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Sugarcane Bagasse as Green Fuel and Reducing Agent for Lump Ore Reduction Process

Hendrik Nemers [1,*], Rianti Dewi Sulamet-Ariobimo [1], Johny Wahyuadi Soedarsono [2], Muh Fajar Ramadhan [3], Agus Paul Setiawan Kaban [3], Ahmad Maksum [4], Theo Thomas [5], Djoko Nirprawitno [6]

[1] Mechanical Engineering Department, Faculty of Industrial Technology, Universitas Trisakti, Jakarta 11440, Indonesia
[2] Laboratory of Prof. Johny Wahyuadi Soedarsono Department of Metallurgy & Material, Faculty of Engineering, Univesitas Indonesia, Depok 16424, Indonesia
[3] Department of Metallurgy & Material, Faculty of Engineering, Univesitas Indonesia, Depok 16424, Indonesia
[4] Research Center for eco-friendly Technology, Mechanical Engineering Department, Politeknik Negeri Jakarta, Depok 16425, Indonesia
[5] PT Refratech Mandala Perkasa, Bogor, Indonesia
[6] PT. Pertamina Geothermal Energy, Jakarta 10340, Indonesia
* Correspondence: nemmers68@gmail.com

Abstract: Carbon is an essential element in the iron reduction process. Cokes are used as a carbon source in the traditional reduction process in the beneficiary of iron. When the Ironmaking Technology Mark 3 (ITMk3) method is applied in the reduction process, many carbon sources are used, especially the sources with sustainable and eco-friendly such as coconut shells, palm kernel shells, rice husk, and sugar cane bagasse. Saccharum officinarum or sugarcane extraction produced bagasse as the by-product. Like coconut shells, this rich carbon by-product is not utilized. This work discussed the utilization of bagasse as a reducing agent in the iron reduction process. An analysis is made based on specific reduction temperature with the various ratio of iron to coal. The lump ore is originated from South Borneo. Unlike the coconut shell, in this work, the Baggasse was dried. The process temperature range between 700 and 1000OC. The ratios of ore to bagasse were 1 to 1, 1 to 2, 1 to 3, and 1 to 4. The reduction process was carried out in a muffle furnace. The result shows that the reduction process produced wustite (FeO). This work also compared sugarcane bagasse with other green reducing agents.

Keywords: Green-reducing agent; Sugarcane bagasse

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1. Introduction

The iron and steel industry remains fundamental to modern infrastructure and economic growth. However, it is also one of the most energy-intensive and carbon-emitting industrial sectors. The production of one metric ton of crude steel consumes approximately 800 kg of coal, contributing to nearly 7% of global industrial CO_2 emissions [1]. Additionally, this sector accounts for around 20% of total annual industrial energy consumption [2], primarily sourced from fossil fuels. Despite mounting environmental concerns, global steel demand is projected to grow steadily until at least 2050 [1], underscoring the urgent need for more sustainable production methods. In Indonesia, which possesses approximately 3.3 billion tons of iron resources—including primary ore, laterite ore, and iron sand—domestic production remains limited and insufficient to meet national demand[3], [4], [5] . This situation presents both a challenge and an opportunity: to develop an independent iron and steel industry that leverages local resources while aligning with global sustainability goals.

In response to the growing environmental concerns surrounding the iron and steel industry, there has been increasing interest in the development of renewable and biomass-based reducing agents as sustainable alternatives to fossil fuels. Biomass is considered carbon-neutral, locally available, and capable of significantly reducing greenhouse gas emissions in metallurgical processes. Various biomass types such as sawdust [6], rice husk [7], rice bran, bamboo, coconut shell [8], and palm kernel shell [9] have been widely studied for their potential in replacing conventional carbon-based reducers like coal and coke. These studies have demonstrated that biomass materials possess sufficient fixed carbon content and thermal reactivity to participate effectively in reduction reactions, especially after undergoing processes such as carbonization, torrefaction, or briquetting.

