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# Kiln-Furnace System: Validation of a Technology for Producing Charcoal with Less Environmental Impact in Brazil

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**Abstract:** Brazil is the world's largest producer of charcoal. Therefore, there is need for improvement in the gravimetric yield of conversion and the reduction of gas emissions, including greenhouse gases (GHGs), released during carbonization. The objective was to apply the methodology of Measurement, Reporting and Verification (MRV) to evaluate the emission of GHG, mainly $CO_2$ and $CH_4$. The charcoal production kiln-furnace system used was composed of 4 kilns with a capacity of ~6 t of wood, each. The MRV cluster of coal gravimetric yield and gas burners were used to determine the gravimetric yield and burner efficiency and thus evaluate the emission of GHGs generated in the carbonization system. The carbonization was performed in an isolated way producing, in total, 3.34 t of charcoal, with an average gravimetric yield of 25.82%. The MRV methodology was effective for evaluating the GHG emissions. The wood burner reduced by 50% the methane burning and provided a reduction of 0.392 $tCO_2$ eq (23.91%). The humidity of wood and high precipitation were the main limiting factors in this research, and responsible for the decrease in the gravimetric yield. The kiln-furnace system was effective for a sustainable production with the use of non-continuous carbonization gas burners.

**Keywords:** greenhouse gas reduction—GHG; burners; energy input; forest biomass; sustainability



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## 1. Introduction

Anthropic activities have been causing an excessive increase in the emissions of Greenhouse Gases—GHG in the atmosphere, which has contributed to intensifying climate change [1]. According to the Intergovernmental Panel on Climate Change—IPCC [1], the average temperature of the planet has already increased by 1.0 °C compared to the pre-industrial period, and the projection is for a rise of 1.5 °C between the years 2030 and 2052, in case GHG emissions continue to increase. Obstacles faced in assessing GHG emissions include the complexity and costs associated with collecting accurate data, the lack of standardization in measurement and reporting methods, and the need to consider various sources of emissions, in addition, the limited availability of historical data and the variability in emission factors also pose significant challenges [1,2].

In this context, the steel sector is responsible for approximately 7% of $CO_2$ emissions worldwide [2]. More than 80% of the emissions of the steel sector result from the use of energy inputs, such as charcoal, coal, and coke [3]. In contrast, Brazil stands out on the world stage for its use of renewable sources for energy supply, with 46.1% of Brazilian internal supply coming from renewable sources [4]. According to Brazil's Energy Balance, in 2019 biomass accounted for 31.9% of the internal energy supply; with firewood and charcoal accounting for 8.7% of the total [4]. In addition, Brazil is the world's largest producer of charcoal (~ 6 million t), a renewable energy input and indispensable to the pig iron, alloy iron, and steel sectors [4], aimed at reducing greenhouse gas emissions.

In Brazil, 30% of the steel industries use charcoal as a reducer [5]. It is important to emphasize that in Brazil, charcoal is mostly produced from the wood of planted forests, especially of the *Eucalyptus* genus [5,6]. An important aspect of charcoal is its renewable character that favors the reduction of GHGs generated along the production chain of pig iron, alloy iron, and steel, compared to the use of coke [7]. The Brazilian steel industry is the only one in the world that uses charcoal in the production processes of pig iron and steel, which positions the country as the main producer of charcoal [6].

Minas Gerais is the main consumption and production hub of charcoal in the country, due to the state's steelmaking vocation [6]. For decades, investment in planted forests has facilitated and enabled the advancement and improvements in the charcoal production chain, which this state has the largest planted area [5,7]. Furthermore, during the development of forests planted for charcoal production, $CO_2$ capture occurs, which contributes positively to the final carbon balance of the steelmaking process [8,9]. Another environmental benefit of using charcoal as a thermal reducer is the low emission of sulfur oxides unlike what occurs in coke steelmaking [10].

Despite the advantages presented in the use of charcoal and the potential for growth of its production in Brazil and the World, some aspects related to its production need to be improved and/or developed to ensure production sustainability and greater competitiveness in the market and in the context of the low carbon economy [11,12].

Thus, to invest in new technologies in charcoal production processes to supply, mainly, to the steel sector, focusing on the reduction of emissions and higher gravimetric yield in charcoal, the United Nations Development Programme—UNDP, with the support of the Ministry of Environment (MMA) and the Global Environment Facility (GEF), implemented the project Sustainable Steelmaking—UNDP [13]. The project aims to establish a low-carbon economy in the production of charcoal from planted forests by encouraging more efficient innovative processes and technologies [13].

The project developed the methodology of Measurement, Reporting and Verification—MRV based on the methodologies of the Clean Development Mechanism—CDM [14,15]. The objective is to assess the reduction of GHG emissions in the carbonization process and increase the gravimetric yield in coal in the kiln-furnace system developed by the Federal University of Viçosa—UFV [13]. The MRV methodology is a set of processes in which the information provided is evaluated to monitor and track the performance of emissions reductions [15]. The "MRV system" refers to any official institutions or processes, through which regulated parties measure, report, and verify their emissions and their mitigation actions for the environment [16–19].

