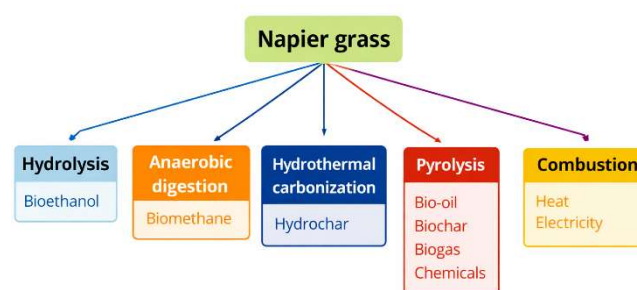


Fig. 5. Conversion Pathways of Napier Grass

Direct combustion of Napier grass is one of the simplest and the commonest ways of utilizing it in generating energy. In this, Napier grass undergoes burning to create heat, and the heat may be converted to either produce electricity or mechanical power. Direct combustion is an established technology which needs rather simple infrastructure. The difficulty however is how to make the combustion process optimum so that it is highly efficient and the harmful emissions are minimally brought down to a minimum[74]. Direct combustion has the issue of excessive air pollution, so stringent regulations should be adhered to reduce the emissions and, as much as possible, make the process efficient. An example of this would be; moisture content of the grass can be well managed so that the combustion would produce much heat and less pollutants such as carbon monoxide, particulate matter as well as nitrogen oxides. Despite the fact that direct combustion may be efficient in certain situations, it is necessary to consider the effect of combustion on the environment and human health in order to attain sustainable energy production using Napier grass[75].

Another state of the art conversion technology is gasification which entails partial oxidation of biomass at a high temperature

in an oxygen-limited space to produce synthesis gas (syngas). Such syngas can be processed to produce electricity or be processed to produce chemical manufacture. Gasification is an option, as opposed to direct combustion, because it generates fewer emissions and the harmful gases may be captured and treated before being emitted to the atmosphere. Also, gasification provides a wide range of shy-syn-gas, such as methanol, ethanol, or hydrogen, and therefore can be further refined into several chemicals or fuels.. The liquidity of gasification is the fact that it enhances the versatility of energy generation through the Napier grass since the syngas can be applied in various ways. Nonetheless, the process entails advanced machinery, liveliness of energy to sustain the high temperatures and close control of the air-to-fuel ratio to avoid the development of undesired substances like tar and carbon monoxide. Other processing processes are also involved in gasification such as purifying and cooling of the gas prior to its usefulness. However, it has a potential to generate high-value products, such as hydrogen or bio-fuel, via gasification, which is why it can be potentially used as a large-scale energy source through Napier grass conversion[76].

Pyrolysis is an anaerobic thermal process that transforms biomass to bio-oil, biochar, and syngas by heating in an environment not contained in the presence of oxygen. The technology is being highlighted due to its capability to generate bio-oil, which can be further converted to a host of biofuels, and biochar, which is of great significance in the improvement of soil and carbon sequestration. Bio-oil is a liquid product which can be used as renewable alternative to petroleum-derived fuels whereas biochar can be used as soil conditioner to enhance the water retention and soil fertility hence making it a good by-product in agriculture[77]. Probably among the main advantages of pyrolysis is that it would produce valuable by-products that have application in several industries such as energy, agriculture and environmental management. Nevertheless, there are

problems concerning the efficient transformation of the biomass into bio-oil and biochar as well in the context of pyrolysis. The effectiveness of the process is determined by a number of factors such as temperature, feedstock composition, and residence time. With increased temperature, more biochar and syngas is produced and vice versa with low temperatures producing more bio-oil. Moreover, the pyrolysis systems must be developed and optimized to generate high biofuels and produce low amounts of unwanted products like tar. Nevertheless, pyrolysis would prove to be a promising technique to transform Napier grass into renewable energy and useful by-products[78].

