Experimental Study on the Utilization of Bio-carbon Reductants in the Rotary Kiln-Electric Furnace for Ferronickel Production

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Abstract. Indonesia is committed to reducing its CO_2 emissions by 31.89% unconditionally by 2030, as reflected in its Enhanced Nationally Determined Contribution (NDC) reported in 2022. The mining sector, including nickel mining and smelting, contributes around 10% of global energy-related carbon emissions and must play a role in achieving this target. The RKEF (Rotary Kiln-Electric Furnace) process, which accounts for approximately 80% of global laterite nickel production, primarily for ferronickel or nickel pig iron, relies heavily on coal as a reductant and energy source. This study explores the use of biocarbon as a renewable alternative reductant. Laboratory-scale calcination and smelting experiments were conducted using laterite ore and four reductants: coal, palm shell charcoal, rubber wood charcoal, and mixed wood charcoal. All were characterized for proximate and ultimate composition, ash content, and bulk density. Rubber wood charcoal had the highest fixed carbon (73.2 wt%), while palm shell charcoal showed the highest ash content (9.40 wt.%). Nickel reduction ranged from 4.07 to 24.85%, with the highest reduction achieved using rubber wood charcoal. The results demonstrate that all tested bio-carbons are feasible substitutes for coal in the RKEF process, offering a pathway to decarbonize nickel production in support of Indonesia's NDC goals.

1 Introduction

Climate change represents one of the most significant challenges confronting the global community in the present era. The UN Climate Change Conference (COP21), held in Paris, France, in 2015, resulted in the adoption of the Paris Agreement, which aims to limit the rise in global average temperatures to below 2 °C, and preferably to 1.5 °C, relative to pre-industrial levels [1]. This agreement has been ratified by 195 nations, including Indonesia. Achieving the Paris Agreement's targets requires commitment from all sectors, including the nickel processing industry, to reduced greenhouse gas emissions.

In 2016, Indonesia officially ratified the Paris Agreement through Law No. 16 of 2016 concerning the Ratification of the Paris Agreement to the United Nations Framework Convention on Climate Change. The country has pledged to cut greenhouse gas emissions by 29% by 2030, as outlined in Indonesia's Nationally Determined Contribution (NDC) [2]. In alignment with Indonesia's NDC goals, PT Vale Indonesia has pledged to decrease its greenhouse gas emissions by 33% by 2030 (compared to 2017 levels) and to reach net-zero emissions by 2050 [3].

The metallurgical industry, including nickel ore processing, is one of the major contributors to global CO_2 emissions. Mining and metal processing contribute about 8 – 10% of current global greenhouse gas emissions, while the nickel mining and processing industry itself contributes around 0.27% of global greenhouse gas emissions [4]. However, the contribution of nickel processing to greenhouse gas emissions is likely to increase, given that nickel is essential for the clean energy transition, both as a cathode material in electric vehicles and in other clean technologies. Schodde and Guj (2025) state that nickel demand will rise from 3 Mt in 2024 to 5.6 Mt in 2030 to meet the demand for electric vehicles and the clean energy transition (Fig. 1) [5].

Indonesia possesses approximately 42% of the global nickel reserves and, in 2023, accounted for 40% of the world's primary nickel output in the form of ferronickel and nickel matte [6]. In tandem with the anticipated rise in worldwide nickel demand, Indonesia's nickel production expanded from 440 kt in 2013 to 1.8 million tons in 2023 [5]. This production increase has correspondingly driven an increase in greenhouse gas emissions, climbing from 9.8 million tons CO_2e in 2013 to 170.2 million tons CO_2e in 2023,

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representing roughly 21% of the emissions originating from the energy and industrial processes (IPPU) sector [7]. PT Vale Indonesia processes saprolite-type laterite ore into nickel matte using a modified RKEF technology with sulfur addition at the end of the calcination process in the reduction kiln [8]. In the nickel ore smelting process, PT Vale Indonesia uses four main energy sources: hydropower, marine fuel oil (MFO), coal, and diesel oil. With hydropower, PT Vale Indonesia can suppress greenhouse gas intensity to 28.7 tCO_2/tNi, far below similar industries in Indonesia, which range from 56 – 69 tCO_2/tNi.