Considering the relevance of charcoal as an energy input, much research has been conducted to evaluate the best *Eucalyptus* genetic materials to improve the productivity and quality of the bio reducer [20]. Other studies focus on the analysis of thermal effects on charcoal production [21], and the environmental benefits of carbonization gas burners [7]. However, the validation of the kiln-furnace system to meet the demands of small and medium producers needs to be effectively carried out. Therefore, technical, and scientific actions need to be encouraged for the continuous improvement of the charcoal production chain in Brazil.

Although there are patents related to the use of carbonization gases [11,12], specific efforts are needed to expand the application of these technologies by small and medium charcoal producers. Based on this context, the objective of this research was to apply the

MRV methodology to assess GHG emissions, in the demonstrative unit of sustainable charcoal production, which uses the kiln-furnace system.

## 2. Background of the Previous Studies

Brazil is the world's biggest charcoal producer and, unfortunately, most charcoal works do not have alternatives for reducing atmospheric pollution. About 70% of Brazilian charcoal production is carried out in production models with low levels of technology and mechanization, with inefficient controls of the carbonization parameters generating low production capacity and high emission of pollutant gases, in addition to social and economic impacts [5].

Within a context that seeks the sustainability of charcoal production, production improvements have been developed and implemented in recent years, seeking an adjustment in relation to the technology of the kilns, monitoring of the carbonization process, and emission of pollutant gases. An important environmental initiative is the Normative Deliberation (DN 227/2018) Publisher: State Council of Environmental Policy (COPAM), Belo Horizonte, Minas Gerais, Brazil, which aims to establish normative guidelines for charcoal production to reduce atmospheric emissions from the process.

Another important initiative is the development of technologies such as the kiln-furnace system, developed by the Feral University of Viçosa, and the Sustainable Steelmaking Project, which is based on the concepts of the Sustainable Development Goals (SDGs), aims to provide a technological basis, human training, and commercial production units to foster the use of a sustainable charcoal production model, has represented a major advance for the sustainability of the sector [13,22].

Producers of charcoal have adopted the burning of carbonization gases using a furnace coupled to the kilns thus reducing the emissions of gases generated during wood carbonization. According to [22], the use of a coupled burner in carbonization plants can mean, depending on the type of combustion chamber, a reduction of up to 80% of the methane produced in the process. The use of the kiln-furnace system has presented a technical and environmental gain, due to the higher gravimetric yield, lower wood consumption, and the low emission of pollutant gases during wood carbonization. In addition, there is financial gain; according to [22], the kiln-furnace system presents greater economic viability compared to hot-tail kilns, generating greater profit in charcoal production.

## 3. Materials and Methods

### *3.1. Study Area, Description of the Kiln-Furnace System, and Wood Carbonization Process*

The experiment was conducted in the Demonstrative Unit of Sustainable Charcoal Production, Figure 1, near the Campus of the Federal University of São João del-Rei/UFSJ/CSL Municipality of Sete Lagoas, Minas Gerais, Brazil. It is characterized as part of the Sustainable Steelmaking project, edict No. JOF-1069/2019—"Incentive to the sustainable production of charcoal from planted forests", in partnership with Antônio Ernesto de Salvo Institute/INAES and with the support of the team of the Laboratory of Panels and Wood Energy, linked to the Department of Forest Engineering of the Federal University of Viçosa/LAPEM/DEF/UFV.

The kiln-furnace system, Figure 2, consists of four circular surface kilns with a volumetric capacity of approximately 14.24 "estereo" st or 9.5 $m^3$ of wood each kiln and or up to 5 t of dry mass. The kilns were connected by ducts assigned to "butterfly" valves that conducted and controlled the gases generated during the wood carbonization process to the furnace. During the combustion of gases, the combustion chamber temperatures of the furnace ranged from 600 °C to 800 °C. These temperatures can promote the combustion of the pollutant gases generated by the carbonization process and minimize the emissions of methane, carbon monoxide, and condensable gases [23,24].