The bioconversion methods such as anaerobic digestion and fermentation provide a friendly and sustainable process of transforming organic substances such as Napier grass into biogas and ethanol respectively. Anaerobic digestion is the degradation of organic substances through the activities of microorganisms in the absence of oxygen and the formation of biogas, mainly made of methane and carbon dioxide. Alternatively, the sugars found in Napier grass are metabolized by the fermentation process to form ethanol, a renewable biofuel that can replace gasoline[79]. An anaerobic digestion and fermentation have a number of advantages, among them the manufacture of useful by-products, such as fertilizers and soil conditioners. The anaerobic digestion products including digestate can be utilized to enhance the soil fertility and augment agricultural yield. Equally, ethanol that is manufactured through fermentation can be an alternative to fossil fuels which can be eco-friendly. Nevertheless, these bioconversion processes are constrained by lignin content of Napier grass which renders the biomass to microbial degradation. To address this difficulty, the pretreatment techniques of physical, chemical and biological treatment are commonly employed in order to simplify the availability of cellulose and hemicellulose which are the important elements of biomass that are transformed into biogas during bioconversion[80].

Table 3. Sugar And Ethanol Yields of Napier Grass

Pretreatment	Enzymatic Hydrolysis and Fermentation	Sugar Yield	Ethanol Yield	References
Steam Explosion	Celluclast® cellulase 15 FPU/g, Novozyme 188® (from Novozymes, Bagsvaerd, Denmark), β-glucosidase 15 IU/g. Saccharomyces cerevisiae (SSF)	Glucose: 0.38 g/g WIS	42.25 g/L	[81]
Alkaline (NaOH)	Cellulase Cellic CTec2 and HTec2, 12 FPU/g. Saccharomyces cerevisiae (SSF)	Glucose: 51.60 g/L, Xylose: 13.50 g/L	0.143 ± 0.006 g/g	[82]
Acid (H ₂ SO ₄)		Glucose: 29.20 g/L, Xylose: 5.10 g/L	0.075 ± 0.003 g/g	
Acid-Alkaline (H ₂ SO ₄ -NaOH)		Glucose: 56.90 g/L, Xylose: 4.20 g/L	0.116 ± 0.006 g/g	
Alkaline (NaOH)	Cellulase Cellic RCTec2 (5-40 FPU/g). Saccharomyces cerevisiae (SHF and SSF)	TRS: 90.00 g/L through SSF	30.60 ± 0.40 g/L (SHF), 28.50 ± 2.30 g/L (SSF)	[83]

Steam Explosion	<i>Aspergillus</i> spp. and <i>Saccharomyces cerevisiae</i>	9 ml	-	[84]
Biological	<i>K. marxianus</i> MTCC1389 and <i>T. reesei</i> MTCC4876 and <i>Phanerochaete chrysosporium</i> MTCC4955	TRS: 84.52 ± 3.5 g/L	14.65 ± 1.75 g/L	[85]
Supercritical Carbon Dioxide (SFE) and Pressurized Liquid Extractions (PLE)	-	124.3 ± 2.7 mg/g (SFE), 198.2 ± 20 mg/g (SFE)	-	[86]
H ₂ SO ₄	5 FPU/g Celluclast 1.5 L and 15 U/g β-glucosidase	330 mg/g	-	[87]
Steam Explosion	10 FPU/g of enzyme produced from the EG	248.34 mg/g	-	[88]
Alkaline (NaOH)	NS22244-CELLIC® HTec2 (28 FPU) and 2% (wt.) for CELLIC® CTec2 113 FPU (from Novozymes, Latin America, Araucária, Brazil) and yeast cells	TRS: 19.88 ± 1.56–25.62 ± 0.83 g/L	3.95–7.94 g/L	[89]
Acid-Microwave	<i>S. cerevisiae</i> ITB-R89 and <i>Pichia stipitis</i> ITB-R58	Glucose: 10.79 g/L	0.45 g/L	[90]