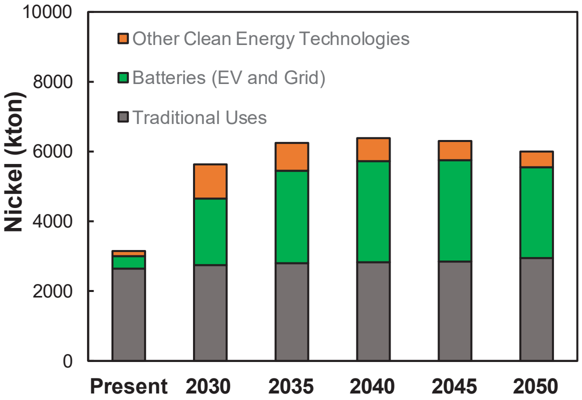

Fig. 1. Global surge in nickel demand under the net-zero emission scenario [5].

Coal is one of the largest energy sources in PT Vale Indonesia's RKEF process, contributing about 31% of total energy consumption or 43% of non-renewable energy consumption. Approximately 68% of coal is used as fuel for dryers and kilns, with the remaining 32% is used as a reductant. Regarding emissions from fossil fuel use, various studies and initiatives have been conducted, including waste heat recovery, biodiesel use, and process optimization. However, emissions from coal as a reductant have received relatively little attention to date. Given its significant contribution to coal usage at PT Vale Indonesia, environmentally friendly alternatives are needed to support company's climate targets. One alternative reductant is biomass and biochar [9-12]. This aligns with Indonesia's decarbonization roadmap, which positions bio-reductants as one of eight policy directions for realizing a low-carbon nickel industry [7].

The purpose of this research is to find environmentally friendly alternative reductant candidates to replace coal. This study examines various types of biocarbon to assess their potential as alternative reductants to coal in nickel laterite smelting, particularly in the RKEF process.

2 Materials and Methods

The materials used in this research were laterite ore, coal, palm kernel shell charcoal, rubber wood charcoal, mixed wood charcoal, and briquette charcoal. The equipment used included X-ray Fluorescence (XRF), X- ray Diffraction (XRD), Scanning Electron Microscope-Energy Dispersive Spectroscopy (SEM-EDS), Scanning Electron Microscope-Bulk Mineral Analysis (SEM-BMA), and LECO-C analyzer.

Samples, including both ore and reductants, were prepared at a particle size of -65 mesh for characterization. Nickel saprolite ore and reductants were sampled using the coning and quartering method to ensure representativeness. All samples were dried in an oven at 115 °C for 3.5 hours to determine moisture content. The dried samples were then ground using a ball mill for homogenization. Ore was characterized using XRF, XRD, and SEM-BMA to determine its chemical composition and mineralogical information, while reductants were characterized by proximate, ultimate, and ash analyses.

2.1 Characterization of Nickel Laterite Ore

The dried saprolite ore was analyzed for chemical composition and mineralogy. XRF results indicated a nickel content of 1.68 wt%, cobalt at 0.07 wt%, Fe_2O_3 at 30.77 wt%, SiO_2 at 36.46 wt%, MgO at 15.50 wt%, and loss on ignition (LOI) at 9.39 wt%. The Fe/Ni ratio was 12.8, and the SiO_2/MgO ratio was 2.35, consistent with saprolite-type laterite suitable for pyrometallurgical processing.