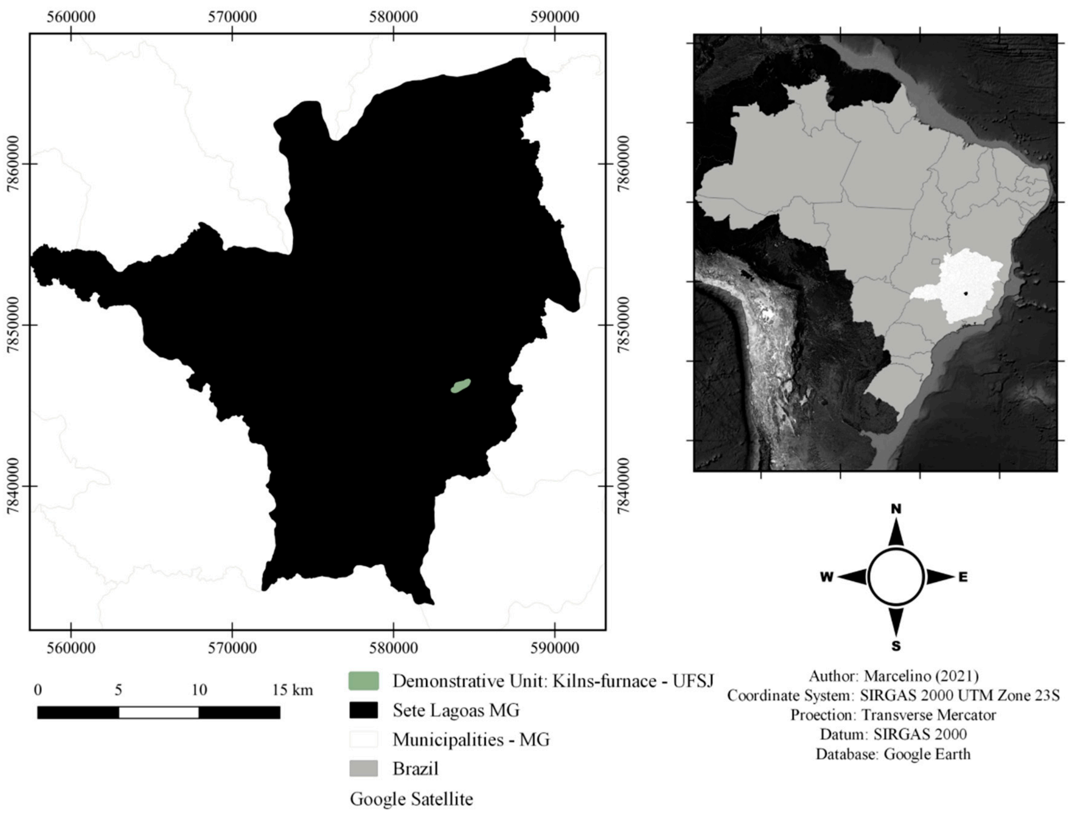


**Figure 1.** Location of the UFSJ campus, where the demonstration unit of the straw oven system for charcoal production is located. Source: Authors (2021).