Several researchers have specifically explored the efficacy of biomass in reducing different metal oxides. Torrefied biomass, for instance, has shown the ability to reduce hematite to metallic iron at lower temperatures than traditional reductants such as graphite [10]. Rath et al. [11] reported that vegetative biomass briquettes could effectively reduce iron ore slime, highlighting the importance of parameters such as particle size, temperature, time, and feed-to-reductant ratio. Similarly, Asmiani [12] found that blending biomass like canary shells with coal could enhance the calorific value and reactivity of briquettes. Research by Mansor [13] also suggests the potential commercialization of bio-coke derived from palm kernel shell due to its economic advantage, with production costs up to 31% lower than conventional biomass briquettes.

In addition to iron and nickel ores, biomass has also been applied in the reduction of other transition metal oxides. Notably, sugarcane bagasse has gained substantial attention not only as a biofuel but also as a reducing agent. Studies by Young et al. [14] revealed that sugarcane bagasse could effectively reduce pyrolusite (MnO_2), achieving manganese recovery rates exceeding 98% under optimal conditions (roasting temperature of 450 °C, 30-minute duration, and mass ratio of 0.9:10). Furthermore, research by Soedarsono et al.[15] confirmed the ability of sugarcane bagasse to reduce lump iron ore and produce wüstite (FeO), indicating its practical applicability in iron extraction. These findings underline a broader trend in green metallurgy that emphasizes the valorization of agricultural waste and by-products as low-cost, renewable inputs for industrial processes. However, further investigation is still needed to optimize the use of sugarcane bagasse—particularly in terms of reaction kinetics, phase transformation, and thermodynamic behavior during reduction—to ensure its scalability and consistency in industrial settings.

This study aims to address these gaps by investigating the effectiveness of sugarcane bagasse as a green reducing agent in the carbothermic reduction of lump iron ore using a muffle furnace. The research focuses on identifying optimum process parameters—such as temperature, time, and biomass-to-ore mass ratio—and evaluating the extent of reduction achieved. By comparing the performance of sugarcane bagasse to that of other biomass-based reducing agents, this work seeks to assess its practical applicability and economic potential in low-carbon iron-making processes. The findings are expected to contribute to the broader transition toward sustainable metallurgical practices, particularly in resource-rich, developing economies such as Indonesia.

2. Experimental Method

This study was conducted in two experimental stages to investigate the reduction behavior of lump iron ore using sugarcane bagasse as a biomass-based reducing agent. The first stage focused on determining the optimum mass ratio between the iron ore and the reducing agent, as well as identifying the most effective reduction temperature. The second stage evaluated the influence of reaction time on the reduction efficiency under selected temperature and ratio conditions.

2.1 Materials Preparation

The iron ore used in this experiment was lump ore sourced from Kalimantan, Indonesia, which was crushed to gravel-sized particles (approximately 1–2 cm). The reducing agent used was sugarcane bagasse (saccharum officinarum), collected from local sugar production residues. Prior to the reduction process, the bagasse was sun-dried under open-air conditions to reduce its moisture content, following the air-dried basis (adb) method. Both materials were used without further chemical treatment.

2.2 Experimental Setup and Procedure

All reduction experiments were carried out on a laboratory scale using a 10 kg capacity muffle furnace. The reduction process was performed in a closed ceramic crucible to ensure controlled reaction conditions. Inside each crucible, lump ore was embedded within a pile of dried bagasse to allow intimate contact between the ore and reducing agent during heating.

In the first stage, the objective was to assess the effects of ore-to-reductant mass ratio and temperature. Two mass ratios of lump ore to bagasse were investigated: 1:2 and 1:4. The crucibles containing the mixture were inserted into the furnace preheated to target temperatures of 700 °C, 800 °C, 900 °C, and 1000 °C. Each reduction run was maintained for a fixed holding time of 30 minutes.

In the second stage, the effect of reaction time was studied at selected temperatures of 700 °C and 1000 °C. For this step, the mass ratio of ore to bagasse was fixed at 1:2. Reduction durations of 45 and 60 minutes were applied to observe time-dependent behavior. After the heat treatment, the crucibles were allowed to cool inside the furnace to ambient temperature before further analysis.