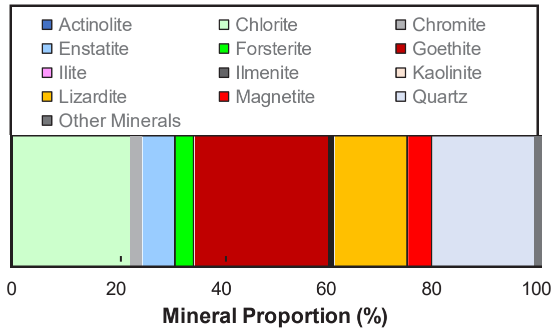

Fig. 2. Mineral proportion in laterite ore sample obtained from SEM-BMA technique.

Mineralogical analysis via SEM-BMA, cross-checked by XRD, in Fig. 2 revealed major phases including goethite, quartz, lizardite, chlorite, and forsterite. SEM-BMA result showed chlorite interlocked with goethite and quartz, enstatite with chlorite and lizardite, and goethite with chlorite and magnetite.

2.2 Characterization of Reductants

Proximate analysis (air-dried basis, adb) highlighted significant differences among reductants (Fig. 3). Rubber wood charcoal exhibited the highest fixed carbon (73.2 wt%). Ash content was highest in palm kernel shell charcoal (9.40 wt%) and lowest in coal (4.62 wt%). Volatile matter ranged from 16.20 wt% (rubber wood) to 41.07 wt% (coal), with moisture varied from 4.56 wt% (rubber wood) and 7.62 wt% (coal). Total sulfur was low across all samples (<0.28 wt%).

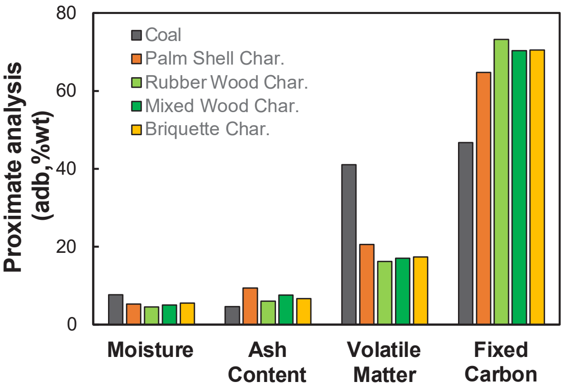

Fig. 3. Proximate analysis of reductants.

Ultimate analysis (adb) shown in Table 1 confirmed high carbon in rubber wood charcoal (73.0 wt%). H/C ratios indicated higher reactivity for bio-carbons (0.04) compared to coal (0.08), while O/C ratios suggested lower oxygen interference in bio-carbons (0.23 – 0.26) relative to coal (0.34). Ash composition was dominated by SiO_2 (52.27 – 59.94 wt% in coal, palm kernel shell charcoal, and briquettes charcoal), except for rubber wood, which was rich in MgO (38.45 wt%).

Table 1. Ultimate analysis results of reductants (adb, wt%).

Sample	H/C	O/C
Coal	0.08	0.34
Palm Shell Char.	0.05	0.26
Rubber Wood Char.	0.04	0.23
Mixed Wood Char.	0.04	0.26
Briquette Char.	0.04	0.25

2.3 Calcination and Smelting Tests

Calcination tests were conducted at the laboratory scale by placing mixtures of dried ore (40 g) and various reductants in Al_2O_3 crucibles, which were then inserted into a horizontal furnace (Fig. 4(a)). The mixtures were heated from room temperature to 950 °C at a rate of 10 °C/min, held at 950 °C for 4 hours, and cooled naturally to room temperature under an inert argon atmosphere flowing at 1 L/min.

Smelting tests were carried out using 2 g of samples placed in MgO crucibles which were heated in a vertical furnace (Fig. 4(b)) to 1550 °C, held for 2 hours, and quenched in water under an argon atmosphere at 1 L/min. Carbon content was varied at 1.51% and 3.02% relative to dry ore. For 1.51% carbon content, tests included both calcinations followed by smelting and direct ore smelting (without calcination). For 3.02% carbon content, only direct ore smelting was conducted (Table 2). The 1.51% carbon content dosage (relative to dry ore weight) was selected to align with PT Vale Indonesia's current operational practice and flowsheet description. While a doubled dosage (3.02% carbon content) was implemented for direct smelting trials to evaluate the system under high-reductant conditions.