**Figure 2.** *Cont*.

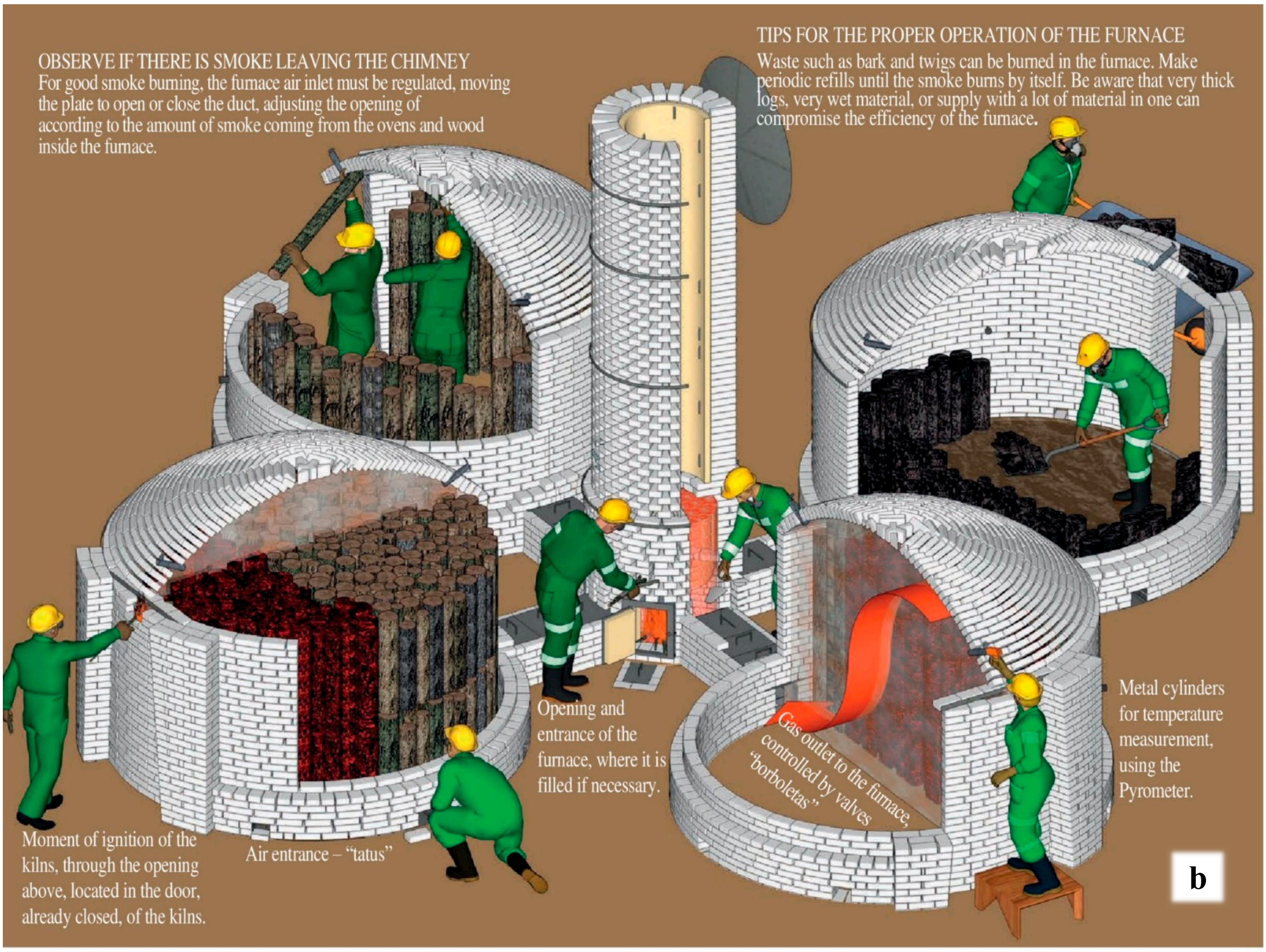


**Figure 2.** (**a**) Kiln-furnace system representation of the four kilns (1–4) present in our carbonization methodology (**b**) Kiln-furnace system and representation of the oven-to-furnace production system and its main components, and main observations regarding the operation. (**b**) Source: Authors (2021), adapted from [23,24].

All the stages of the construction of the kiln-furnace system as well as the technical specifications are as available in the Construction Manual of Kiln-Furnace System [23]. Clones of the *Eucalyptus* sp. genus from two regions were used, a commercial plantation of clone I144, seven years old, located in the Municipality of Paraopeba, Minas Gerais; and clones of *Eucalyptus* sp. and *Corymbia* sp. from the UFSJ/CSL Campus with approximately 30 years old. The wood was hung with a length of 1 m, density ranging from 544 to 550 kg $m^{-3}$, average moisture content of 53.21%, and diameter from 6 to 26 cm. For better quality and control of the operation of the whole process, the information, and technical methodologies available in the Kiln-Furnace System Operation Manual established by the Programme were considered [24], as a guarantee of the quality of the wood and charcoal obtained.

The wood from *Eucalyptus* sp. and *Corymbia* sp., collected at the UFSJ campus, was burned in kiln 1, while the wood from clone I144 was burned in kilns 2 and 3. Kiln 4 (Figure 2a) was not used due to restrictions of on-site activities at UFSJ, because of the beginning of the COVID-19 pandemic. During carbonization, the furnace was periodically filled (bark and wood waste) until the gases generated in carbonization were able to maintain combustion inside (Figure 2b). Three carbonizations were carried out in an isolated way, thus the furnace and burner operated in a non-continuous way, due to the intense rainy period during all the carbonizations during the months of December

2019 to March 2020. The control of the entire process was carried out by controlling the temperatures using the infrared temperature sensor (pyrometer).

After opening the oven door, the produced charcoal, as well as the fines and semi-carbonized wood were weighed and arranged on a tarpaulin to avoid contact with soil humidity and contamination. The gravimetric yield of carbonization was determined by dividing the total mass of dry charcoal obtained by the dry mass of hanging wood.

### *3.2. Application of the MRV Methodology for the Assessment of the Kiln-Furnace System*

The application of the MRV methodology to evaluate the kiln-furnace system occurred as elaborated by [22,25,26], composed of mitigation clusters of gravimetric yield, gas burner clusters, and heat exchanger clusters, according to Figure 3. Two scenarios based on the reduction of greenhouse gas emissions were considered: one from the use of activity that allows the increase in gravimetric yield, and another that considers the flaring system of gases emitted in the wood carbonization process.