2.3 Characterization and Analytical Methods

To evaluate the composition and properties of the raw materials and reduced products, several laboratory tests were conducted. Proximate and ultimate analyses of sugarcane bagasse were performed prior to the reduction process to determine its moisture, volatile matter, fixed carbon, ash content, and elemental composition (C, H, N, S, O). These analyses were carried out at the Tekmira Coal Laboratory, Bandung, Indonesia.

The mineralogical phases of the lump ore before and after reduction were identified using X-ray Diffraction (XRD) analysis. This characterization aimed to determine the transformation of iron oxide phases (e.g., Fe_2O_3, Fe_3O_4, FeO) during the reduction process. XRD testing was conducted using standard powder diffraction methods with Cu-Kα radiation over a scanning range appropriate for iron-bearing minerals.

3. Result and Discussion

Table 1 presents the proximate and ultimate test result from sugarcane bagasse. Moisture content in bagasse is 6.75%. The calculated amount of moisture content in bagasse is a difference of 19% from the standard value. However, it remains within the limit for ideal moisturization content for a 5-15% reduction process and direct reduction process of less than 10%. The ash content is 1.77% which is a difference of 77% below the standard.

Moreover, the ideal ash content is 3%, within a variation between 0.5 to 5.0%. The ash content in bagasse is lower than the ideal content but still beyond the limit. Volatile matter (VM) of bagasse is 78.40%. It is 0.02% less than the standard value and 160% higher than the ideal value of 30%. Fixed carbon (FC) in bagasse is 13.08%. It is an extra 3% higher than the bagasse standard. Bagasse moisture content and ash are still within the limit compared to SNI 06-3730-1995 , with a maximum of 15% and 10%. FC is the most critical element among other components owing to its role in producing reduction gas. Results based on moisture, ash, and fixed carbon analysis showed that sugarcane bagasse is suitable as a reducing agent; however, with its high VM, the charcoal will quickly burn and disperse a lot of smoke.

Table 1. Result of Proximate and Ultimate Test of Sugarcane Bagasse

Parameters	**Bagasse**		**Unit**	**Based**
	Standard	**Tested**		
Proximate Test:				
Moisture in Air Dried Sample	8.35	6.75	%	adb
Ash	7.06	1.77	%	adb
Volatile Matter	72.95	78.40	%	adb
Fixed Carbon	12.70	13.08	%	adb
Ultimate Test				
Carbon	-	45.68	%	adb
Hydrogen	-	6.71	%	adb
Nitrogen	-	0.30	%	adb
Sulphur	-	0.24	%	adb
Oxygen	-	45.43	%	adb

Tabel 2. Result of Proximate and Ultimate Process of Several Green Reducing Agents

Parameters	**Bagasse**	**Coconut Shells** [16],[17]	**Palm Kernel Shells** [18], [19], [20]	**Rice Husk** [21]	**Unit**	**Based**
Proximate Test:						
Moisture in Air Dried Sample	6.75	7.98	3.70	8.70	%	adb
Ash	1.77	4.16	2.09	23.85	%	adb
Volatile Matter	78.40	9.02	74.04	54.10	%	adb
Fixed Carbon	13.08	78.84	20.17	13.35	%	adb
Ultimate Test						
Carbon	45.68	74.30	49.90	33.14	%	adb
Hydrogen	6.71	-	6.00	5.14	%	adb
Nitrogen	0.30	-	0.28	0.55	%	adb
Sulphur	0.24	0.50	-	0.12	%	adb
Oxygen	45.43	21.90	41.66	37.20	%	adb

Comparing the proximate and ultimate test result of sugarcane bagasse to other green reducing agents: coconut shells, palm kernel shells, and risk husk is presented in Table 2. It is possible to describe the advantage of bagasse compared to coconut shells and rice husk. The moisture content in bagasse is 15% below the moisture content of coconut shells and 22% below rice husk but 82% higher than palm kernel shells. It corresponds to the capability of bagasse to consume less energy and time in the drying process. Palm kernel shells have lower moisture than bagasse, but the moisture of palm kernel shells is below the standard of ideal moisture content for the reduction process. Lower moisturization might inhibit the formation of hydrogen and slower the reduction process.