Bioethanol is produced using Napier grass which follows several major steps such as pretreatment followed by fermentation and cellulose hydrolysis. It is necessary to undergo pretreatment to disintegrate the lignocellulosic structure of the grass to expose the cellulose content to be more readily available to enzymatic hydrolysis. To improve the cellulose content and eliminate the lignin, which is a difficult to process component in manufacturing bioethanol, multiple pretreatment processes, such as physical, chemical, and biological ones are applied. Biological pretreatment is regarded as the least harmful of such approaches because it does not use harsh chemicals and creates the minimal amount of waste[91]. Nonetheless, treatment by biological means is inefficient and takes long in incubation, rendering it inappropriate in cases of use on an industrial scale. After the lignocellulosic material is pretreated, enzymes are added to degrade the cellulose to simple sugars and these sugars are fermented by microorganisms to make ethanol. The pretreatment method and the hydrolysis efficiency determine the efficiency of the bioethanol production. It has also been established that Napier grass is able to produce large quantities of glucose following pretreatment and this can be further fermented to form ethanol. The enzymatic hydrolysis of Napier grass following acid pretreatment has yielded glucose contents of up to 89.20, 43.54, and 76.01 percent on leaves, stems, and the whole plant respectively. These results show that Napier grass may be a good source of bioethanol as a viable feedstock through its ability to be converted to bioethanol[92].

Although Napier grass has significant potential of being used as a biomass in energy conversion, it has a number of challenges that have to be addressed before it could be allowed to be used at large scale in bioenergy conversion. The lignin level, which blocks the breakdown of cellulose and makes bioconversion processes like fermentation and anaerobic digestion less productive, is one of the major barriers; a large lignin content makes biomass thus determining biomass utilization less cost-effective. Pretreatment processes such as acid and alkaline treatments have been reported to enhance the accessibility of cellulose, however, they have their own challenges e.g., the presence of inhibitory compounds in the case of acid treatment and high operational costs in the case of alkaline treatment [93]. Moreover, a change in chemical compositions of Napier grass that can be affected by weather conditions and the general type of soil is another challenge towards optimizing energy conversion. It has been demonstrated that the effectiveness of biogas production and bioethanol yields can be influenced by the particle size, genetic diversity, and stages of crop maturity among others[94]. To overcome these challenges, more studies should be conducted on areas of investigation in trying to come up with new methods of pretreatment, optimizing bioconversion, and implementing sustainable practices in planting and harvesting Napier grass. The application of Napier grass provides a high potential source of bioenergy because the technology generates high biomass production and the ability to convert the bio-mass to a form of energy is wide-ranged[95]. Each of the conversion technologies directly combustion,

gasification, pyrolysis and bioconversion has its pros and cons. Nevertheless, Napier grass can be an important component of the renewable energy process with further study and technological promotion, offering a long-term and ecologically safe alternative to fossil energy sources[96].

Discussion

The renewable bioenergy production that has attracted a large amount of attention is the use of napier grass (*Pennisetum purpureum*) in biogas. This is because of the high biomass and rapid growth rate of this grass, which is presumed to be a high potential feedstock in the bio-gas production process as it contains cellulose. The biggest problem in biogas production using Napier grass however is the fact that it is lignocellulosic and therefore biodegradation by the microorganisms is not very easy, particularly the lignin component in its biogas production. Some of the pretreatment modes studied include; mechanical, thermal, alkaline, and also chemical treatment process which aimed at enhancing the effectiveness of biogas production by degrading the complex lignin, cellulose and hemicellulose fiber of the grass. Research has also shown that pretreatment of Napier grass with alkaline solutions such as sodium hydroxide (NaOH) is a great way of increasing the yield of methane. Dahunsi et al. (2021) state that pretreating Napier grass in question leads to the improved accessibility of the microbial enzymes and, thus, to the increased yield of biogas during the process of anaerobic digestion. These pretreatments are especially advantageous in the removal of lignin which is a barrier to the action of microbes in the process of anaerobic digestion. Subsequent research by Ojediran et al. (2021) affirmed that mechanical pretreatment methods and NaOH treatment enhanced the production of higher levels of methane through the dismantling of the lignin structure to enhance the level of digestibility and higher production of methane by 30 percent of untreated grass.

