LIFE CYCLE ASSESSMENT OF RICE HUSK-BASED ELECTRICITY GENERATION IN A THERMAL POWER PLANT

AVALIAÇÃO DO CICLO DE VIDA DA GERAÇÃO DE ELETRICIDADE A PARTIR DE CASCA DE ARROZ EM UMA USINA TERMELÉTRICA

EVALUACIÓN DEL CICLO DE VIDA DE LA GENERACIÓN DE ELECTRICIDAD A PARTIR DE CÁSCARA DE ARROZ EN UNA CENTRAL TERMOELÉCTRICA

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ABSTRACT
The present study assessed the carbon footprint of electricity generation from rice husk in a thermal power plant located in São Sepé, Rio Grande do Sul, Brazil. For this purpose, the Life Cycle Assessment (LCA) methodology was applied in accordance with ISO 14040/14044 standards, using the OpenLCA software and the Ecoinvent 3.6 database. The functional unit considered was 1 kWh of electricity produced, covering the stages of rice cultivation and processing, biomass transportation, power plant operation, and ash disposal. The results indicated a carbon footprint of 0.036 kg CO_2 eq/kWh, with emissions associated with biomass and ash transportation accounting for more than 80% of the total. Compared with other energy sources, rice husk-based electricity generation demonstrated better environmental performance than coal and natural gas, standing out as a low-impact renewable alternative. The analysis also revealed that mitigation opportunities are mainly concentrated in transportation logistics and in the local valorization of ashes as an agricultural soil amendment.

Keywords: Biomass. Rice Husk. Thermal Power Plant. Carbon Footprint. Life Cycle Assessment.

RESUMO
O presente estudo avaliou a pegada de carbono da geração de eletricidade a partir da casca de arroz em uma usina termelétrica localizada em São Sepé, Rio Grande do Sul, Brasil. Para isso, foi aplicada a metodologia de Avaliação do Ciclo de Vida (ACV), de acordo com as normas ISO 14040/14044, utilizando o software OpenLCA e a base de dados Ecoinvent 3.6. A unidade funcional considerada foi 1 kWh de eletricidade produzida, abrangendo as etapas de cultivo e beneficiamento do arroz, transporte da biomassa, operação da usina e

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disposição das cinzas. Os resultados indicaram uma pegada de carbono de 0,036 kg CO_2 eq/kWh, sendo que as emissões associadas ao transporte da biomassa e das cinzas representaram mais de 80% do total. Em comparação com outras fontes de energia, a geração de eletricidade a partir da casca de arroz apresentou melhor desempenho ambiental do que o carvão mineral e o gás natural, destacando-se como uma alternativa renovável de baixo impacto. A análise também revelou que as principais oportunidades de mitigação concentram-se na logística de transporte e na valorização local das cinzas como corretivo agrícola do solo.

Palavras-chave: Biomassa. Casca de Arroz. Usina Termelétrica. Pegada de Carbono. Avaliação do Ciclo de Vida.

RESUMEN

El presente estudio evaluó la huella de carbono de la generación de electricidad a partir de la cáscara de arroz en una central termoeléctrica ubicada en São Sepé, Rio Grande do Sul, Brasil. Para ello, se aplicó la metodología de Evaluación del Ciclo de Vida (ECV), de acuerdo con las normas ISO 14040/14044, utilizando el software OpenLCA y la base de datos Ecoinvent 3.6. La unidad funcional considerada fue 1 kWh de electricidad producida, abarcando las etapas de cultivo y procesamiento del arroz, transporte de la biomasa, operación de la central y disposición de las cenizas. Los resultados indicaron una huella de carbono de 0,036 kg CO_2 eq/kWh, siendo que las emisiones asociadas al transporte de la biomasa y de las cenizas representaron más del 80% del total. En comparación con otras fuentes de energía, la generación eléctrica a partir de la cáscara de arroz mostró un mejor desempeño ambiental que el carbón y el gas natural, destacándose como una alternativa renovable de bajo impacto. El análisis también reveló que las principales oportunidades de mitigación se concentran en la logística de transporte y en la valorización local de las cenizas como enmienda agrícola del suelo.

Palabras clave: Biomasa. Cáscara de Arroz. Central Termoeléctrica. Huella de Carbono. Evaluación del Ciclo de Vida.