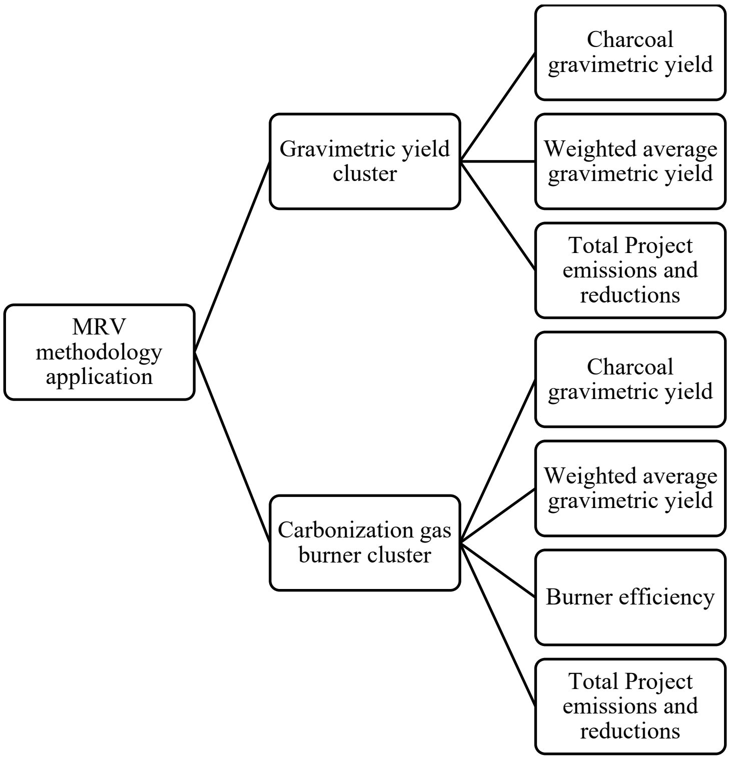


**Figure 3.** Flowchart of the steps in applying the MRV methodology.

Among the three possible clusters in the MRV methodology, the system implemented in the present work used the clusters of gravimetric yield and gas burner because the system implemented did not acquire the heat exchange cluster, and the carbonization occurred in an isolated way, the furnace was presented as a non-continuous burner.

### *3.3. MRV Cluster—Gravimetric Yield of Charcoal*

The cluster based on gravimetric yield considered the mitigation activity based on technological and process innovation in charcoal production, which reduces methane ($CH_4$) emissions and increases the gravimetric yield known as the ratio of the mass of charcoal produced by the dry mass of wood used.

To estimate the GHG emissions from the kiln-furnace system arising from the gravimetric efficiency of the system, the following equations were applied, obtained from the methodologies [27,28].

$$PEy = EF_{CH4,BP} \times GWP_{CH4} \times P_{charcoal,\, y} \quad (1)$$

$$EF_{CH4,BP} = (A - B \times Y_{P,i}) \quad (2)$$

where:

**PE**$_Y$ = Project emissions in year y ($tCO_2$/year);

**EF**$_{CH4,BP}$ = Methane emission factor in the implemented system ($tCH_4$/t charcoal);

**GWP**$_{CH4}$ = Global warming potential of methane ($tCO_2e/tCH_4$);

**P**$_{charcoal,y}$ = Charcoal production during year y (t charcoal/year);

**Y**$_{P,i}$ = Weighted average of the gravimetric yield of carbonization of the kilns (tons of charcoal/tons of wood/dry basis);

**A, B** = adjusted parameters of the regression equation that expresses the statistical relationship between methane emissions and carbonization gravimetric yield.

### 3.4. MRV Cluster—Carbonization Gas Burners

The cluster based on the burning system assumed the mitigation activity with the installation of kilns for the degradation of methane ($CH_4$), regardless of the value of the gravimetric yield. If there is a difference between the gravimetric yield in the baseline and the project activity, the gravimetric yield cluster must be used.

The efficiency of each type of burner was verified by means of the methodology [29]. In the system implemented, the burner was characterized as non-continuous due to the isolated carbonization of each kiln, considering the efficiency of the burner with 50% reduction of methane gas, according to the methodology ACM0001 of CDM, described and standardized by [30].

Estimate and process the burner cluster data, Equations (3) and (4) determined by the standard baseline definition methodology [27,28] were used.

$$PEy = EF_{CH4,P} \times GWP_{CH4} \times P_{charcoal,y} \times \left[\frac{B_{total,y} - B_{qual,b,y} - B_{qual,c,y}}{B_{total,y}} + \frac{B_{qual,b,y}}{B_{tatal,y}} \times \left(1 - \eta_{PJ,c}\right)\right] \quad (3)$$

$$EF_{CH4,BP} = (A - B \times Y_{P,i}) \quad (4)$$

where:

**PE**$_Y$ = Project emissions in year y ($tCO_2$/year);

**EF**$_{CH4,BP}$ = methane emission factor in the implemented system ($tCH_4$/t charcoal);

**GWP**$_{CH4}$ = Global warming potential of methane ($tCO_2e/tCH_4$);

**P**$_{charcoal,y}$ = Charcoal production during year y (t charcoal/year);

**Y**$_{P,i}$ = Weighted average of gravimetric yield of charcoal kiln carbonization (tons charcoal/tons wood/dry base);

**A, B** = Parameters of the regression equation expressing the statistical relationship between methane emissions and carbonization gravimetric yield.

**B**$_{total,y}$ = Total number of "furnaces" operated by the project during the year (carbonization cycle);

**B**$_{qual,b,y}$ = Number of " furnaces" which passed through the burner in a non-continuous way. If there is no non-continuous operation, the number of "furnaces" = 0;

**B**$_{total,c,y}$ = Number of furnaces that passed through the burner continuously. If there is no continuous operation, the number of "furnaces" = 0;

$\eta_{PJ,b}$ = Methane destruction efficiency by the burner in non-continuous operation = 50%;

$\eta_{PJ,c}$ = Efficiency of methane destruction by the burner in continuous operations = 80%.

