Review

Elephant Grass (*Pennisetum purpureum*): A Bioenergy Resource Overview

Lovisa Panduleni Johannes¹, Tran Thi Ngoc Minh² and Tran Dang Xuan¹,³,⁴,*

¹ Transdisciplinary Science and Engineering Program, Graduate School of Advanced Science and Engineering, Hiroshima University, Kagamiyama 1-5-1, Hiroshima 739-8529, Japan
² Victory Christian Academy, 810 Buena Vista Way, Chula Vista, CA 91910, USA
³ Faculty of Smart Agriculture, Graduate School of Innovation and Practice for Smart Society, Hiroshima University, Hiroshima 739-8529, Japan
⁴ The IDEC Institute, Hiroshima University, Kagamiyama 1-5-1, Hiroshima 739-8529, Japan

* Correspondence: tdxuan@hiroshima-u.ac.jp; Tel.: +81-82-424-6927

Abstract: Elephant grass (EG), or *Pennisetum purpureum*, is gaining attention as a robust renewable biomass source for energy production amidst growing global energy demands and the push for alternatives to fossil fuels. This review paper explores the status of EG as a sustainable bioenergy resource, integrating various studies to present a comprehensive analysis of its potential in renewable energy markets. Methods employed include assessing the efficiency and yield of biomass conversion methods such as pretreatment for bioethanol production, biomethane yields, direct combustion, and pyrolysis. The analysis also encompasses a technoeconomic evaluation of the economic viability and scalability of using EG for energy production, along with an examination of its environmental impacts, focusing on its water and carbon footprint. Results demonstrate that EG has considerable potential for sustainable energy practices due to its high biomass production and ecological benefits such as carbon sequestration. Despite challenges in cost competitiveness with traditional energy sources, specific applications like small-scale combined heat and power (CHP) systems and charcoal production show economic promise. Conclusively, EG presents a viable option for biomass energy, potentially playing a pivotal role in the biomass sector as the energy landscape shifts towards more sustainable solutions; although, technological and economic barriers need further addressing.

Keywords: elephant grass; biomass; bioenergy; biofuels; energy crops; bioethanol; pyrolysis

1. Introduction

As global energy demands rise, the exploration of alternatives to fossil fuels has intensified, with a particular focus on renewable resources [1]. Biomass is emerging as a key renewable energy resource, offering solutions to the energy crisis and mitigating climate change [2]. The energy extraction from biomass can be accomplished through several methods: direct combustion for heat and electricity, a traditional approach that remains widely used due to its simplicity and directness, chemical or enzymatic treatment to break down complex carbohydrates in biomass into fermentable sugars, which are then processed into liquid biofuels, offering a renewable alternative to conventional gasoline and diesel. Gasification which converts biomass into synthesis gas or biogas through controlled, high-temperature processing. This gas can then be used as a clean-burning fuel for power generation or heating. Pyrolysis involves heating biomass in the absence of oxygen to produce bio-oil, biogas and biochar, which can be used as direct fuel or further processed into chemicals and other fuels [3].

Technological advancements have shifted the focus from first-generation food crops like corn and sugarcane to second-generation biomass sources, such as energy crops and perennial grasses. These second-generation sources offer ecological advantages by requiring less water and fertilizers and thriving on marginal lands, thus conserving arable land for
food production and reducing the environmental footprint of biomass cultivation. Among

the various perennial grasses, Pennisetum purpureum, commonly known as Napier grass

or elephant grass (EG), has gained considerable attention for its robust growth and minimal

resource demands. EG can grow in various climates, is drought-resistant, and produces

high yields on marginal soils, making it ideal for sustainable biomass energy production.

Its rapid growth and suitability for repeated harvesting make it an economically viable

option for farmers in both developed and developing countries. EG not only provides a

sustainable energy source but also aids in land management and erosion control, enhancing

its ecological value [4].

The primary objective of this review paper is to provide a comprehensive analysis

of the status of EG as a sustainable bioenergy resource. The analysis covers its biofuel

production capabilities by assessing the efficiency and yield of different biomass conver-

sion methods such as in pretreatment for bioethanol production, biomethane and direct

combustion and pyrolysis. Additionally, a technoeconomic analysis to evaluate the eco-

nomic viability and scalability of using EG for energy production is included with its

environmental impacts, focusing on its water and carbon footprint.

2. Elephant Grass (Growth Patterns, Geographic Distribution, Adaptability and
Environmental Benefits)

EG belonging to the Poaceae family is indigenous to tropical Africa. It is highly valued

both as a forage grass and as an energy crop across numerous tropical regions due to

its remarkable growth capabilities and substantial biomass yield. Capable of reaching

up to 6 m in height, the grass features robust leaves that are 30–90 cm long and up to

3 cm wide. It has adaptability to harsh conditions characterized by high temperatures,

intense sunlight, and limited water, nitrogen, or carbon dioxide availability, making it

exceptionally resilient and adaptable [5,6]. It demonstrates an extraordinary growth rate,

with average yields ranging from 30 to 40 metric tons per hectare (MT/ha) annually.

The dry mater yields of EG vary significantly worldwide from 14 MT/ha in Malawi

to 85 MT/ha in El Salvador [7]. The rapid growth cycle allows for multiple harvests

within a single year, typically 3–4 times resulting in the high annual dry matter yields,

surpassing other bioenergy crops such as switchgrass and sugarcane, establishing EG as

a superior alternative for biofuel production [8–10]. In northern Rio de Janeiro, Brazil, a

study evaluated 53 elephant grass (EG) genotypes to enhance forage availability and reduce

seasonal production variations. Employing a randomized block design, the study measured

traits such as dry matter yield, number of tillers per clump, plant height, and stem diameter.

Genotypes including Mercker 86 México, Mercker Comum, Gramafante, Guaçu/I.Z.2, and

Pasto Panamá stood out for their superior productivity, adaptability, and stability [11]. This

method demonstrated the capability of genetic selection to significantly improve EG forage

production, thereby aiding in the advancement of sustainable agricultural practices and

consequently advancing bioenergy resources.

EG along with other short rotation crops have been acknowledged for their environ-

mental benefits, particularly in carbon dioxide sequestration. They are capable of capturing

approximately 40 tons of carbon dioxide per hectare. The high content of cellulosic fibers

in EG renders it an excellent resource for ethanol production [12,13]. The calorific value

of EG is found to be quite high compared to other biomasses ranging from about 14 MJ/kg to

19 MJ/kg (see Section 3.3), which indicates that its dry biomass can produce substantial

heat energy, comparable to conventional fossil fuels while offering a much lower carbon

footprint. This makes it an attractive option for sustainable energy production [12]. Its

versatility extends beyond energy production, with applications to paper manufacturing,

owing to its lignocellulosic biomass content [5,14,15].

The study by [16] presents a comprehensive analysis of the biomass yield, nitrogen

absorption, and nitrogen use efficiency (NUE) of several cellulosic energy crops, including

EG with comparisons to traditional first-generation energy crops like maize and sugarcane

under different planting densities. EG stood out significantly with the highest dry biomass
yield recording an impressive 53.2 tons per hectare annually, significantly surpassing other crops like sorghum, maize, sugarcane, switchgrass, johnsongrass, and Erianthus whose yields ranged between 2.6 and 25.3 t ha\(^{-1}\) y\(^{-1}\) [16]. Laurent et al. also reported EG to have higher productivity compared to Miscanthus x giganteus. Regarding nitrogen absorption, EG exhibited an exceptionally high ability to absorb nitrogen from the soil, with absorption rates up to 775.1 kg ha\(^{-1}\), which is tenfold higher than the nitrogen application rate from chemical fertilizers (72 kg ha\(^{-1}\)) [17]. Higher planting densities were recommended within suitable ranges to improve NUE and decrease soil nitrogen depletion. Sugarcane and sorghum showed higher NUE than other crops under both high and conventional planting densities. However, EG’s NUE was significantly impacted by planting density, indicating that cultivation practices could be optimized for better nitrogen utilization [16].

3. Composition

3.1. Lignocellulosic Composition

The cellulosic composition of EG is extensively documented, primarily consisting of cellulose, hemicellulose, and lignin, the major composition of lignocellulosic biomass as shown in Table 1. Variations in composition are influenced by factors such as location, growth conditions, and analytical methods used for assessment. EG is highly recognized for its substantial ability to accumulate dry matter, closely linked to its biomass quality attributes including lower heating value (LHV) and ash content. These qualities make EG an excellent candidate for lignocellulosic feedstocks, particularly suitable for direct combustion processes [3].