Bagasse ash content is 58% below the coconut shell, 15% below palm kernel shells, and 93% below the risk husk. It indicates that bagasse is a better reducing agent than coconut shells, palm kernel shells, and rice husk since the ash formed is minor. VM in bagasse is 770% higher than coconut shell, 6% than palm kernel shells, and 45% than of rice husk. VM will affect the carbonization process. A high value of VM will form charcoal that is quickly burned but produces a lot of smoke, while the low value will result in hard burned charcoal but produces burned flammability. Sugarcane bagasse will be rapidly burned and make a lot of smoke compared to coconut shells, palm kernel shells, and rice husk. However, the bagasse VM contained CH_4 is used as reduction gas. The bagasse FC is 83% lower than coconut shells, 35% below the palm kernel shells, and 2% below the rice husk. Based on this finding, for the same condition, sugarcane bagasse will need more ratio in weight than coconut, palm kernel shells, and rice husk. In addition, the presence of CH_4 is consider as reducing gas to meet the process requirements.

Table 3. The Calculation for Carbon Requirement

Process [12]		**Reducing Agent Needed**			
CO for Hematite (Fe_2O_3) to Magnetite (Fe_3O_4)	mol	0.0145			
CO for Magnetite (Fe_3O_4) to Wustite (FeO)	mol	0,0292			
CO for Wustite (FeO) to Fe	mol	0,0876			
Total CO	mol	0,1313			
Total Carbon Required	mol	0.0656			
	gram	0.7872			
Total Carbon Required on 1000 ˚C (100%) [15]	gram	0.787			
Total Carbon Required on 700 ˚C (60%) [15]	gram	1.312			
Weight Ratio		**1:1**	**1:2**	**1:3**	**1:4**
Total Carbon Exsisted with 13.08% fixed Carbon	gram	1.44	2.09	2.75	2.88

Total carbon requirement based on calculation published by Soedarsono et. [17][17], as presented in Table 3, showed that the total required carbon at 700 ˚C and 1000 ˚C is 1.312 gram and 0.787 gram, respectively. The needs in weight ratio are presented in Table 2. Carbon content in 13.08% of fixed carbon for all weight ratios is greater than 10 to 265% of the needs. Based on this observation, the reduction will occur and be sufficient to complete the reaction.

Figure 1 depicts the result of the XRD analysis of the lump ore. The XRD spectrum shows that the ore contains hematite (Fe_2O_3) and magnetite (Fe_3O_4). In addition, other oxides appear as impurities, such as aluminum-iron oxide ($AlFeO_3$), nickel-titanium oxide $NiTiO_2$, and fayalite ($Fe_2(SiO_4)$). Magnetite and hematite have similar content of 26.32% based on their peak analysis.