## 4. Results

### 4.1. Characterization of the Wood and Charcoal Obtained from Carbonization

The results indicate that the gravimetric yield values obtained were low for kilns 2 and 3 (Table 1). This may be associated with the high moisture content of the wood, which increases the energy demand to remove the water present in the load. The highest gravimetric yield was observed for kiln 1, contributing to the average gravimetric yield, which was 25.82%.

**Table 1.** Characteristics of the wood and charcoal obtained from the kiln-furnace system, for the studied kilns.

| Carbonization | Wood | | Charcoal | | Gravimetric Yield Yp,i (%) | Wood Moisture b. s. (%) | Log Diameter (cm) |
|---|---|---|---|---|---|---|---|
| | Wet Mass (t) | Dry Mass (t) | Wet Mass (t) | Dry Mass (t) | | | |
| 1 | 6.357 | 4.846 | 1.737 | 1.644 | 33.92 | 31.17 | 16.5 |
| 2 | 6.311 | 3.863 | 1.033 | 0.972 | 25.17 | 63.37 | 9.51 |
| 3 | 6.457 | 3.911 | 0.863 | 0.719 | 18.38 | 65.09 | 9.91 |
| Average | 19.125 | 12.621 | 3.633 | 3.335 | - | - | - |

This same carbonization, despite the higher gravimetric yield, had logs with larger diameters, on average 16.5 cm, resulting in 45.5 kg of fines and 57.5 kg of semi-carbonized wood. Kilns 2 and 3 had average diameters varying between 9.51 and 9.91 cm, producing 50.5 and 65.9 kg of fines and 70.8 and 58.7 kg of semi-carbonized wood, respectively. This shows the negative impact of moisture content and diameter on carbonization, implying the use of wood with lower moisture content.

### *4.2. MRV Cluster—Gravimetric Yield of Charcoal—Reviews*

For the cluster of Gravimetric Yield of the MRV methodology acquired through the carbonizations of kilns 1, 2, and 3 of the kiln-furnace system, the results are shown in Table 2. With a total production of 3.335 t of charcoal, the straw-furnace system implemented at UFSJ/CSL achieved an average gravimetric yield of charcoal of 18.38%, considering the mitigation activity.

**Table 2.** Emissions data from the demonstration unit (kiln-furnaces) and the baseline for the dry-base gravimetric yield cluster.

| Parameters | Unit | Project (Kiln Furnace System) |
|---|---|---|
| Sum of Coal Production of All PCUs (Pcharcoal,y) | t | 3.335 |
| Gravimetric Yield (Yp) | % | 18.38 |
| Emission Factor | $tCH_4$/t Charcoal | 0.1188 |
| Total Emission | t $CO_{2e}$ | 8.323 |
| Total Emission Reduction | t $CO_{2e}$ | −2.855 |
| Emissions per Tonne | t $CO_{2e/t}$ Charcoal | 2.495 |
| Emissions Reduction | t $CO_{2e/t}$ Charcoal | −0.855 |

According to MRV methodology data, the standard deviation was 7.83% and the coefficient of variation was 30.33%. Thus, due to the weighted average of this technique, the lower limit for gravimetric yield was considered to avoid extrapolation error, being the average gravimetric yield of 18.38%.

The emission factor was 0.1188 $tCH_4$/tCoal produced. Thus, it is possible to relate the methane emission and the gravimetric yield of carbonization, as they are inversely proportional according to the methodology [28] used. The total emissions of the implemented production system were 8.32 t of total charcoal.

### *4.3. MRV Cluster—Gas Burning System*

The use of the gas burning system during the wood carbonization process for charcoal production provided GHG reductions (Table 3).

**Table 3.** Emissions data from the demonstration unit (kiln-furnaces) and the baseline for the cluster of burners.

| Parameters | | Unit | Project (Kiln-Furnace System) |
|---|---|---|---|
| Sum of Coal Production of All PCUs | (Pcharcoal,y) | t | 3.338 |
| Gravimetric yield | (YP) | % | 18.38 |
| Emission Factor | | $tCH_4$/t Charcoal | 0.1188 |
| gas burning Efficiency | | % | 50.00 |
| Methane Undestroyed | | % | 50.00 |
| Total Emission | | t $CO_{2e}$ | 4.162 |
| Total Emission Reduction | | t $CO_{2e}$ | 1.307 |
| Emissions per Ton | | t $CO_{2e/t}$ Charcoal | 1.247 |
| Emissions Reduction | | t $CO_{2e/t}$ Charcoal | 0.392 |

For the non-continuous gas-burning system we observed an emission factor of 0.1188 $tCH_4$/t coal and a reduction of 50% of $CH_4$ resulting in 0.397 $tCH_4$ to produce 3.338 t of charcoal. The emission factor of $CH_4$ was considered high if, compared with the carbonization without the burning of gases, a reduction factor of 0.078 $tCH_4$/tCoal was obtained. For the $CO_2$ emission reduction values, compared with carbonization without burning and with burning of the gases, a reduction of 23.91% of $CO_2$eq was observed. The value of $CO_2$ reduction acquired was considered low.