Table 1. Lignocellulosic composition of EG.

<table>
<thead>
<tr>
<th>Cellulose [%]</th>
<th>Hemicellulose [%]</th>
<th>Lignin [%]</th>
<th>Location</th>
<th>Age</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.60–42.40</td>
<td>16.9–22.4</td>
<td>18.40–23.40</td>
<td>Nigeria</td>
<td>3 weeks regrowth</td>
<td>[8]</td>
</tr>
<tr>
<td>36.18 ± 5.40</td>
<td>27.50 ± 5.92</td>
<td>12.19 ± 4.93</td>
<td>Indonesia</td>
<td>3 months</td>
<td>[10]</td>
</tr>
<tr>
<td>35.00 ± 2.90–39.4 ± 2.20</td>
<td>19.20 ± 1.20–21.70 ± 1.00</td>
<td>15.30 ± 3.40–18.8 ± 2.3</td>
<td>Hawaii</td>
<td>2–8 months</td>
<td>[18]</td>
</tr>
<tr>
<td>33.60 ± 0.11</td>
<td>20.62 ± 0.02</td>
<td>18.42 ± 0.11</td>
<td>Brazil</td>
<td>-</td>
<td>[19]</td>
</tr>
<tr>
<td>36.80 ± 2.20</td>
<td>23.20 ± 1.10</td>
<td>25.00 ± 0.30</td>
<td>Taiwan</td>
<td>-</td>
<td>[20]</td>
</tr>
<tr>
<td>41.70</td>
<td>18.00</td>
<td>20.90</td>
<td>Brazil</td>
<td>-</td>
<td>[22]</td>
</tr>
<tr>
<td>36.00</td>
<td>30.30</td>
<td>8.80</td>
<td>Brazil</td>
<td>6 months</td>
<td>[3]</td>
</tr>
<tr>
<td>35.69 ± 3.01</td>
<td>15.26 ± 2.72</td>
<td>18.03 ± 1.03</td>
<td>Brazil</td>
<td>-</td>
<td>[23]</td>
</tr>
</tbody>
</table>

EG’s cellulose content from the reviewed literature ranges from 22.60% to 42.40%, with an average around 35.69%. The cellulose content is higher or comparable to that of switchgrass (31.0%) and sugarcane bagasse (39.0%); although, it falls slightly below Miscanthus giganteus (48.6%) and eucalyptus wood (48.1%). The hemicellulose content ranges from 15.26% to 27.50%, averaging at 15.26%, which matches or surpasses the higher ranges observed in other biomasses such as rice straw (23–28%), wheat straw (26–32%), and sugarcane bagasse (27–32%). Additionally, it is lignin content ranges from 12.19% to 25.00%, which is comparable to rice straw (15–25%) and within the normal range for grass species (10–30%), and therefore, EG is ideal for biorefining processes utilizing selective extraction techniques [22].

During the combustion of biomass, the ratio of cellulose to lignin plays a crucial role in determining the efficiency and completeness of the combustion process. Biomass with a high cellulose content relative to lignin tends to undergo charring and incomplete combustion, which can significantly limit the production of heat. This is because cellulose, while highly combustible, lacks the structural rigidity provided by lignin, leading to less efficient burning and the potential for residual unburnt material. The activation energy required for combustion, which is a measure of the energy needed to initiate the combustion
process, is primarily influenced by the lignin content. Lignin, with its complex aromatic structure, provides a higher energy barrier, thus impacting the overall energy release during combustion [24]. Conversely, in the production of bioethanol, a higher cellulose to lignin ratio is advantageous. This is because the bioethanol production process involves a pretreatment step where the biomass is processed to make the cellulose more accessible to enzymes that convert it into sugars. The lower the lignin content relative to cellulose, the more efficiently these enzymes can access and break down the cellulose into fermentable sugars. Lignin acts as a physical and chemical barrier that hinders enzymatic access to cellulose; therefore, reducing its presence through selective pretreatment can significantly enhance the efficiency of sugar extraction and subsequent fermentation into bioethanol [25].

3.2. Proximate and Ultimate Analysis

3.2.1. Proximate Analysis

The proximate analysis of biomass feedstocks enables the assessment of moisture content (MC), volatile matter (VM), fixed carbon (FC), and ash content (AC). MC refers to the water content in a dry biomass sample, where a high percentage of moisture can adversely affect pyrolysis reactivity and biofuel quality. MC values below 10% are conducive to efficient thermochemical breakdown during pyrolysis [26]. Proximate analyses of EG from different studies are summarized in Table 2. The MC of EG ranges from as low as 5.93% to a high of 12.20%, with the majority of the values under 10%, indicating favorable conditions for efficient thermochemical conversion during pyrolysis. Volatile matter in biomass, consisting mainly of hydrocarbons, carbon monoxide, carbon dioxide, hydrogen gas, and some tars, enhances reactivity in thermochemical processes, typically ranging from 60 to 85% [27]. The VM percentages fluctuate between 67.34% and 82.39%, generally fitting within the typical range mentioned earlier that is known to enhance reactivity in thermochemical processes. High AC usually impedes the combustion process by causing fouling, erosion, and slag formation, whereas lower ash values contribute to higher efficiency in biofuel production during pyrolysis [27,28]. AC of EG varies considerably, from as low as 3.0% to as high as 13.30%, with most studies reporting values above the lower threshold, suggesting a potential for fouling and erosion during combustion but also indicating the presence of minerals that might catalyze pyrolysis reactions. Nevertheless, for purposes such as activated carbon production, the samples with the lowest ash content, like the one reported by [29] with 3.0%, would be most efficient [30]. The AC of EG predominantly comprises elements such as potassium, chlorine, and silicon [31]. FC is the residue left after volatile matter, ash content, and moisture have been expelled from the biomass, and it spans from 7.70% to 19.20% from the reviewed studies. Higher FC content, such as that reported by [32], suggests that the EG in question may provide a more stable energy output during the combustion process. Disparities in the proximate analysis results of EG, as summarized, may stem from factors such as the plant’s location, age, and the methods used for sample preparation, which collectively influence the analytical outcomes [26].

<table>
<thead>
<tr>
<th>Moisture [%]</th>
<th>Fixed Carbon [%]</th>
<th>Volatile Matter [%]</th>
<th>Ash [%]</th>
<th>Location</th>
<th>Age</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.90</td>
<td>18.80</td>
<td>70.30</td>
<td>3.00</td>
<td>Brazil</td>
<td>-</td>
<td>[29]</td>
</tr>
<tr>
<td>5.93</td>
<td>16.81</td>
<td>69.44</td>
<td>7.82</td>
<td>Brunei</td>
<td>-</td>
<td>[27]</td>
</tr>
<tr>
<td>11.70</td>
<td>9.53</td>
<td>82.39</td>
<td>8.07</td>
<td>Brazil</td>
<td>4 months</td>
<td>[9]</td>
</tr>
<tr>
<td>9.80</td>
<td>7.70</td>
<td>69.20</td>
<td>13.30</td>
<td>Brazil</td>
<td>-</td>
<td>[33]</td>
</tr>
<tr>
<td>10.63</td>
<td>19.20</td>
<td>72.54</td>
<td>8.26</td>
<td>Brazil</td>
<td>6 months</td>
<td>[32]</td>
</tr>
<tr>
<td>12.20</td>
<td>15.54</td>
<td>67.34</td>
<td>4.92</td>
<td>Brazil</td>
<td>-</td>
<td>[34]</td>
</tr>
<tr>
<td>9.43</td>
<td>8.35</td>
<td>72.58</td>
<td>9.68</td>
<td>Taiwan</td>
<td>3 months</td>
<td>[35]</td>
</tr>
</tbody>
</table>
3.2.2. Ultimate Analysis

Ultimate analysis provides insights into the elemental composition of biomass, specifically the content of carbon, hydrogen, nitrogen, and oxygen, which are fundamental to evaluating its potential as a heating fuel. A biomass with a high carbon content and lower oxygen levels typically exhibits a higher heating value, making it a more efficient fuel source [36]. The ultimate analysis results of EG from different studies are summarized in Table 3. The carbon content, pivotal for heating value, shows a range between 38.20% and 46.52%. Higher carbon contents correlate with a greater heating value [36], suggesting that the sample from [32] with the highest carbon percentage may yield the most energy upon combustion. However, this is balanced against oxygen levels ranging from 41.78% to 54.94%, which are inversely related to the heating value. The sample with the lowest oxygen content may indicate a higher heating value, provided the carbon content is also high. Nitrogen percentages, although lower in comparison, are noteworthy since they can influence emissions during combustion, potentially forming NOx pollutants. Elevated levels of carbon and hydrogen are directly associated with increased energy yield in direct combustion. The presence of nitrogen, oxygen, and sulfur can present challenges and may diminish the energy potential due to undesirable reactions. Particularly in direct combustion, sulfur reacts with oxygen to form sulfur dioxide gas, which is a significant contributor to air pollution. Therefore, for biomass to be considered suitable for this process, it is recommended that the sulfur content remain below 0.3% [37]. The interplay of elements in the ultimate analysis signifies the complexity of biomass assessment for energy applications.