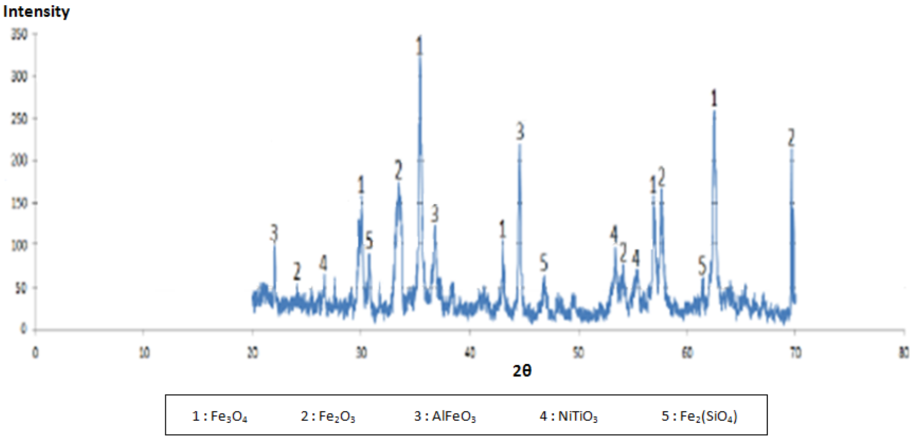

Figure 1. XRD Analysis for the Ores

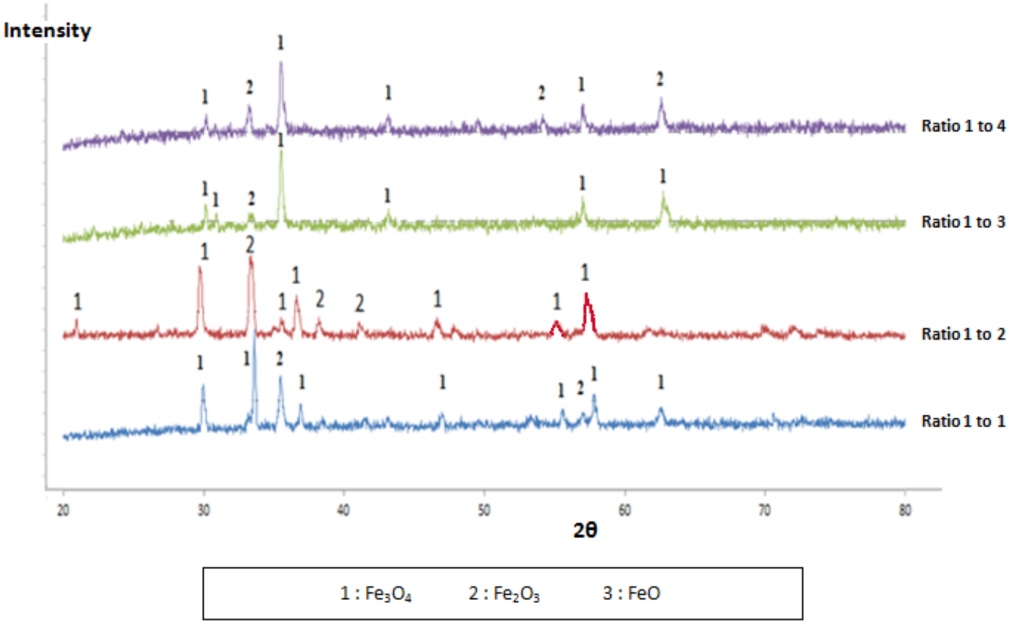

Figure 2. XRD Analysis in Reduction Process at 700OC for 30 minutes

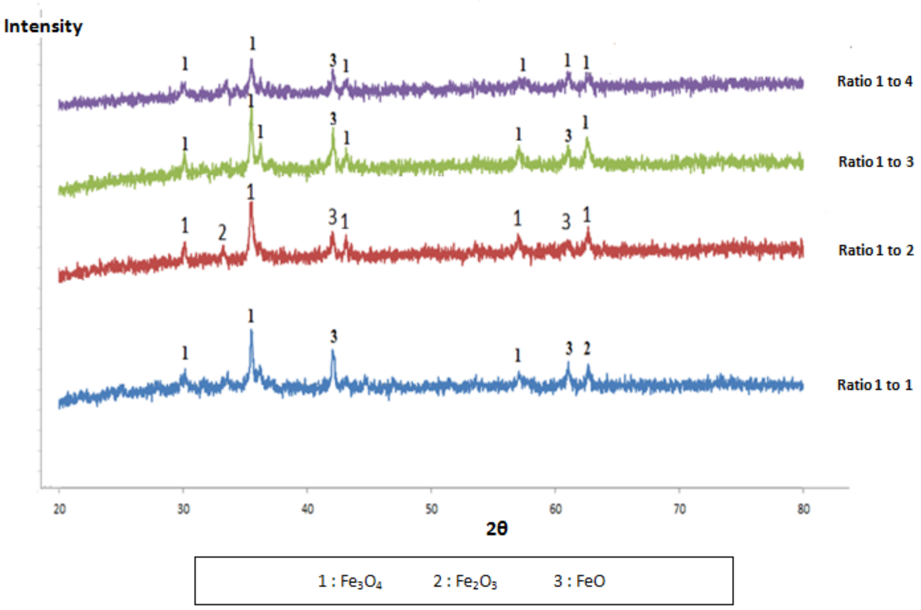

Figure 3. XRD Analysis in Reduction Process at 1000^{O}C for 30 minutes

Figure 2 shows the result of the XRD analysis during the reduction process at 700 °C. The weight ratios indicate the formation of hematite and magnetite. The formation of these compounds demonstrates that the reduction process has occurred. The level of intensity indicates the extent of the formation of the two phases. For magnetite, the highest intensity in the ore before the reduction process is 325 and after the process is 1800. In addition, hematite achieves the highest peak intensity before the process began is 225, whereas, after the process, the peak is slightly decreasing to 1400. The formation of magnetite indicates that the reduction process occurred and acted as a product in the first-stage process.

The number of peaks appearing in the XRD analysis represents the surface area. The greater the number, the larger the surface area. The larger the surface area has a pivotal correlation to the greater the amount of the formed magnetite phase. On this basis, the most significant magnetite formation, at 85%, occurred with a weight ratio of 1 to 3. Magnetite formation is given by the number of peaks for the other weight ratios. The resulting magnetite phase and their ratio are given in 78%, 70%, and 57% at 1:1, 1:2, and 1:4. Based on the result, the optimum ore of the bagasse weight ratio for the reduction process at 700 °C and 30 minutes is 1:3.