1 INTRODUCTION

Brazil stands out as a global leader in conventional renewable energy generation, with hydropower accounting for 51.97% of the country's electricity production (ANEEL, 2025). Despite its recognized low level of greenhouse gas emissions, the high dependence on this source exposes the electricity sector to significant vulnerability in the face of recurrent drought events (BONDARIK et al., 2018). In this context, diversifying the energy mix through the incorporation of other renewable sources emerges as a necessary strategy.

Among the available alternatives, biomass holds a prominent position due to its wide availability resulting from agricultural, agro-industrial, and forestry activities in the country (SANTOS et al., 2017). The most commonly used residues for energy generation include firewood, charcoal, sugarcane bagasse, wood residues, and rice husk (REZENDE, 2018). The latter represents about 20% of the weight of the processed grain and, due to its low nutritional value and high silica content, it is unsuitable for animal feed or direct agricultural use (CHUNGSANGUNSIT et al., 2010; ALMEIDA, 2010). However, it presents high calorific value, making it a promising alternative for use in thermal power plants.

Rice production in Brazil is concentrated in five states, with Rio Grande do Sul accounting for the majority share (70.7%), followed by Santa Catarina (10.2%), Tocantins (6.1%), Mato Grosso (3.6%), and Maranhão (1.5%) (MAPA, 2021). Milling, usually carried out near cultivation areas, generates rice husk as a by-product (MURARO et al., 2018). Currently, around 15 thermal power plants use this residue as fuel, totaling 59.46 MWh of installed capacity, 10 of which are located in Rio Grande do Sul, accounting for 50.14 MWh (SIGA, 2025).

Although rice husk-based thermal power generation has lower environmental impacts compared to fossil sources, it is not free from externalities. A comprehensive analysis of these effects requires the application of consolidated methodologies such as Life Cycle Assessment (LCA), as established by ISO 14040, which enables the measurement of environmental impacts throughout all stages of a product's or process's life cycle.

Considering the scarcity of specific studies in Brazil, this work aims to build an inventory and evaluate the carbon footprint of the life cycle of electricity generation in a rice husk-fired thermal power plant located in the central region of Rio Grande do Sul.

2 METHODOLOGY

In this study, a life cycle inventory of electricity generation from rice husk was developed based on primary data from the São Sepé Thermal Power Plant, which has an installed capacity of 8.0 MWh and stands out as the second largest operating unit in this segment in Brazil. In addition, the carbon footprint of electricity production was calculated using the Life Cycle Assessment (LCA) methodology, in accordance with ISO 14040/14044 guidelines (ISO, 2006a).

LCA, structured in the stages of goal and scope definition, inventory analysis, impact assessment, and interpretation, enables the quantification of environmental impacts associated with the analyzed system. For the modeling, the OpenLCA software was employed, together with the Ecoinvent 3.6 database, internationally recognized for the comprehensiveness of its datasets and available impact assessment methods (OPENLCA, 2025).

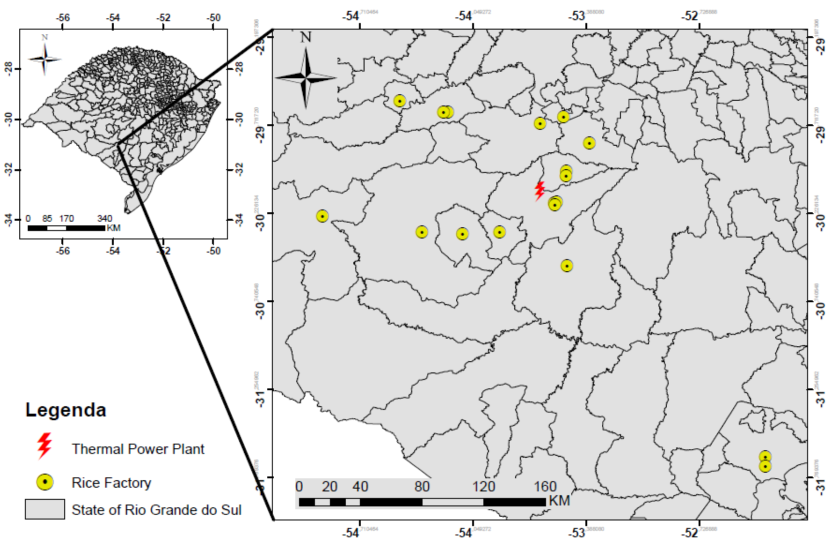
2.1 FUNCTIONAL UNIT, SCENARIO, AND SYSTEM BOUNDARY

This study is based on the use of rice husk, a by-product of grain milling, as a renewable energy source in a thermal power plant. The analyzed facility is located in the municipality of São Sepé, in the central region of Rio Grande do Sul, approximately 281 km from Porto Alegre, and receives biomass from around 13 local milling industries, with the possibility of including suppliers from other regions depending on availability.