In addition, co-digestion that entails mixing Napier grass with other organic materials such as piggery manure or food waste has been proved to have great impacts on enhancing biogas production. Co-digestion maximizes the amount of carbon to nitrogen (C/N) ratio and enhances digestion. According to a study by Wu et al. (2022), co-digestion of Napier grass and food waste led to an increased production of methane since the co-digestion of the two created balance in the biomass, which was colonized by microbes, and therefore, biodegraded more efficiently. The results suggested that the methane production was the highest in the representation of optimal ratio of Napier grass to food waste than when the Napier grass was digested individually. This complementarity of feedstocks is accurate because it will aid in overcoming the shortcomings of the overly high content of lignin in the Napier grass that prevents digestion by microbes. Co-digestion assists in producing a more balanced microbial atmosphere by adding food waste that is generally more easily degraded by organic matter hence increasing the overall biogas production. Besides, Ojediran et al. (2021) demonstrated that co-digestion with piggery manure (PM) did not only enhance the yield of methane but also the effectiveness

of the anaerobic digestion process by supplementing necessary trace nutrients that could otherwise be lacking in case Napier grass is digested in isolation.

The two stage anaerobic digestion (AD) system is also very critical in the increase of the biogas production on Napier grass. In this system, biohydrogen production then methane production is done on Napier grass. The research findings described by Wainaina et al. (2019) have shown that this two-step process led to an increased rate of methane by 30 per cent as compared to a conventional single-stage process. This is attributed to the fact that in the first stage, production of biohydrogen facilitates degradation of the complex organic feeds which can be converted in the second stage to methane with ease. Moreover, the two-stage system can be used, so that the biochemical steps can be better separated and the toxic intermediates will not accumulate to inhibit a growth of methanogens. The two-stage process gives a more controlled medium to produce biogas by maximizing the amount of methane produced on Napier grass by optimum levels of specific microbial communities, thus allowing better control over microbial communities.

Last but not least are the economic and environmental concerns of using Napier grass in the production of biogas products. Napier grass is a highly viable feedstock meal as a substitute to other feedstock materials (such as corn or sugarcane), which may be linked to greater land utilization and water use because they are easy to grow and grow more rapidly. The biogas production using Napier grass with sophisticated pretreatment technique and co digestion plans are also feasible solution to sustainable energy generation. A study conducted by Akcakaya et al. (2022) highlights the possible Napier grass as an energy crop but also in decreasing the environmental footprint caused by waste management. Using agricultural and organic garbage into biogas, Napier grass-based biogas plants allow to reduce the wastes, and to generate renewable energy, which could be utilized to generate electricity or used as a vehicle fuel. All these findings show that Napier grass in the presence of suitable pretreatment methods and the ideal approaches to co-digestion can eventually become a major contender in the renewable energy industry, as it can help in the production of renewable energy as well as effective disposal of waste. More studies on how to maximize the feedstock blends, perfected pretreatment processes and increased production of biogas through scaled-up biogas plants will also come in handy in fulfilling Napier grass potential as an affordable and dependable source of bioenergy.

Conclusion and Future Perspectives

Finally, Napier grass (*Pennisetum purpureum*), being a lignocellulosic biomass, has a high potential in biogas and biomethane production because of its high production, high growth rate and the multi-purpose use in renewable energy. Other pretreatment alternatives, such as alkaline chemical treatment, have been found to increase the generation of methane by as much as 70 percent, thus it can be considered as tried and tested strategies of increasing the effectiveness of biogas production in full scale and pilot bio-methanation projects.

Although these pretreatment approaches proved effective, some of the challenges that come about include high energy consumption, hence the need to consider more efficient answers that can be industrialized to allow application at industrial scale. Future investigations are recommended in optimising the processes of hydrolysis and partial acidification at regulated pH levels, improving the methods of screening and identification of new enzymes and chemical agents to maximise the use of biogas and reduce toxicity and pre-treatment period. Moreover, the multi-objective optimization tools may be used to determine the optimal pretreatment parameters to achieve the highest biogas generation and the positive energy balance. It can be concluded that the opportunities of Napier grass in bioenergy production are enormous due to the combination of innovative technologies and low-cost solutions in the future. Its use in the process of pyrolysis, hydrolysis, and direct combustion can be further explored to add value to its use as a renewable energy source. Further studies on its economic viability particularly when used in small-scale combined heat and power (CHP) systems will be essential to overcome the problem of price competitiveness with fossil fuels. Due to the need to develop sustainable energy sources, Napier grass will be instrumental in the world switching to renewable energy.

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