Table 3. Ultimate analysis of elephant grass.

<table>
<thead>
<tr>
<th>Carbon [%]</th>
<th>Hydrogen [%]</th>
<th>Nitrogen [%]</th>
<th>Oxygen [%]</th>
<th>Sulfur [%]</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>43.8</td>
<td>5.08</td>
<td>0.45</td>
<td>-</td>
<td>5.70</td>
<td>[29]</td>
</tr>
<tr>
<td>41.9–44.6</td>
<td>5.83–6.24</td>
<td>0.49–0.84</td>
<td>42.1–046.6</td>
<td>-</td>
<td>[3]</td>
</tr>
<tr>
<td>43.32</td>
<td>5.80</td>
<td>1.17</td>
<td>41.78</td>
<td>0.11</td>
<td>[27]</td>
</tr>
<tr>
<td>38.20</td>
<td>5.70</td>
<td>1.16</td>
<td>54.94</td>
<td>-</td>
<td>[9]</td>
</tr>
<tr>
<td>39.63</td>
<td>6.31</td>
<td>1.70</td>
<td>52.16</td>
<td>0.20</td>
<td>[32]</td>
</tr>
<tr>
<td>46.52</td>
<td>5.87</td>
<td>1.47</td>
<td>46.04</td>
<td>0.10</td>
<td>[33]</td>
</tr>
<tr>
<td>41.16</td>
<td>5.55</td>
<td>1.78</td>
<td>46.59</td>
<td>-</td>
<td>[34]</td>
</tr>
<tr>
<td>42.40</td>
<td>5.96</td>
<td>1.71</td>
<td>45.32</td>
<td>0.09</td>
<td>[35]</td>
</tr>
</tbody>
</table>

The Van Krevelen diagram displayed in Figure 1 was plotted against the H/C atomic ratio versus the O/C atomic ratio of EG for the values in Table 3 from different studies. The cluster labeled “biomass” on the diagram, where the points for EG from different studies are located, shows a relatively high H/C ratio, generally above 1.4, and a moderate O/C ratio between 0.4 and 0.8. This indicates that EG, like most raw biomass, is rich in both hydrogen and oxygen relative to its carbon content. Such a composition is typical for cellulose and lignocellulosic materials, which are major constituents of biomass. This graphical representation helps in understanding the suitability of EG and other energy resources in different energy generation contexts, based on their elemental composition.
3.3. Lower and Higher Heating Value of EG

In biofuels, the caloric value measures energy content by unit mass for solids (MJ/kg) and by volume for liquids (MJ/L) and gases (MJ/Nm$^3$), with higher heating values (HHVs) capturing the total energy from biomass combustion, including water vapor’s latent heat, for optimal energy yield. The HHV values rise with increased carbon and hydrogen content, while a higher nitrogen content leads to a decrease in these values. Lower heating values (LHVs) reflect the combustible energy minus water vapor’s latent heat. Biomass with higher LHVs offers increased energy efficiency and yield [3,22,27]. Biomass utilized for the production of bioenergy should have a minimum energy content of 14.01 MJ/kg [37].

The HHV of EG of 18.55 MJ/kg reported by [27] aligned closely with the HHV of 18.44 MJ/kg by [22] and exceeds the 14.7 MJ/kg noted by [34], (see Table 4). This variation in HHV, which can range from 16.96 MJ/kg at 4 months to 22.04 MJ/kg at 6 months, is expected due to factors such as plant age. The HHV of EG is on par with various wood species, typically around 20 MJ/kg, and compares favorably to, or slightly exceeds, the values of energy crops with shorter lifecycles like Leucaena leucocephala (19.3–20.6 MJ/kg), switchgrass (18.8 MJ/kg), and wheat straw (18.55 MJ/kg) [22]. An analysis of the chemical composition and caloric values of EG varieties alongside other biomass feedstocks intended for direct combustion, shedding light on their LHVs was conducted [3]. Across 18 elephant grass varieties, LHVs were consistent, ranging between 16.29 MJ/kg and 17.28 MJ/kg, with an average LHV of 16.7 MJ/kg, indicating EG’s high energy potential as a bioenergy source. Compared to rice husk (15.3 MJ/kg), sugarcane bagasse (16.0 MJ/kg), and sorghum (15.9 MJ/kg), elephant grass exhibited superior LHVs, aligning closely with sugarcane straw (17.26 MJ/kg), coconut fiber (17.0 MJ/kg), and corn stover (16.9 MJ/kg). Rice husk and sorghum, with the lowest LHVs among the studied feedstocks, were indicated to have comparatively lower energy contents suitable for combustion [3].
Table 4. Calorific values of elephant grass.

<table>
<thead>
<tr>
<th>HHV [MJ/kg]</th>
<th>LHV [MJ/kg]</th>
<th>Location</th>
<th>Age</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>18.55</td>
<td>-</td>
<td>Brunei</td>
<td>-</td>
<td>[27]</td>
</tr>
<tr>
<td>14.70</td>
<td>-</td>
<td>Brazil</td>
<td>-</td>
<td>[34]</td>
</tr>
<tr>
<td>15.77</td>
<td>-</td>
<td>Brazil</td>
<td>6 months</td>
<td>[32]</td>
</tr>
<tr>
<td>15.97</td>
<td>-</td>
<td>Brazil</td>
<td>4 months</td>
<td>[9]</td>
</tr>
<tr>
<td>-</td>
<td>16.29–17.28</td>
<td>Brazil</td>
<td>6 months</td>
<td>[3]</td>
</tr>
<tr>
<td>-</td>
<td>14.85–15.86</td>
<td>Thailand</td>
<td>1, 2, 3, 6 months</td>
<td>[37]</td>
</tr>
<tr>
<td>16.30</td>
<td>-</td>
<td>Taiwan</td>
<td>-</td>
<td>[38]</td>
</tr>
<tr>
<td>18.05 ± 0.07</td>
<td>-</td>
<td>Malaysia</td>
<td>-</td>
<td>[39]</td>
</tr>
<tr>
<td>-</td>
<td>17.10</td>
<td>Brazil</td>
<td>-</td>
<td>[40]</td>
</tr>
<tr>
<td>18.44</td>
<td>-</td>
<td>Brazil</td>
<td>6 months</td>
<td>[22]</td>
</tr>
</tbody>
</table>

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The findings from [3,22,27] emphasize the considerable potential of EG as a bioenergy feedstock, given its relatively high HHV and high LHV compared to other biomass sources. This positions EG as a competitive option for bioenergy applications, particularly in regions where it can be sustainably cultivated. The comparison of HHVs and LHVs across various feedstocks provides valuable information for selecting appropriate biomass sources for bioenergy production, emphasizing the importance of optimizing feedstock selection based on energy content.