The results of the XRD analysis for the reduction process at 1000 °C indicate the presence of magnetite, wustite, and hematite, as shown in Fig. 3. Unlike the reduction process results at 700 °C, there is a difference in phases formation at each ratio. Magnetite, wustite, and hematite phases are formed at weight ratios of 1:1 and 1:2. For weight ratios of 1:3 and 1:4, however, only wustite and magnetite are formed. These results show that at weight ratios of 1:3 and 1:4, the second-stage reduction is completed. The highest intensities for wustite, magnetite, and hematite are 1700, 1700, and 1200. The highest wustite intensity is found at a weight ratio of 1:3. This pattern is the same as a result for the reduction process at 700 °C. Based on the number of peaks, wustite formation occurred to the extent of 33%, 25%, 37%, and 14% for weight ratios of 1:1, 1:2, 1:3, and 1:4, respectively. The corresponding values for magnetite are 50% for 1:1, 63% for 1:2, 63% for 1:3 and 86% for 1:4. As mentioned previously, hematite is only found at weight ratios of 1:1 and 1:2 with 17% and 12% content. Peak analysis compositions for weight ratios of 1:2 and 1:3 revealed that the weight of reduction required to complete the first-stage reduction at 1000 °C, three times the ore's weight required at 700 °C.

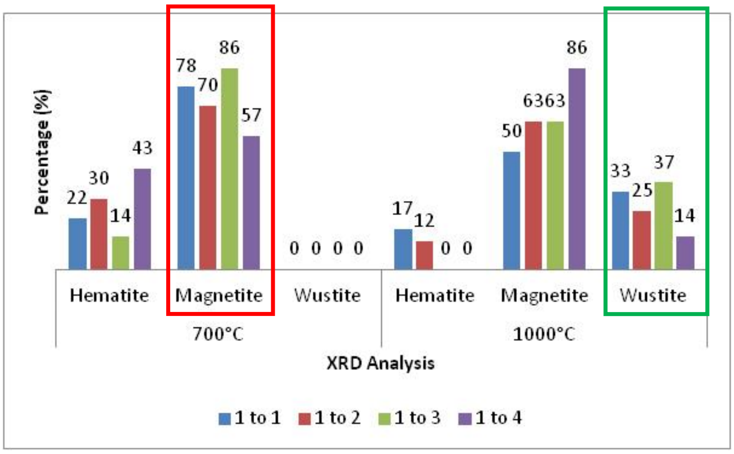

Figure 4. The percentage values for peak intensity in reduction process at 700 °C and 1000 °C

Figure 4 shows the pattern similarity by comparing the peak intensity values for the final product in each reduction process at their reduction temperature. Reductor weight gain is invariable with the final product of the reduction process. It confirms the presence of gases, which may have caused the reduction process to become an oxidation process. Hematite disappeared at the reduction temperature of 1000°C in a weight ratio of 1:3. In this circumstance, the amount of reducing agent is sufficient to complete the first stage of the reduction process.