## 5. Discussion

The chemical and physical properties of wood and the conditions of the carbonization process are important variables for obtaining higher charcoal yields, which corroborates the great impact of moisture on gravimetric yield. However, the kiln-furnace systems are presented as an alternative of great technical, economic, and social feasibility for charcoal production, when evaluating and considering the realities of small producers [22,31].

In addition, the chemical and physical properties of the wood, as well as the conditions of climatological variables, such as relative humidity of the air, average temperature, wind speed, and high rates of precipitation, exposed and imposed by the whole carbonization process are important variables for obtaining a good gravimetric yield in charcoal in carbonization, especially from forest biomasses [20,32,33]. The yield values found are directly related to these factors.

High moisture content was observed in the wood used. The moisture of the hanging material influenced the low gravimetric yield of kilns 2 and 3, which caused a greater combustion of part of the woody material to remove water from the wood, thus also influencing the increase in emissions. An experiment on the impact of wood humidity on production and charcoal quality, carried out by [34], proved that the charcoal yield decreases with the use of *Eucalyptus* sp. woods with high humidity, and recommended the use of woods with humidity levels lower than 20% (dry basis). Added to this are the recommendations for good practices for charcoal production in the Normative Deliberation 227 [35], which suggests, for carbonization purposes, the use of wood with a moisture content below 40%.

However, the diameter of the wood did not directly influence the gravimetric yield of charcoal, when observing the average values of the wood in each kiln. In that, woods of larger diameter need a longer time in relation to woods of smaller diameters (fine) for the conversion into charcoal, due to the need for more time for heat transfer, which contributes to the formation of steel and ash decreasing in gravimetric yield [36,37]. Thus, under the conditions of this study, moisture was the most important physical factor to be observed, where the high water content in the wood used in kilns 2 and 3 led to a significant reduction in gravimetric yield and charcoal productivity.

The control of carbonization temperature is an important factor that influences the gravimetric yield and the quality of the produced charcoal. Due to the climatic conditions of heavy rainfall and the absence of measurements in nocturnal periods was crucial to obtain these results, which were limiting factors for the implementation and obtaining better results. The studies conducted by [38], found average coal yield results of 26.4% for carbonization without temperature control and 33.2% with temperature control. This emphasises the importance of monitoring at all stages of carbonization and its impact on the gravimetric yield and quality of the charcoal produced.

The high water content present in wood significantly influenced the thermal degradation process of wood, reducing the gravimetric yield and intensifying the emission of gases [39–41]. High moisture contents of wood contribute to the emission of a higher amount of GHGs during carbonization [34,39]. The MRV method used in this study allowed the identification of an inversely proportional relationship between methane emission and the gravimetric yield of charcoal. Due to these factors, the value of $CO_2$ reduction acquired was considered low, since better results have been found in the literature [31,42–45].

The burning of the gases from wood carbonization, besides considerably reducing the visual aspect and the toxic effect of the emission, reduces the emission of harmful gases to the environment, such as GHGs with great global warming potential [44,46]. The reduction of methane in charcoal production provides an environmentally friendly addition to the project, making it eligible for CDM classification [47,48]. Furthermore, the increase in $CO_2$ levels resulting from the combustion reaction can be absorbed by the *Eucalyptus* sp. Forest plantations that promote carbon sequestration and storage, releasing $O_2$ into the atmosphere, and generating a positive equilibrium in the balance of emissions [4–6].

Considering this, the performance of a CDM project is considered advantageous if the anthropically generated GHG emissions are lower or if the carbon sequestration is higher than it would be in the absence of the project [49,50]. It is worth noting that, for this to become possible, the government of the country where the projects occur must agree that the project activity is voluntary and contributes to national sustainable development [51].

Furthermore, most Brazilian charcoal production is carried out in production models characterized by low levels of technology and mechanization, which influence charcoal production and yield [43,52]. Thus, efforts aimed at productive improvements for small and medium charcoal producers have been developed and implemented, as has this research, to improve adequacy in relation to the proposed technology.

However, the Federal Universities, as well as the Institutes of Technical Education have a fundamental role in this horizon of change in charcoal production mainly for independent charcoal producers, located outside the private industrial environment [52,53]. The development of technologies aimed at producing charcoal with low pollutant emissions and maximizing the gravimetric yield has represented a major advance for the sustainability of the sector, mainly to meet the demands of the central mesoregion of Minas Gerais.

The MRV methodology offers significant advantages by providing a structured framework for collecting, reporting, and verifying emissions, ensuring transparency and consistency in the results. In addition, it allows for the identification of areas for improvement, evaluation of performance over time and comparison with pre-established standards, facilitating the implementation of effective mitigation measures. As far as research is concerned, the use of the MRV methodology in the assessment of emissions from the furnace-oven system was crucial in indicating new routes for charcoal production prospects, especially for rural producers, and new routes for future research in the sector.