4. Energy Conversion Technologies/Pathways of EG

EG characterized by its rapid growth and significant biomass yield, serves as an exemplary biomass resource capable of conversion into various energy forms through distinct pathways (see Figure 2). Direct combustion of this grass facilitates the generation of heat and power; however, this method demands careful regulations to maximize efficiency and reduce environmental pollution [41]. Through the process of gasification, biomass is transformed into synthesis gas (syngas) via partial oxidation at elevated temperatures, rendering it suitable for electricity production or as a precursor for chemical manufacturing [27]. Pyrolysis, conducted in an anaerobic setting, yields bio-oil, biochar, and syngas from the biomass, where the bio-oil may be further refined into diverse biofuels and the biochar utilized for soil enhancement or carbon sequestration [33]. Furthermore, bioconversion techniques such as anaerobic digestion and fermentation metabolize the organic constituents of biomass into biogas and ethanol, respectively, concurrently generating advantageous by-products like fertilizers and soil conditioners [9].

![Figure 2. Conversion pathways of elephant grass.](image_url)

4.1. Bioethanol

In the bioconversion of lignocellulosic biomass, including EG, into bioethanol, several essential steps are involved. These steps include pretreatment to eliminate lignin and enhance cellulose content, followed by cellulose hydrolysis to break down complex structures into simple sugars by enzymes. Subsequently, microorganisms are employed to utilize these sugars for ethanol production. To achieve optimal product yields, pretreatment of
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Lignocellulosic material is crucial. This pretreatment can take various forms, including physical, chemical, biological, or a combination of these methods [25]. Biological pretreatment stands as the most environmentally friendly approach, as it avoids harsh chemicals, reduces waste, and minimizes fermentation inhibitors. However, its low efficiency, due to long incubation times, results in high operational costs and makes it unsuitable for industrial and pilot-scale applications. Additionally, microorganisms can consume simple sugars, leading to carbohydrate loss. Despite being cheaper than most pretreatment methods, the need for sterile conditions further increases costs [10,42].

Pretreatment of whole EG and its individual leaf and stem components with different concentrations of diluted sulfuric acid (5–20%) was carried out by [43]. They found that the stem was notably more resistant, as demonstrated by the high retention of water-insoluble solids and lower enzymatic hydrolysis efficiency post-acid treatment. Additionally, the enzymatic hydrolysis tests revealed that glucose yields escalated with increasing acid concentrations, reaching peak values of 89.20% for leaves, 43.54% for stems, and 76.01% for the entire plant [43]. The increase in sugar concentration was also found to be proportional to the duration of pretreatment and ethanol yields of EG by [20] using dilute acid; however, longer durations resulted in inhibitory compounds formation, namely acetic acid and furfural which were more pronounced at 180 °C. Similarly, Lima et al. reported the presence of the inhibitory compound 2-furfuraldehyde at 180 °C in EG and two other grasses [44]. At this temperature, all biomasses showed a decrease in glucose content despite an increase in xylose, particularly evident with acid pretreatment. This reduction in glucose at higher temperatures is attributed to the formation of inhibitors, such as 5-hydroxymethyl-furfural and 2-furaldehyde, which was most prevalent in all biomasses treated with sulfuric acid at 180 °C. EG showed the lowest content of inhibitory compounds amongst the three grasses. Lower yields of inhibitory compounds were observed at 90 °C and above 90 °C, acidic conditions accelerate the transformation of glucose into 5-hydroxymethyl-furfural through dehydration. To address the formation of inhibitory compounds, activated carbon was used to adsorb toxic derivatives, achieving significant reductions; 69% in furfural, 31% in 5-hydroxymethyl-furfural and 40% in acetic acid. This treatment also led to slight increases in glucose and xylose levels due to the influence of temperature [19]. Additionally, acid pretreatment was found not be effective for lignin removal even at higher temperatures. Alkaline pretreatment of EG proved to be more effective in sugar production, yielding 0.245 g of glucose per gram of EG following enzymatic hydrolysis, compared to 0.146 g/g with dilute acid pretreatment and 0.217 g/g with two-stage pretreatment [44]. This superiority is attributed to the alkaline method’s enhanced ability to remove both lignin and hemicellulose while retaining glucan, resulting more extensively in higher sugar extraction efficiency [20]. Many studies have found alkaline pretreatment to be superior to acid pretreatment yielding higher sugar yields and higher ethanol yields because alkali pretreatment was associated with high lignin removal [45–47]. Tables 5 and 6 show the sugar and ethanol yields and inhibitory compounds obtained after pretreatment of EG.
Table 5. Sugar and ethanol yields of elephant grass.

<table>
<thead>
<tr>
<th>Pretreatment</th>
<th>Enzymatic Hydrolysis and Fermentation</th>
<th>Sugar Yield</th>
<th>Ethanol Yield</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steam explosion</td>
<td>Celluclast® cellulase 15 FPU/g, Novozyme 188® (from Novozymes, Bagsvaerd, Denmark), β-glucosidase 15 IU/g, Saccharomyces cerevisiae (SSF)</td>
<td>Glucose 0.38 g/g WIS</td>
<td>42.25 g/L</td>
<td>[19]</td>
</tr>
<tr>
<td>Alkaline (NaOH)</td>
<td>Cellulase Cellic CTec2 and HTec2 S. cerevisiae SSF</td>
<td>Glucose: 51.60 g/L</td>
<td>0.143 ± 0.006 g/g</td>
<td></td>
</tr>
<tr>
<td>Acid (H₂SO₄)</td>
<td>12 FPU/g. S. cerevisiae</td>
<td>Xylose: 13.50 g/L</td>
<td></td>
<td>[20]</td>
</tr>
<tr>
<td>Acid-Alkaline</td>
<td>H₂SO₄-NaOH cellulase CellicR CTec2 (5–40 FPU/g). S. cerevisiae SHF and SSF</td>
<td>TRS: 90.00 g/L through SSF</td>
<td>30.60 ± 0.40 g/L</td>
<td>[48]</td>
</tr>
<tr>
<td>Alkaline (NaOH)</td>
<td>Cellulase CellicR CTec2 (5–40 FPU/g). S. cerevisiae SHF and SSF</td>
<td>TRS: 84.52 ± 3.5 g/L</td>
<td>14.65 ± 1.75 g/L</td>
<td>[50]</td>
</tr>
<tr>
<td>Biological</td>
<td>K. marxianus MTCC 1389 and T. reesei MTCC 4876 and Phanerochaete chrysosporium MTCC4955</td>
<td>-</td>
<td>124.3 ± 2.7 mg/g (SFE)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-</td>
<td>198.2 ± 20 mg/g (SFE)</td>
<td></td>
</tr>
<tr>
<td>Supercritical</td>
<td></td>
<td>-</td>
<td>330 mg/g</td>
<td>[43]</td>
</tr>
<tr>
<td></td>
<td>carbon dioxide (SFE) and pressurized liquid extractions (PLE)</td>
<td>-</td>
<td></td>
<td>[51]</td>
</tr>
<tr>
<td>H₂SO₄</td>
<td>5 FPU/g Celluclast 1.5 L and 15 U/g β-glucosidase</td>
<td>TRS: 19.88 ± 1.56–25.62 ± 0.83 g/L</td>
<td>3.95–7.94 g/L</td>
<td>[23]</td>
</tr>
<tr>
<td>Steam explosion</td>
<td>10 FPU/g of enzyme produced from the EG</td>
<td>-</td>
<td>248.34 mg/g</td>
<td>[13]</td>
</tr>
<tr>
<td>Alkaline</td>
<td>NS22244-CELLIC® HTec228 FPU (from Novozymes Latin America, Araucária, Brazil) and 2% (wt.) for CELLIC® CTec2113 FPU (from Novozymes, Bagsvaerd, Denmark) and yeast cells</td>
<td>TRS: 10.79 g/L</td>
<td>0.45 g/L</td>
<td>[52]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Inhibitory Compounds</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acid</td>
<td>Acetic acid: 3.9 ± 0.1 g/L</td>
<td>[20]</td>
</tr>
<tr>
<td></td>
<td>Furfural: 0.31 ± 0.03 g/L</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5-HMF: 0.63 ± 0.06 g/L</td>
<td></td>
</tr>
<tr>
<td>Acid</td>
<td>5-HMF: (18 µg/g)</td>
<td>[44]</td>
</tr>
<tr>
<td></td>
<td>2-Furaldehyde: (very minimal)</td>
<td></td>
</tr>
<tr>
<td>Alkaline</td>
<td>Acetic acid: 2.48 ± 0.05</td>
<td>[23]</td>
</tr>
<tr>
<td></td>
<td>Others: 2.48 ± 0.05</td>
<td></td>
</tr>
</tbody>
</table>

4.2. Biogas/Biomethane

EG is recognized for its high carbohydrate contents making it a promising carbon source for biogas production [21]. However, elevated lignin content presents a challenge by hindering cellulose degradation, thereby restricting their biomethane potential [53].
In evaluating biomass viability for methane production via anaerobic digestion (AD), an essential procedure is the biochemical methane potential (BMP) test conducted under anaerobic conditions. Within AD, microorganisms decompose biomass in the absence of oxygen to yield methane-rich biogas [54]. Various constraints linked to the single fermentation of grass silages within the AD process have been identified, notably their resilience to biodegradation and insufficient trace element presence in the reactor. Subsequently, numerous investigators have explored pretreatment techniques and enhanced trace nutrient supplementation as potential solutions to mitigate these issues [55]. Furthermore, challenges like the buoyancy of grass silages, stemming from their low densities and fibrous compositions, frequently result in blockages within digester pumps and pipeline networks [8].