In contrast, the same result is different at a reduction temperature of 700°C. The Glaessner–Boudouard diagram (Fig. 5) shows the sequential reduction process at 5000C to promote the formation of magnetite from hematite. The most satisfactory result of this process is the production of wustite from magnetite and iron from wustite. The entire sequence will be completed when the supply of reducing agents is sufficient. The Glaessner – Boudouard diagram also displays the relationship between temperature and the reducing agent's formation. The graph shows that the reduction process at 700°C will require more reducing agents than at 1000°C since at 700°C, only 60% of the carbon reacted to form carbon monoxide, whereas, at 1000°C, all of the carbon created carbon monoxide.

Based on the Ellingham Diagram, magnetite formation began at 290°C and wustite at 700°C, as shown in Fig.6. The reduction temperatures used in this process are all in the range of metallic iron formation, which is more than 500°C. As shown in Tabel 3, the carbon supplied exceeded the calculation of the carbon requirement. The reaction should be completed based on this data, and metallic iron is present at 700°C and 1000°C. However, metallic iron is not formed at either temperature or with any of the weight ratios. It is now understood that the possibility of the incomplete formation of CO plays an essential role in the absence of metallic iron. Also, the stability of CO itself is an essential driving factor in the formation of metallic iron. Because of this temperature, carbon monoxide tends to react with oxygen and forms carbon dioxide.

Moreover, this case has shown that wustite (FeO) is not formed at 700°C due to the instability of carbon monoxide formation. Higher temperature facilitates metallic iron formation, as shown at 1000°C and supported by the Ellingham Diagram.

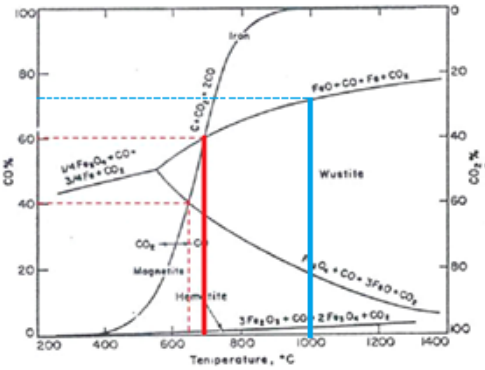

Figure 5. The Glaessner – Boudouard Diagram [22]

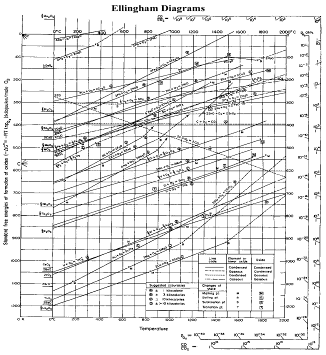

Figure 6. The Ellingham Diagram[23]