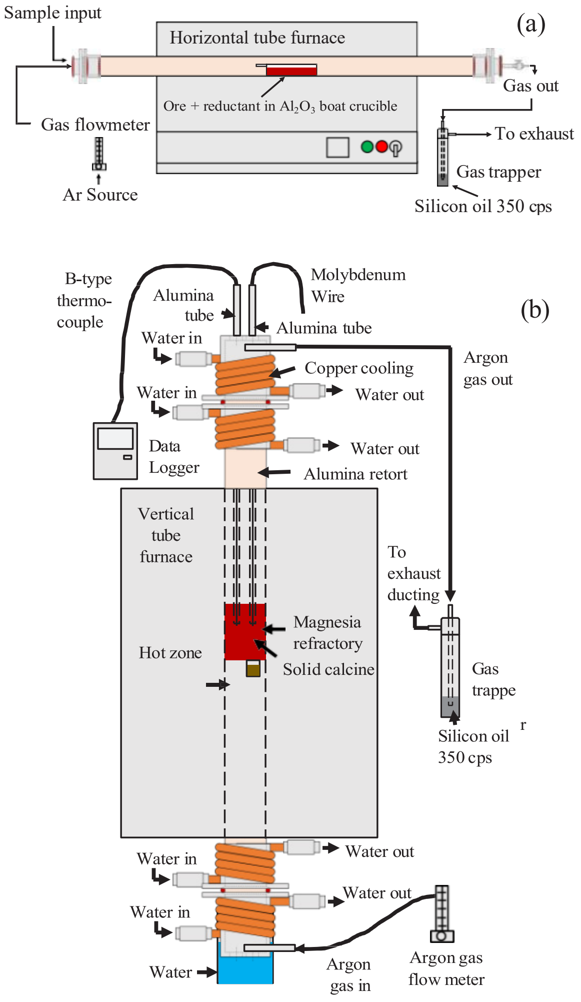

Fig. 4. (a) Horizontal furnace for calcination test. (b) Vertical furnace for smelting test.

Table 2. Experimental Variations: Pre-treatment, Reductant Type, and Dosage.

Pre-treatment	Reductant Type	Target C/Ore Ratio
Variation 1: Calcination + Smelting		
Pre-treatment	**Reductant Type**	**Target C/Ore Ratio**
Calcination (950 °C)	Coal	1.51%
Calcination (950 °C)	Palm Shell Charcoal	1.51%
Calcination (950 °C)	Rubber Wood Charcoal	1.51%
Calcination (950 °C)	Mixed Wood Charcoal	1.51%
Calcination (950 °C)	Charcoal Briquette	1.51%
Variation 2: Direct Smelting (Direct Smelting - Baseline)		
Pre-treatment	**Reductant Type**	**Target C/Ore Ratio**
No Calcination	Coal	1.51%
No Calcination	Palm Shell Charcoal	1.51%
No Calcination	Rubber Wood Charcoal	1.51%
No Calcination	Mixed Wood Charcoal	1.51%
No Calcination	Charcoal Briquette	1.51%
Variation 3: Effect of Excess Reductant (Double Carbon Dosage)		
Pre-treatment	**Reductant Type**	**Target C/Ore Ratio**
No Calcination	Coal	3.02%
No Calcination	Palm Shell Charcoal	3.02%
No Calcination	Rubber Wood Charcoal	3.02%
No Calcination	Mixed Wood Charcoal	3.02%
No Calcination	Charcoal Briquette	3.02%

Calcines were analyzed using XRF for composition determination, LECO-C for residual carbon, the bromine-methanol method for Fe/Ni metal content, and SEM-BMA and XRD for phase identification. Smelting products were embedded in resin, cross-sectioned, polished, and analyzed using SEM-EDS.