Biomethane production from EG investigated by [8] was 68 ± 1.6%, falling within the typical range observed in biogas which is 60–70%. The experimental BMP derived from un-supplemented EG was found to be 303.1 mL CH4/g of volatile solids (VS), comparable to methane yields reported for common energy crops (298–467 (mL/g VS)). These findings were consistent with results from similar studies, such as that by [55] (293.81 ± 0.15–334.69 ± 22.75 mL/g), although slightly higher than values reported by [56] (190–340 mL CH4/g VS) and significantly higher than those reported by [57] (219 ± 4.9 mL CH4/g VS). The discrepancies in BMP values were attributed to differences in biomass particle size, which impacts hydrolysis efficiency. Genetic diversity, composition, soil characteristics, climatic conditions, and crop maturity stages as indicated by [58] were found to cause variations in BMP too. Investigating the synergistic potential of EG and cow dung for biogas production, a study utilized a batch digester process where fresh EG was finely chopped to a maximum strand length of 3 cm. The optimum substrate mixture comprising 25 parts cow dung, 25 parts grass, and 100 parts water yielded a significant total biogas volume of 524.3 L. However, when assessing the biogas yield from this co-digestion mix, it underperformed in comparison to the biogas yield from a control sample of solely cow dung. The control sample’s biogas contained a methane concentration of 53.88%, while the mixed treatments generated a considerably lower methane content, with the highest being 31.37%. The particle size of the EG is a critical factor to consider, as the intricate lignocellulosic structure of the grass may impede microorganism’s access to fermentable sugars, thereby affecting biogas yield and its composition [59].

4.3. Pyrolysis

4.3.1. Bio-Oil

Pyrolysis emerges as the most efficient method for biomass conversion into biofuel, with the potential to transform up to 70% of biomass into bio-oil [60,61]. Bio-oil yields from EG pyrolysis were reported as 30.56% at 400 °C, 33.25% at 500 °C, and 35.11% at 600 °C [27]. Similarly, the bio-oil yield for EG by [9] remained relatively stable across similar temperatures, achieving 27 wt.% at 400 °C, 28 wt.% at 500 °C, and 30 wt.% at 600 °C and a maximum of 36 wt.% achieved by [35]. The specific composition of the bio-oil in both studies, however, was not detailed. These yields reported for EG are lower than the 50 wt.% yield from cassava rhizome reported by [62] and lower than those obtained for olive stone by [63], 28 wt.% at 400 °C, 37 wt.% at 500 °C, and 35 wt.% at 700 °C, but they were similar to that of Arundo donax which was 26.18 wt.% at 500 °C. The difference in yields is possibly due to differences in heat transfer efficiency and vapor residence time within the reactors [64]. It is suggested that bio-oil production is largely influenced by cellulose’s thermal degradation, with the addition of heat transfer mediums like silica sand and sweep gas potentially increasing yield by facilitating faster heat transfer and reducing vapor residence time [9,65]. The composition of bio-oil from EG includes a significant proportion of organic acids (27.3%), phthalate esters (11.9%), benzene compounds, and amides, with variations observed at different heating rates. A faster heating rate of 50 °C/min was found to decrease organic acids and benzene compounds while increasing phthalate esters and naphthalene compounds, indicating that pyrolysis conditions can be tailored to optimize
bio-oil output for specific applications. The pyrolysis process offers considerable potential for refining based on the targeted production of fuel or chemical feedstocks [29].

4.3.2. Biogas

Biogas yields from EG showed an increase with temperature, reaching 34.31%, 38.34%, and 41.87% at 400 °C, 500 °C, and 600 °C, respectively, as reported by [27]. A similar biogas yield of 44.7% at 600 °C for EG was obtained by [9], while [64] found a comparable yield of 44.59 wt.% at 600 °C for Arundo donax and for olive stone, 35 wt.% at 500 °C with a hydrogen concentration of 25.3% volume [63]. The increase in biogas yield at higher temperatures is attributed to the secondary cracking of pyrolytic vapors and the formation of non-condensable gases from the secondary decomposition of char [66]. However, the bio-gas yields obtained for EG in the mentioned studies were lower at the respective temperatures compared to the bio-gas yield of wheat straw by [67], whereby at 500 °C and 600 °C, the bio-gas yields were 60 wt.% and 50 wt.%, respectively. Yan et al. also noted that syngas yield escalates with pyrolysis temperature, consisting primarily of H₂, CH₄, CO₂, and CO [68], alongside complex hydrocarbons as identified by [29,69]. Intriguingly, the combustion energy of these bio-gas components was found to be significantly greater by a factor of 3.7 to 7.4 than the energy input required for the pyrolysis of the grass, suggesting the possibility of achieving a self-sustaining process. For the effect of heating rate, it was found that increasing the heating rate to 50 °C/min, as opposed to a slower rate of 10 °C/min, resulted in a reduced production of volatile gases, a factor that could crucially impact the overall energy efficiency of the pyrolysis operation [29].

4.3.3. Biochar

Biochar is a carbon-rich product derived from the pyrolysis of organic material, where biomass is thermally decomposed in an oxygen limited environment. Pyrolysis entails biomass decomposition into smaller compounds at elevated temperatures ranging from 300 °C to 800 °C under an inert atmosphere [70,71]. This process not only breaks down the weaker chemical bonds within the biomass but also leads to the formation of denser structures, particularly from the lignin component [72]. The amount of lignin plays a crucial role in biochar production; a higher lignin content in biomass directly correlates with increased yields of biochar and tar from the pyrolysis process. Slow pyrolysis favors producing a greater yield of biochar, while fast pyrolysis yields higher amounts of tar, oil, and gas [73].

EG was subjected to pyrolysis by [27]. The process was conducted at three distinct temperatures, 400 °C, 500 °C, and 600 °C, each with a consistent heating rate of 5 °C/min. To ensure a controlled pyrolysis environment, an inert atmosphere was maintained using a nitrogen flow of 0.5 L/min. The outcomes revealed a decrease in biochar yield, from 35.13% at 400 °C to 23.02% at 600 °C, while keeping all other parameters constant. This observed decline in biochar production with increasing temperature is consistent with the patterns reported in other scholarly works such as that by [9], whereby they found that as the temperature rose from 400 °C to 600 °C, the biochar yield significantly decreased from 37.5 wt.% to 25.6 wt.%. This phenomenon was not isolated to EG alone. Sirijanusorn et al. also reported a comparable behavior in their experiments with cassava rhizome in an auger reactor, observing a reduction in biochar yield from 22 wt.% at 500 °C to 18 wt.% at 700 °C [62]. These findings suggest that the biochar characteristics of elephant grass closely mirror those of other types of biomasses when subjected to pyrolysis. Strezov et al. also reported a minor variation in biochar yield from EG with different heating rates, suggesting minimal impact of heating rate on yield, their experiments, conducted at a steady temperature of 500 °C but with heating rates fluctuating between 10 and 50 °C/min, resulted in a slight variation in biochar yield, from 29.3 to 31.0 wt.%, respectively [29]. This subtle disparity implies that the heating rate might not significantly influence the yield of biochar. Lower temperature biochar had higher volatile matter content, whereas higher
temperature biochar had a higher fixed carbon percentage, indicating a consistent pattern of biochar characteristics across different biomass types during pyrolysis [27,30].