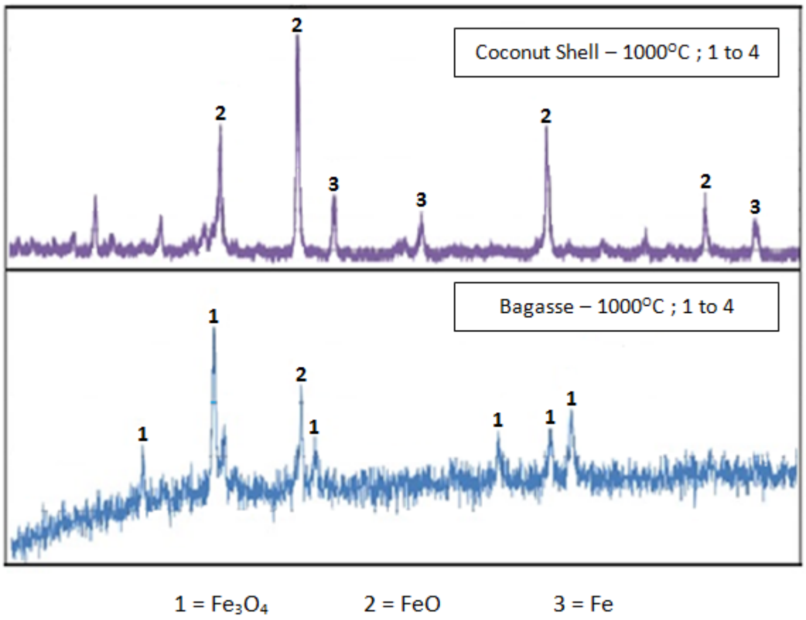

Figure 7. XRD analysis for reduction process with different reductors

The XRD result of the reduction process using coconut shell [16] showed the formation of metallic iron at a reduction temperature of 1000 °C with a 1:4 weight ratio. In contrast to earlier findings, however, a different result was obtained for bagasse. This fact is undoubtedly true in the case of a 1000 °C reduction temperature with a 1:4 weight ratio, the reaction gives magnetite and wustite formation. As mentioned previously, the process temperature and amount of carbon available fulfilled the requirements. Still, the reaction that occurred during the reduction process with bagasse was different from coconut shell. Bagasse supplied several types of gases that are essential sources of carbon monoxide. It also contained an amount of volatile matter that was 88% higher than for coconut shell, producing char. The XRD result showed that optimum wustite formation occurred at a weight ratio of 1:3. Based on all these data, the occurrence of oxidation was suspected to be the cause of the failure in the formation of metallic iron due to the excess of carbon from the oversupplied reducing agent.

Reduction of lump ore using sugarcane bagasse is different from lateritic nickel ore using palm kernel shell as a reducing agent at the same temperature and weight ratio parameter. The roasting temperature at 700 °C or 1000 °C gives the hematite of the lateritic nickel ore; however, the lump ore magnetite appears at 700 °C and wustite at 1000 °C [18], [19], [20]. Another advantage of this studies is to provide the optimum hematite content in lateritic nickel and lump ore. Based on our result, the weight proportion of 1:4 and 1:3 is suitable to meet the above requirement. These findings could be related to the effectiveness of sugarcane bagasse as a reducing agent compared to palm kernel shells.

In general view, the use of rice husk as a reducing agent for limonite ore [7] and iron sand [23] shows that the reduction process takes place until hematite is wholly trans-formed to magnetite. Meanwhile, the reduction process using sugarcane bagasse progresses the transformation to wustite. Based on this general observation, it may conclude that sugarcane bagasse is more effective than rice husk. Extensive investigations are needed to verify this claim due to the difference in product targets.

4. Conclusion

Bagasse has demonstrated its ability to sustain a reduction process. It retains the double-acting features to supply carbon and several gasses such as hydrogen and methane to quicken the reduction process. Our findings show that the capability of sugarcane bagasse as a reducing agent is comparable to the coconut shells and husk rice. The rank of reducing agent is given as follows: Coconut shells > Bagasse Sugarcane > Husk Rice. However, it requires more profound attention and research to verify the claim.

The initial stage of the sugarcane bagasse reduction process shows the optimum roasting temperature is 700 °C and gives the magnetite state. Meanwhile, the subsequent stage gives wustite formed with the maximum roasting temperature at 1000 °C. Although the variation of roasting temperature and the product in each step may differ, the pattern of products based on their weight ratio is similar. The most significant degree of magnetite formation, as well as of wustite formation, occurred at a weight ratio of 1:3. The absence of metallic iron was suspected to be due to an oxidation process.

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Declaration

The corresponding author, on behalf of all the authors, declare that there is no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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