3 Results

The laboratory experiments yielded detailed insights into the performance of bio-carbons as reductants compared to coal. Key findings from ore and reductant characterizations, calcination, and smelting are presented below, based on data from XRF, XRD, SEM-EDS, SEM-BMA, LECO-C, and bromine–methanol analysis.

3.1 Calcination Outcomes

Calcination at 950 °C for 4 hours resulted in weight losses of 16.30 – 17.96 wt%, with highest in coal (17.66 wt% average) due to greater volatile release, and the lowest in mixed wood charcoal (16.44 wt%). XRF of calcines showed Ni enrichment (1.89 – 1.97 wt%) due to LOI loss, with SiO_2/MgO and Fe/Ni ratios remained stable. Residual carbon (LECO-C) ranged from 1.03 to 1.47 wt%, with coal calcines highest at 1.44 wt%, indicating 10 ~ 38% carbon reaction with ore.

Fig. 5 presents the extent of nickel and iron reduction in calcines, as determined using the bromine- methanol method. The results indicate that nickel reduction varied significantly depending on the type of reductant. Rubber wood charcoal achieved the highest degree of nickel reduction, whereas briquette charcoal exhibited the lowest. In contrast, the extent of iron reduction remained relatively consistent across all reductants.

SEM analysis revealed dominant mineral phases such as fayalite, forsterite, and quartz, with metallic including iron and taenite (Fig. 6). XRD confirmed consistent phase proportions across reductants, with taenite at 6.0 – 6.2 wt%.

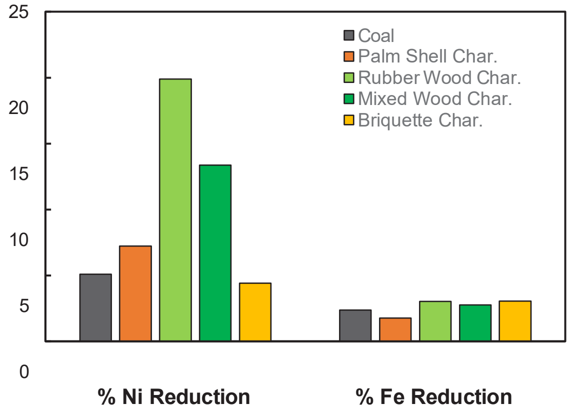

Fig. 5. Nickel and iron reduction extents in calcines from experiments at holding temperature of 950 °C for 4 hours measured by bromine–methanol method. Note: %Ni Reduction = 100% × Ni as metal / (Ni as metal + Ni as oxide) and %Fe Reduction = 100% × Fe as metal / (Fe as metal + Fe as oxide).

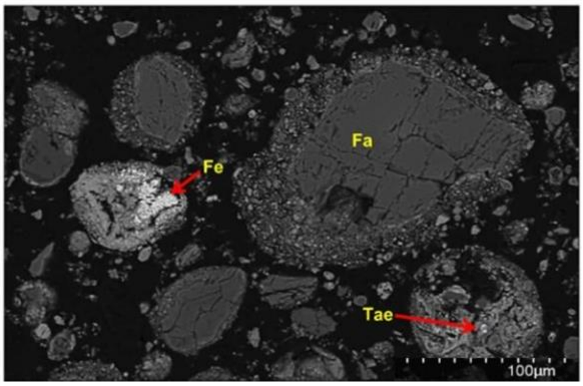

Fig. 6. Example of calcine + coal SEM-BMA mineralogy analysis (Tae = Taenite, Fa = Fayalite, Fe = Iron).