In the steam gasification of biochar, alkali metal salts, particularly potassium (K) is recognized as the most effective catalyst. The catalytic activities of metals in biochar were found with the sequence; K > Ca > Mg > Na [74]. Contrasting concentrations in miscanthus biochar were observed by [75], with potassium at 4.24 wt.% and calcium at 6.24 wt.%, which differ from those in EG biochar. In EG, considerably higher potassium levels, ranging from 52.2 to 72.7 g/kg across temperatures of 400 °C to 600 °C were observed [74]. It is well known that potassium has catalytic effects on hydrogen production. Given potassium’s known catalytic effects on hydrogen production, EG biochar holds significant potential for hydrogen generation in the gasification processes [74].

### 4.4. Pelletization

Like other grass biomass types, EG faces challenges due to its relatively low bulk density (73.6–123 kg/m³), which is lower than that of eucalyptus sawdust (288.4 kg/m³), bamboo (280.95 kg/m³), and corn cob (157.3 kg/m³) [76]. Additionally, its variable structure and high moisture content complicate handling, storage, and transportation. Although it is possible to transport EG directly from farms to bioenergy facilities, pelletization effectively densifies this biomass into globally recognized solid biofuels. Pelletization increases its bulk density, improving handling efficiency, enhancing flowability, and boosting storage and transport capabilities [4,41]. The conversion of EG into densified pellets substantially raises its bulk density to between 593 and 709 kg/m³, representing significant enhancement. This densification process aligns with the standard requirements for biomass pellets, which necessitate a bulk density range of 600 to 750 kg/m³ to ensure their commercial viability [4].

This substantial enhancement in bulk density through pelletization not only aligns with but also supports the findings from other studies, such as those by [77,78], who recorded similar bulk densities of 654.1 kg/m³ and 674.7 kg/m³, respectively. Furthermore, the assessment of energy density of EG by [4], which ranged from 12.00 to 12.19 GJ/m³, closely mirrors that by [78] who reported an energy density of 12.18 GJ/m³. These findings affirm that optimal bulk density levels for biomass pellets can be achieved through a strategic densification process, thereby enhancing their logistical and commercial viability.

### 4.5. Value Added Chemicals

Biomass extracts can be processed into various products such as phenolics, sterols, and hydrocarbons, used in coatings, polishes, detergents, antioxidants, nutraceuticals, and cosmetics. The residual solids from these extractions can further be transformed into biofuels, enhancing the production chain and promoting cleaner production in the chemical industry [79]. EG has the advantage of being rich in ethanol-extractable compounds, yielding significantly higher extract amounts compared to sugarcane bagasse. Specifically, extracts from milled EG leaves, obtained over an 8 h period, were four times greater than those from sugarcane bagasse, about 3% under similar conditions [44]. Additionally, the antioxidant activity of lignin extracted from EG surpasses others, being eight times higher than that of corn cob lignin and sixteen times higher than that of sugarcane bagasse [44].

An integrated approach utilizing supercritical carbon dioxide (SFE) and pressurized liquid extractions (PLEs) was developed to extract high-value organic molecules from EG, employing eco-friendly methods [51]. Post-extraction, the remaining solids were converted into fermentable sugars for ethanol production. The use of water and ethanol (PLE-WE) yielded significantly better results than ethyl acetate (PLE-EA), which achieved only 3.8% and 1.4% from leaves and stems, respectively. PLE-WE yields were notably higher than those from SFE. PLE’s efficiency was due to the polar nature of EG compounds and the conditions of extraction. SFE’s lower yields of 0.85% w/w for leaves and 0.17% w/w for stems were comparable to those seen with sugarcane residues (1.6% w/w for leaves and 0.5–0.8% w/w for bagasse) according to [80]. Fatty acids were predominantly extracted from both leaves and stems using SFE, achieving up to 21% for leaves and 18% for stems.
In contrast, alcohols and phenolics were primarily extracted through PLE-WE and SFE-WE, reaching up to 27% for leaves and 35% for stems, facilitated by the use of polar solvents [51].

The compounds present in EG, such as phenol and coniferyl alcohol, are valuable in industrial applications. They serve as antioxidants and ultraviolet protectors, making them particularly beneficial for the cosmetic industry. Natural compounds from EG are also used in sunscreens [81]. Additionally, sterols from the plant have potential uses as anti-inflammatory and anti-cancer agents [82,83]. Trevisan et al. employed an acid–alkali method to recover lignin solubilized in black liquor, achieving a yield of precipitated lignin of 85 ± 5 wt.% [81]. These recovery yields align with those documented in the literature for wood pretreatments using NaOH solutions and exceed typical yields for lignin extraction from sugarcane bagasse, which range from 5.5 to 13 wt.% [84,85].

Valuable compounds, primarily derived from the organic phase of bio-oil from pyrolysis are frequently extracted, while the aqueous phase is typically considered less valuable and often discarded due to its limited applications. However, studies, such as that by [86], have suggested the potential for hydrogen production from this stream through catalytic aqueous and steam reforming processes. According to [39], the composition of organic phase bio-oil from EG pyrolysis is similar to that reported by [29,87] consisting mainly of benzene derivatives like phenols, methyl-phenol, ethyl-phenol, methoxy-phenols, methoxy-benzene, benzaldehyde, and benzene carboxylic acid, along with various hydrocarbons. In contrast, the aqueous phase contains mostly organic acids, esters, ketones, and aldehydes. Table 7 summarizes different yields of value-added chemicals from EG.

Table 7. Chemicals from elephant grass.

<table>
<thead>
<tr>
<th>Method</th>
<th>Extraction Yield</th>
<th>Compounds Obtained</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFE</td>
<td>0.85% for leaves</td>
<td>Acids: SFE (21%-L;18%-S)</td>
<td>[51]</td>
</tr>
<tr>
<td></td>
<td>0.17% for stems</td>
<td>PLE-EA (9%-L-S)</td>
<td></td>
</tr>
<tr>
<td>SFE (Water and ethanol)</td>
<td>7.91% for leaves</td>
<td>Alcohols and phenolics: SFE-WE (~42%-L; 35%-S)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.39% for stems</td>
<td>PLE-WE (~27%-L; 35%-S)</td>
<td></td>
</tr>
<tr>
<td>PLE (Water and ethanol)</td>
<td>7.5–8.0% for leaves</td>
<td>PLE-WE (27%-L; 35%-S)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6.3–7.8% for stems</td>
<td>PLE-EA (15%-L; 25%-S)</td>
<td></td>
</tr>
<tr>
<td>Acid-alkali</td>
<td>37% for lignin</td>
<td>Lignin: 98% purity</td>
<td>[81]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phenolics: 3.85 mmol/g</td>
<td></td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>50.57 wt.% (Bio-oil yield)</td>
<td>Hydrocarbons: Benzene derivatives (60%)</td>
<td>[39]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Acids:</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ketones</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aldehydes</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phenolics</td>
<td></td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>37–62% pyrolysis yield</td>
<td>Organic acids (27.2%)</td>
<td>[35]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Phenols (7.9%)</td>
<td></td>
</tr>
<tr>
<td>Pyrolysis</td>
<td>-</td>
<td>Benzene derivatives (24.46 wt.%)</td>
<td>[29]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Organic acids; 27.3%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Esters; 11.9%</td>
<td></td>
</tr>
</tbody>
</table>

4.6. Combined Heat and Power (CHP) Generation

Direct combustion stands as the primary technology employed for harnessing heat and mechanical energy from biomass. In a combined heat and power (CHP) plant, also known as cogeneration, the simultaneous production of heat and power significantly enhances energy efficiency by capturing heat that would otherwise be wasted in conventional power generation. These systems have become globally popular as effective tools for improving
energy efficiency and reducing carbon emissions. They contribute to carbon mitigation by utilizing otherwise unused energy, which is a major source of emissions in the energy sector of many countries [88]. Sustainably managed biomass resources are viewed as environmentally friendly because they do not contribute to global warming. The carbon dioxide released during biomass combustion is offset by its absorption during plant regrowth, ensuring that with sustainable management, there is no net increase in atmospheric carbon dioxide. Combustion of biomass is a complex process involving heat and mass transfer and chemical reactions, and therefore, predicting its behavior for design and control purposes depends on understanding the fuel properties and how they affect combustion [40]. The energy content of a fuel is directly linked to its calorific power, emphasizing the importance of this characteristic when evaluating biomass as an energy source. Biomass suitable for thermal energy production via combustion should ideally exhibit high concentrations of lignin and cellulose, a favorable calorific value, a beneficial carbon to nitrogen (C/N) ratio, and minimal levels of moisture, ash, and nitrogen, which EG possesses [3,89].