The modeling considered a cradle-to-gate system boundary, encompassing the stages of rice cultivation and milling, husk transportation, and electricity generation in the thermal power plant. The adopted functional unit was 1.0 kWh of electricity produced. Figures 1 and 2 show, respectively, the geographical location of the power plant and the flowchart of the stages included in the analysis.

Figure 1

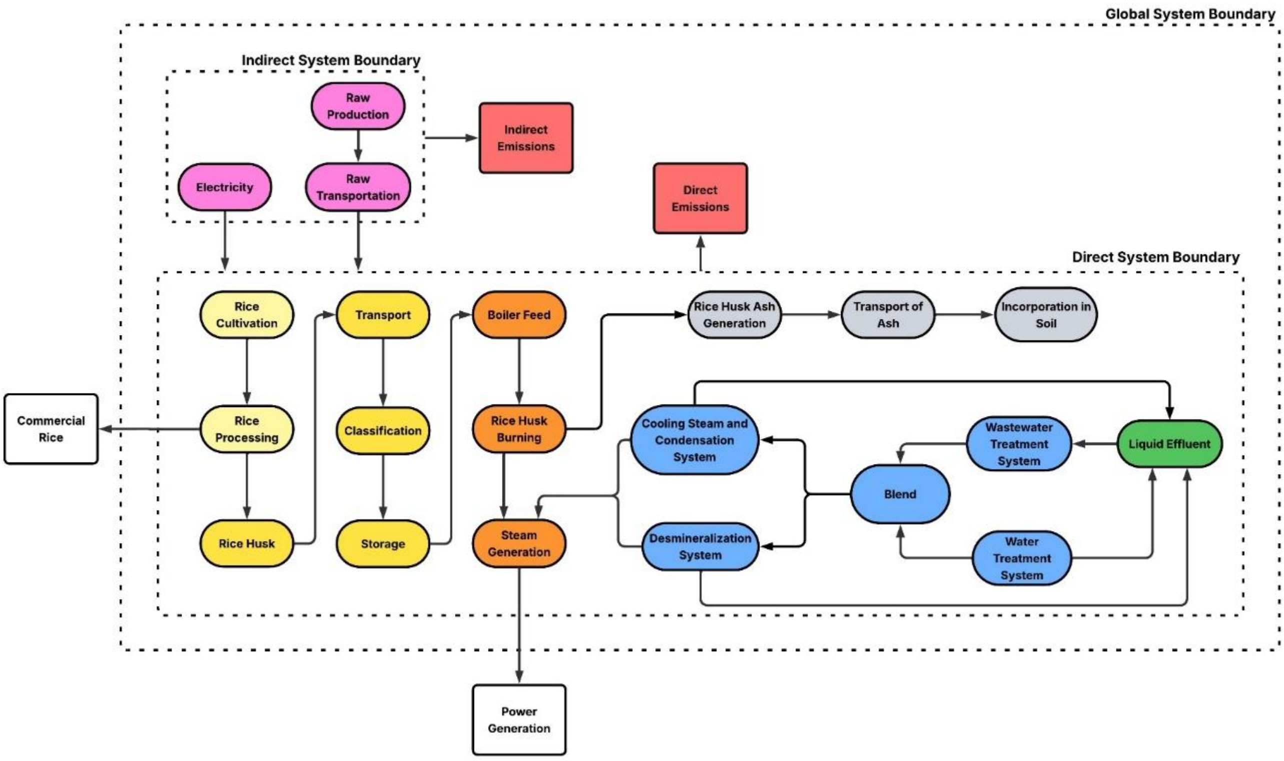
Location map of the thermal power plant



Source: Author.

Figure 2

Flowchart of processes and system boundaries



Source: Author.

To estimate the environmental impacts of energy generation from rice husk combustion, the IPCC 2021 methodology was applied in the OpenLCA software, using the Ecoinvent database. This method, based on the Sixth Assessment Report of the IPCC (AR6), provides updated greenhouse gas (GHG) metrics for the calculation of different impact categories (OPENLCA, 2022). For this study, emissions related to the 100-year Global Warming Potential (GWP100) were considered, expressed in kg of CO_2 equivalent.