3.2 Smelting Outcomes

Smelting at 1550 °C for 2 hours produced distinct metal and slag phases as shown in Fig. 7. Fig. 8 presents nickel and iron content in the smelting products. For calcined samples with 1.51% carbon, metal Ni content in the smelting products ranged from 80.12 to 90.01 wt% (highest with rubber wood charcoal at 90.01 wt%), with Fe at 5 – 15 wt%. Direct ore smelting at 1.51% carbon yielded similar results (Ni: 79.5 – 89.8 wt%). At 3.02% carbon (direct ore smelting), Ni dropped to 10.13 – 20.68 wt%, with Fe increased to 66.47 – 84.65 wt%, indicating a phenomenon of over-reduction of iron oxide into metallic iron.

Slag compositions, measured using SEM-EDS over wide-area of samples, revealed SiO_2 content at 40 – 45 wt%, MgO 15 – 20 wt%, with Ni recovery rates of 85 – 95% Ni to metal. Microstructures (Fig. 7) revealed dendritic slag in non-quenched areas, while element mapping confirming Ni concentration in metal phases and Fe distribution between slag and metal as shown in Fig. 9.

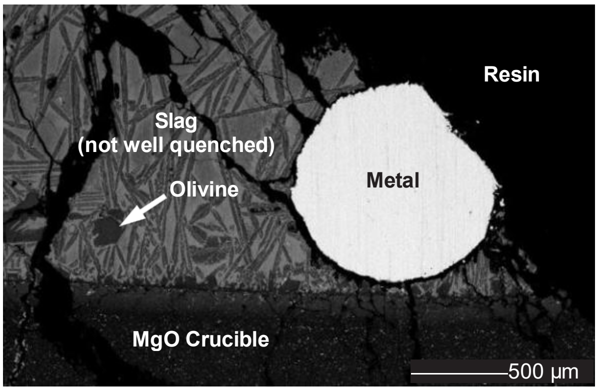

Fig. 7. Example of secondary electron image of calcine with 1.51% carbon addition using briquette charcoal reductant after smelting at 1550 °C for 2 hours.

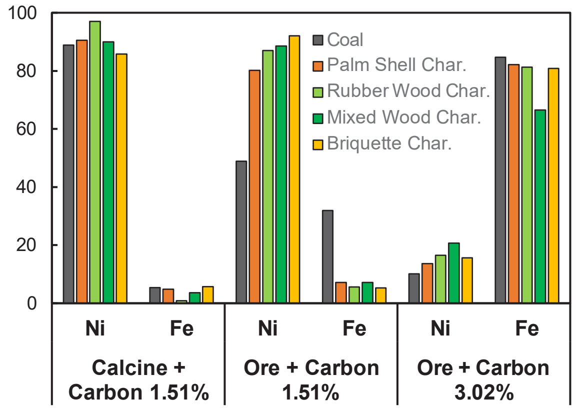

Fig. 8. Nickel and iron contents in metals in calcine/ore with various carbon additions after smelting at 1550 °C for 2 hours.

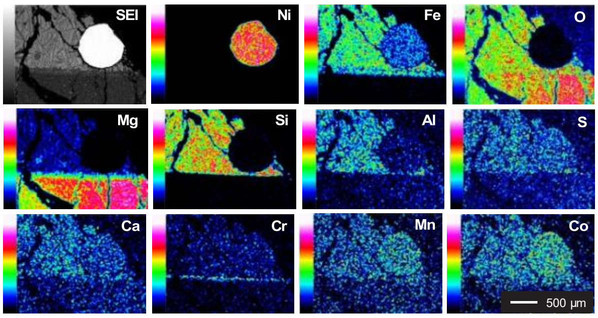

Fig. 9. Example of elemental mapping of calcine with 1.51% carbon addition using briquette charcoal reductant after smelting at 1550 °C for 2 hours.