EG biomass holds significant potential as a solid biofuel for direct combustion [3]. EG, specifically the Cameroon genotype group, was found to exhibit superior potential as a bioenergy source through direct combustion, producing a total dry biomass of 24.13 Mg ha\(^{-1}\) and achieving a calorific value of 18.16 MJ/kg [89].

The boiler/steam turbine-based CHP system is the prevalent CHP configuration for solid fuels like coal and biomass, accounting for 32% of the total CHP capacity in the USA with a typical capacity of biomass-fired CHP plants under 50 MW. CHP systems could potentially utilize EG as a feedstock for cogenerating heat and power to reduce the overall greenhouse gas emissions compared to fossil fuel-based CHP plants. Specifically, the reduction in global warming potential was between 73 and 92% compared to traditional fossil fuel sources [41]. A feasibility study on CHP generation using biomass in Brazil, specifically coffee husks, rice husks, and EG highlights the economic and operational advantages for electric arc furnace for steel making processes [40]. The detailed operational parameters within the Rankine cycle for the cogeneration plant showed that EG was the most cost-effective biomass fuel, reducing costs by approximately 9–15% compared to natural gas. Biomass combustion in CHP plants tends to produce sulfur compounds, which can affect the chemical composition of the produced metal. Therefore, it is advisable to utilize biomass primarily for generating electricity and using boiler exhaust gases for scrap preheating in the electric arc furnace process. Due to the lower calorific value of biomass, such as EG compared to that of natural gas at 47 MJ/kg, biomass combustion results in a greater volume of exhaust gases. The thermal energy in EG exhaust gas ranged from 445 kWh to 175 kWh, whereas that of natural gas ranged from 150 kWh to 80 kWh. This increase in exhaust mass flow provides more thermal energy, making biomass particularly effective for preheating scrap, irrespective of equipment efficiency. This capability shows the suitability of biomass in CHP systems for industrial applications requiring both electrical and thermal energy outputs [40].

5. Techno-Economic Analysis
5.1. Cost Analysis

The agronomic requirements for EG with an average yield of 28.04 dry metric tons per hectare each year over a productive life span of a decade where determined; herbicide application is conducted biennially at a volume of 4.7 L per hectare. Fertilization practices involve the annual application of 200 kg/ha of nitrogen from urea, complemented by 20 kg/ha each of phosphorus and potash fertilizers. Lime is introduced at a significant one-time rate of 10 000 kg/ha, along with clover seeds at 25 kg/ha to naturally enrich the soil through nitrogen fixation, thereby potentially reducing the need for synthetic nitrogen inputs.. Diesel fuel usage for cultivation processes stands at 13.6 L per hectare annually, increasing to 125.8 L per hectare for harvesting activities, reflecting the intensity and fuel-dependency of these agricultural operations. Machinery utilization further indicated the
energy-intensive nature of EG production, with 19.2 kg/ha used for cultivation and a substantial 117.1 kg/ha for harvesting [41,90,91].

For implementing an EG fired CHP system with a capacity of 13 MWe, capital cost estimations were derived for two different operational approaches, the first approach when utilizing pelletized EG feedstock and the second approach EG used as baled feedstock. The initial approach presented an estimated capital investment of approximately USD 40.09 million, with the alternative approach slightly higher at USD 42.96 million. Operating expenses were assessed at about USD 16.26 million for the former and reduced to USD 11.47 million for the latter. Despite the disparity in capital and operational expenditures, both approaches yielded comparable outputs in terms of annual electricity (equating to 89 million kWh) and useful heat production [41].

5.2. Economic Viability and Market Potential

EG has been explored for its potential in sustainable energy and material production, demonstrating varied economic viability across different applications. A technoeconomic analysis by [92] indicated a high likelihood of profitability for charcoal production using EG, with a 91% chance of breaking even and an 84% likelihood of achieving a 25% return on investment over ten years. The selected 10-year period aligns with investor expectations for returns amidst regional volatility. Charcoal sale price variability was critical, with a 90% confidence interval potentially swinging the net present value (NPV) from a positive USD 438,300 to a negative (USD −30,000), making it the sole variable that could lead to a loss. Following this, high feedstock costs significantly reduce NPV to USD 76,000, impacting returns but not causing a loss. Other costs like equipment, labor, and taxes have a much smaller effect on NPV compared to charcoal prices and feedstock costs [92]. Conversely, the economic feasibility of standalone bioethanol production from EG appears gloomy; the research by [93] scrutinized the economic viability of standalone bioethanol production and its by-products from EG. They concluded that the sector is currently unprofitable, as reflected by the negative NPV. Factors like raw material type, production scale, and bioethanol market price significantly impact the NPV. Specifically, EG requires a substantial capital investment of approximately USD 335.34 million, the second highest after corn at USD 177.91 million and the lowest capital investment being from sugar beet at USD 2.91 million. The yearly operating costs of EG stand at about USD 27.64 million, moderate compared to corn at USD 106.01 million, but higher than sugar beet (USD 1.22 million), other grasses (USD 2.5 million), and straw (USD 22.70 million) with annual revenues at USD 28.18 million, lower than that of corn at USD 147.64 million. The NPV for EG was negative, translating to a deficit of around USD 142.35 million. This figure indicated that even with a reasonable return on investment (ROI) of 7.35%; EG production is not financially sustainable under the current conditions, with the initial investment and operational costs outweighing the income over a 10-year period [93]. Conversely to that, the economic viability of transforming an EG-based biomass power plant into a biorefinery in Brazil was assessed. Initially, the power plant’s base scenario NPV was calculated at a fixed price through a 20-year supply contract. Alternative biorefinery configurations were then evaluated, incorporating a hybrid commercialization model where 20 MW is sold via long-term contracts and the remaining 10 MW (or equivalent in charcoal or ethanol) is sold on the short-term market. These setups involved additional investments in charcoaling and ethanol production. The results demonstrated that all biorefinery strategies significantly add value to the project, with option values ranging from approximately USD 90 million to USD 101 million. The NPVs for the biorefinery strategies were also positive, ranging from USD 21 million to USD 31 million, indicating that these biorefineries are economically feasible and offer a promising opportunity for enhancing Brazil’s sustainable energy matrix [6].

For CHP systems, EG presents a better economic case with a ROI ratio of 5:1 suggesting that energy output is five times the energy input. Despite various incentives such as tax credits and carbon pricing benefits, the minimum selling price (MSP) of electricity generated
from EG remains less competitive compared to traditional energy sources like coal and natural gas. Specifically, the MSP was reported at USD 0.13 per kWh for baled EG and USD 0.18 per kWh for EG in pellet form, in contrast to coal's MSP of USD 0.08 per kWh and natural gas at USD 0.07 per kWh [41]. This pricing disparity is largely due to the higher costs associated with the production and processing of EG, particularly when pelletized. Although pelletization offers logistical benefits such as improved handling and operational efficiency, it also leads to increased emissions and higher energy consumption presenting significant challenges for EG's competitiveness in the energy market [41,92].

6. Environmental Analysis

The transition from fossil fuels to biofuels has led to increased agricultural land demand, altering land use, and accelerating the conversion of various land types for bioenergy production. This change has heightened environmental concerns such as soil erosion, pollution, loss of biodiversity, and significant carbon debt due to CO₂ emissions. However, the use of perennial grasses like EG in bioenergy production can positively affect environmental metrics by reducing sediment and nutrient runoff, enhancing soil carbon sequestration, and promoting biodiversity, thereby helping mitigate climate change impacts. Despite these benefits, the allocation of prime agricultural land to bioenergy can conflict with food and feedstock production; although, using marginal lands presents a sustainable alternative that minimizes competition between food and fuel [94].

6.1. Life Cycle Assessment

Life cycle assessment (LCA) is a beneficial tool to assess and quantify the environmental impacts related to energy and material consumption, and emissions of waste for the entire life cycle of bioenergy production [41,95]. The outcomes of LCA are significantly influenced by several key factors: the types and sources of feedstock used, the selection of system boundaries, the methods employed for calculating emissions, and the approaches chosen for allocating inputs and outputs [96].