*Limitations, Prospects, and Political Implications of This Study*

The carbonization technology evaluated in this research has demonstrated the possibility of charcoal production from biomass from renewable sources, associated with lower environmental impacts. Substantial improvements in $CO_{2eq}$ reduction were observed in the carbonization of *Eucalyptus* wood in the kiln-furnace system and when compared to the conventional production model. Despite the lack of consolidated technologies for burning carbonization gases, the kiln-furnace system stands out as a pioneer in the development of gas burning systems for small and medium-sized producers and can be adapted to certain existing layouts.

The research comprises actions of the Sustainable Steel Industry Project ("Projeto Siderurgia Sustentável" in Portuguese) funded by the United Nations Development Programme and collaborates directly to meet national and international policies aimed at reducing the impact of greenhouse gas emissions associated with power generation and energy products [13].

The criteria or standards for achieving a green and sustainable economy in charcoal production go beyond the value of emissions. They encompass a series of environmental, social, and economic aspects that must be considered in an integrated manner. This includes the adoption of sustainable forest management practices, the use of clean and efficient technologies in production processes, the promotion of social equity and workers' rights, as well as the monitoring and mitigation of greenhouse gas emissions. In addition, it is essential to guarantee the conservation of biodiversity, the protection of water and soil resources, and respect for local communities and indigenous peoples affected by the activity.

The search for a green and sustainable economy in charcoal production requires a holistic and integrated approach that considers not only environmental impacts but also social and economic aspects. The definition and implementation of rigorous and comprehensive criteria, together with the adoption of innovative practices and technologies, are essential to ensure that charcoal production contributes to the transition to a more sustainable development model that is resilient to climate change.

The development of technologies to mitigate emissions from the conversion of wood into charcoal contributes to the fulfillment of the actions set out in Law No. 12187 of 29 December 2009 establishing the National Policy on Climate Change—PNMC and the Sustainable Development Goals. It is important to highlight the commitments made by Brazil in the United Nations Framework Convention on Climate Change and the Kyoto Protocol. Furthermore, this research aims to contribute to the requirements of the COPAM DN n°227/2018, which aims to improve specific normative guidelines for the activity of charcoal production from planted forests (mainly from the *Eucalyptus* genus), and its co-products and derivatives, regarding its installation, operation, and atmospheric emissions. This normative deliberation is specific to the State of Minas Gerais, the largest charcoal and pig iron producer in Brazil.

For rural producers, innovation in charcoal production through the kiln-furnace system represents an opportunity to achieve new perspectives on sustainability. This approach offers a more efficient and environmentally responsible way of producing charcoal, reducing the negative impact on the environment, and promoting more sustainable practices. By adopting this innovation, rural producers can improve the energy efficiency of their processes, reduce the waste of natural resources, and mitigate adverse effects on biodiversity. In addition, this new technique can provide economic benefits, such as reducing production costs and opening new markets for sustainable products. Ultimately, the adoption of kiln-furnace systems represents a promising opportunity for rural producers to improve the sustainability of their operations and contribute to a greener, more balanced future.

In addition to this, the difficulty reported and the intensity of rain throughout the process was also one of the main reasons for obtaining these results, since the burner/furnace suffered some interruptions, requiring its reignition, which caused interference in the burning of gases during carbonization. Moreover, the fact of it being the first carbonization of the system used also influenced the results, because it was recommended to meet the demands and deadlines, which coincided with these rainy periods and high humidity of the air.

However, it is essential that the wood used as raw material for the furnaces-furnace system has lower water contents (humidity below 40%), as stressed by DN n°227/2018, and adequate chemical characteristics and basic density allied to the required objective. The humidity of the hanging wood was an extremely important factor in reducing the gravimetric yield of charcoal. Therefore, the results of this study show that there is a need for wood quality control and the application of more efficient carbonization technologies to maximize the productivity of masonry kilns. Thus, environmental, economic, and social benefits may be obtained to achieve an increasingly green and sustainable economy.

## 6. Conclusions

The MRV methodology developed by the Sustainable Steelmaking Project has been shown to be efficient and appropriate for evaluating the emission of GHGs generated in the carbonization process when the kiln-furnace system is used. However, the humidity of the hanging wood and the associated climatic conditions are primordial factors for alterations in the gravimetric yield of the charcoal. In addition, the humidity intensifies the emission of GHGs identified in the methane emission factor in the charcoal produced, which corroborates and strengthens the use of COPAM Normative Deliberation No. 227.

The kiln-furnace system reduced the emission of $CH_4$ and $CO_2$ with the use of non-continuous gas burning systems, which makes them extremely efficient from the point of view of sustainability to obtain a green economy, besides being indicated as suitable for small and medium charcoal producers. However, to have effective control of the carbonization process it is necessary to consider the season of the year and the properties of the hanged wood when aiming to reduce GHG emissions into the atmosphere.

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