4 Discussion

The laboratory-scale results provide strong evidence that bio-carbons can serve as effective alternatives to coal in nickel laterite processing, with direct implications for decarbonization in Indonesia's RKEF- based industry. Among the reductants tested, rubber wood charcoal consistently outperformed other reductants, achieving the highest nickel reduction (up to 24.85%) and the greatest metal Ni content (90.01 wt% in calcined smelting at 1.51% carbon). This superior performance is attributed to its high fixed carbon content (73.20 wt%) and low H/C ratio (0.04). The low H/C ratio indicates a carbon structure with minimal volatile matter, ensuring that the reductant remains thermally stable and physically present as solid carbon when the ore reaches the calcination temperature (950 °C). This facilitates efficient solid-state reduction of nickel oxide prior to smelting. In contrast, coal with lower fixed carbon (46.69 wt%) and higher volatile matter (41.07 wt%) showed greater weight loss (17.66 wt% average) but much lower Ni reductions (4.64 – 5.53%), consistent with previous reports of coal's inefficiencies in high-temperature processes [13].

Smelting outcomes further highlight the advantages of bio-carbons. At 1.51% carbon addition, all bio-carbons reductants produced high-Ni content in metals (80.12 – 90.01 wt%) with Ni recovery rates of 85 – 95%, 5 – 10% higher than coal. This improvement is likely due to stronger carbon-ore interactions with controlled over-reduction of iron (5 – 15 wt% Fe in slag vs. coal's higher Fe in slag).

When carbon input was increased to 3.02%, over-reduction occurred, with Fe content in metal rising to 66.47 – 84.65 wt% and Ni content in metal decreasing to 10.13 – 20.68 wt%, consistent with Hambali and Rivai (2017) [15], who reported that excessive carbon promotes nickel dilution in ferronickel.

These results align with broader findings in the literature on bio-carbon in metallurgy. For instance, Sommerfeld and Friedrich (2021) reported that bio-carbons can significantly reduce CO_2 emissions (by ~10 kg CO_2eq/kg product) owing to their near-neutral carbon cycle, in contrast with coal's fossil carbon [7]. In nickel processing, Sari et al. (2024) observed emission reductions of 18.67% and carbon savings of 19.7%, when substituting coal with bio-carbons. These results are corroborated by the present study, where residual carbon data (1.03 – 1.47 wt%) indicating efficient utilization [14]. The extent of nickel and iron reduction in calcines further confirms that bio-carbons can achieve comparable or superior metallurgical performance to coal, suggesting potential integration into existing RKEF operations without requiring substantial modifications.

Nonetheless, challenges remain. Variability in bio-carbon composition, for example the elevated MgO in rubber wood ash (38.45 wt%), could alter slag chemistry, potentially increasing viscosity or affecting refractory performance. Moreover, their lower density and higher reactivity may necessitate feedstock blending or adjustments to kiln operation [15]. At the industrial scale, supply chain sustainability will be critical. Indonesia's biomass potential-such as an estimated 8.4 Mt/year of palm kernel shells [14], supports large-scale use, but carful management is required to avoid risks such as deforestation [12]. Life cycle assessments indicate that full substitution with bio-carbons could reduce emissions by 15 – 20% per ton of Ni, directly supporting PT Vale Indonesia's net-zero commitments and Indonesia's NDC targets [11]. Future pilot-scale trials should therefore address both economic viability and long-term furnace performance implications of bio-carbon adoption.

In conclusion, the results underscore the potential of bio-carbons in decarbonizing nickel production, offering both technical validation for PT Vale Indonesia's RKEF process optimization and broader contributions to global clean energy transitions.

5 Conclusion

Laboratory experiments have confirmed that bio-carbons derived from palm kernel shell charcoal, rubber wood charcoal, mixed wood charcoal, and briquette charcoal can serve as effective substitutes for coal in processing nickel laterite ores through the RKEF method. These materials achieved comparable or even superior nickel recovery rates (up to 95%) while supporting decarbonization efforts, consistent with Indonesia's NDC and PT Vale Indonesia's net-zero emission targets. Future research should focus on scaling up these trials and assessing their economic feasibility.

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