An extensive energy balance assessment was conducted for the entire lifecycle of producing EG biomass. The energy output-to-input ratio stood at 15.1:1 indicating that for each unit of energy used in the growth and processing of EG, approximately 15 units of energy were produced from the biomass [97]. This substantial ratio shows the effectiveness and viability of utilizing EG as an energy resource.

An energy analysis of a lignocellulosic biomass-based biorefinery using EG from Thailand, assessing the environmental sustainability by tracking resource consumption and waste generation in solar energy terms, was conducted [98]. They found that while EG cultivation had a lower unit energy value compared to other feedstocks, indicating a more resource efficient production, it also had a lower renewable fraction, signaling sustainability concerns. Energy inputs were heavily reliant on non-renewable resources, with 33% from evapotranspiration and 30% from diesel, resulting in nearly 60% non-renewable resource use and significant environmental impact. Despite this, the cultivation's energy yield ratio of 1.53 suggested that EG acts as a net producer, but it still lagged behind other bioenergy crops due to its dependency on external, non-renewable inputs. It was suggested that integrating biorefinery processes could minimize material use and waste, offering a more energy-efficient solution than existing methods [98].

Various grasses including EG were evaluated for production yields and nutrient uptake under low-input scenarios. EG stood out for its high resilience and productivity, achieving over 25 Mg DM ha⁻¹ yearly in the first two years. While switchgrass yielded the lowest at 8.6 Mg DM ha⁻¹ annually over four years, it showed lower moisture and nutrient content, suggesting less soil nutrient depletion. In contrast, energy cane and EG had significantly higher nutrient removal, notably nitrogen (N) and potassium (K), removing between 269 and 386 kg N ha⁻¹ and 830–1159 kg K ha⁻¹. This level of nutrient removal was significantly higher than that of the other grasses, with giant reed and switchgrass removing considerably less N and K indicating more intensive nutrient extraction from the
Therefore, there is a need for a balanced approach to EG biomass production, one that considers the nutrient dynamics of the ecosystem to ensure sustainability.

6.2. Water Footprint and Carbon Footprint

The water and carbon footprint are essential for evaluating the environmental sustainability of any product. The water footprint specifically measures the total amount of freshwater used, polluted, and consumed during the production process, offering insights into the water-related impacts across a product’s lifecycle. This metric is crucial for understanding how the production and use of goods and services affect water resources. In parallel, the carbon footprint assesses the amount of carbon dioxide emissions associated with all the activities from production to end-use, providing a comprehensive view of a product’s impact on global warming. Together, these footprints play a role in understanding the broader environmental impacts of any biomass, guiding sustainable practices in its cultivation and utilization [99].

EG’s water footprint, like that of any crop, depends on factors such as climate, soil type, and farming practices. Known for its efficient water use and drought resistance, EG generally has a lower water footprint than traditional bioenergy crops like corn or sugarcane, though exact figures can differ by region [11].

While specific water consumption figures for the EG-fired CHP system were not discussed in detail, there were significant reductions in most environmental impacts, including carbon emissions and the eutrophication impact remained comparable to that of coal-fired CHP systems, primarily due to nutrient runoff into water bodies [41]. Furthermore, studies such as that by [100] demonstrates EG’s capacity for environmental remediation through its ability to adsorb contaminants such as methylene blue dye from wastewater. The adsorption was marked by physical changes in the grass, as evidenced by a scanning electron microscopy image that show the emergence and disappearance of pores on the surface of the EG [100]. Employing EG in this manner not only aids in wastewater treatment but also plays a role in broader environmental contamination management and showing potential in phytoremediation, a technique that employs plants to remove, transfer, stabilize, and destroy contaminants in soil and water. This attribute is especially valuable in regions where resources for costly water treatment technologies are scarce, providing a sustainable approach to lessen the impact of industrial pollutants. Therefore, EG has its role in enhancing water quality, thus contributing positively to its green water footprint.

As a bioenergy crop, EG also plays a significant role in carbon sequestration during its growth, contributing to carbon mitigation. Research by [23] highlights the effective use of EG for producing second-generation bioethanol, which can significantly offset carbon emissions compared to fossil fuels. Analysis by [41] confirms that the total greenhouse gas (GHG) emissions from EG-based CHP generation plants are substantially lower, approximately 8% and 18% than those of natural gas-fired and coal-fired CHP plants, respectively. In a comprehensive review of the lifecycle GHG emissions for two electricity generation scenarios, standalone biomass and cofiring with coal. For the electricity generation systems exclusively using biomass, the average lifecycle GHG emissions were as follows: agricultural residues resulted in 291.25 gCO$_2$ e/kWh; dedicated energy crops, 208.41 gCO$_2$ e/kWh; forestry residues, 43 gCO$_2$ e/kWh; industrial biomass, 45.93 gCO$_2$ e/kWh; and waste-derived biomass, 1731.36 gCO$_2$ e/kWh. On the other hand, cofiring systems had higher mean lifecycle GHG emissions: 1039.92 gCO$_2$ e/kWh for agricultural residues; 1001.38 gCO$_2$ e/kWh for dedicated energy crops; 961.45 gCO$_2$ e/kWh for forestry residues; 926.1 gCO$_2$ e/kWh for industrial biomass; and 1065.92 gCO$_2$ e/kWh for biomass from parks and gardens [101]. These findings indicate the environmental efficiency of using dedicated energy crops like EG in clean energy production, showing lower GHG emissions relative to other biomass options.
7. Future Prospects and Recommendations for Further Studies

The prospects for EG as a bioresource are promising, particularly due to its high biomass yield and adaptability to diverse climates, making it an appealing candidate for sustainable energy production. EG has garnered attention for its potential in bioenergy, with various studies showing its sustainability benefits. However, economic challenges persist, specifically the high initial costs of establishing biomass power plants compared to traditional coal and natural gas options. To enhance its economic viability, detailed economic analyses are necessary to evaluate the lifecycle costs and potential returns from large-scale applications. One promising avenue for increasing the economic appeal of EG is its integration into existing fossil fuel power plants. This approach could yield higher returns on investment and reduce the minimum selling price of electricity by leveraging the already established infrastructure of these plants, thus avoiding the high capital costs associated with building new facilities from scratch. More comprehensive research is needed on the use of EG in CHP systems, as the current literature is limited. Such studies would fill gaps and optimize EG’s application in these systems by examining its performance and environmental impacts. Additionally, future research should also investigate the hydrothermal carbonization of EG. Hydrothermal carbonization has gained attention for its ability to process high moisture biomass, potentially reducing costs by eliminating the need for expensive drying steps [102]. Given the current lack of literature on this topic, such research could provide valuable insights into optimizing EG’s use in biomass conversion. Strategic integrations and economic assessments should also be a focus for future research to fully realize the potential of EG in transitioning to a more sustainable energy matrix.

8. Conclusions

Elephant grass (EG) presents a viable option for biomass energy, demonstrating substantial benefits in terms of renewable energy production and environmental sustainability. Its capacity for high biomass production, coupled with relatively low input requirements, positions it well as an alternative to conventional fossil fuels and other biomass sources. EG has been extensively studied for its conversion into bioenergy through various processes such as pyrolysis, hydrolysis, and direct combustion to yield biofuels, heat and power. These studies have aimed to determine the optimal conditions for these conversion processes, focusing on maximizing biofuel yields and quality. Pyrolysis studies have investigated the effects of temperature, heating rate, and residence time on bio-oil production from EG, while hydrolysis studies have focused on enzymatic or chemical treatment to convert carbohydrates into fermentable sugars for bioethanol production. Additionally, EG’s suitability for direct combustion has been evaluated, considering factors such as combustion efficiency and emissions. Overall, these studies have provided valuable insights into the potential of EG as a sustainable source of biofuels and its application in renewable energy production. Economic analyses suggest that while challenges remain in terms of competitiveness with fossil fuels, certain applications, such as small-scale CHP systems and charcoal production, are economically promising. As the global energy landscape shifts towards more sustainable solutions, EG could play a pivotal role in the biomass sector, provided that technological and economic barriers are effectively addressed.

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