2.2 IMPACT ALLOCATION METHOD

Since rice processing generates other products in addition to husk, such as white rice, broken rice, and bran, it was necessary to allocate the environmental impact associated with the husk (MAYER, 2009). This allocation was based on the economic value of the products, as adopted in LCA studies of rice production (COLTRO et al., 2017; DA SILVA, 2021).

2.3 SYSTEM DESCRIPTION, INVENTORY, AND DATA COLLECTION

The life cycle inventory of electricity generation from rice husk was developed based on primary data collected in situ and through bibliographic research. While the inventory of rice cultivation and milling relied on secondary data, the inventory of electricity generation at the thermal power plant and the life cycle model were constructed using primary data obtained from the operational, control, and monitoring reports of the São Sepé Thermal Power Plant. The involvement of one of the authors, an engineer responsible for the plant's operation and environmental processes, enhances the relevance of the study, which seeks practical solutions grounded in real-world data.

2.3.1 Inventory of Rice Cultivation and Milling

The inventory of rice cultivation and milling was developed using both primary and secondary data from the functional units. Table 1 presents the main inputs used in the stages of cultivation, drying, transportation, and packaging (NUNES et al., 2016).

Table 1

Inventory of data for rice cultivation and milling

	Entradas (*Inputs*)		
Stage	**Inputs**	**Value**	**Unit**
Standard Rice Cultivation	Water	$7{,}20\times10^{-4}$	m³/kg rice
	Arable Land Occupation	1,33	m²/kg rice
	Rice Seed	$1{,}30\times10^{-2}$	kg/kg rice
	Herbicides	$7{,}20\times10^{-7}$	kg/kg rice
	Ureia, as N	$4{,}03\times10^{-2}$	kg/kg rice
	Ammonium Nitrate, as N	$1{,}08\times10^{-2}$	kg/kg rice
	Triple Superphosphate, as P2O5	$1{,}37\times10^{-2}$	kg/kg rice
	Potassium Chloride, as K2O	$3{,}10\times10^{-2}$	kg/kg rice
	Fungicides	$3{,}60\times10^{-8}$	kg/kg rice
	Insecticides	$1{,}07\times10^{-8}$	kg/kg rice
	Diesel – Rice Plantation	$8{,}64\times10^{-3}$	kg/kg rice
	Diesel – Rice Harvest	$4{,}32\times10^{-3}$	kg/kg rice
	Electricity, Pump (50 HP)	$4{,}90\times10^{-6}$	kWh/kg rice
	Electricity, Pump (30 HP)	$2{,}94\times10^{-6}$	kWh/kg rice
	Fertilizer Transportation	$2{,}66\times10^{-2}$	tkm/kg rice
	Herbicide Transportation	$2{,}23\times10^{-2}$	tkm/kg rice
	Diesel - Transport	$1{,}92\times10^{-4}$	kg/kg rice
Rice Processing	Wood	$1{,}00\times10^{-3}$	m³/ha/kg rice
	Packaging Transportation, Truck 3.5 -7.5t	21,74	tkm/kg rice
	Processing Transport, 16-32t Truck	5,64	tkm/kg rice
	Drying Transport, 7.5-16t Truck	6,17	tkm/kg rice
	Packing 1kg (LDPE)	$3{,}89\times10^{-1}$	kg/kg rice
	Packing 5kg (LDPE)	$4{,}17\times10^{-1}$	kg/kg rice
	Electric Forklift	706,0	J/kg rice
	Paddy Rice	1,54	kg/kg rice

Source: Adapted from Nunes et al. (2016).

In the cultivation stage, the pesticides used were Standak (25%) as an insecticide, glyphosate (48%) as a herbicide, and Vitavax (40%) as a fungicide. Diesel consumption was 80 L/ha for soil preparation and 40 L/ha during harvesting.

Milling includes husking, separation of the grain from the husk, and pre-polishing. The handling of the grains encompasses transportation and packaging. Partial milling generates the following co-products: white rice (65.5%), broken grains (3.5%), rice bran (7%), and rice husk (24%).

2.3.2 Description of the Energy Generation System in the Thermal Power Plant

The São Sepé Thermal Power Plant uses rice husk as fuel, with a maximum capacity of 8.0 MWh and a daily production of 192 MWh, of which 163.2 MWh is exported to the market. The technology employs a rotary grate, allowing the combustion of up to 217 t/day of rice husk, sourced from 12 municipalities at an average distance of 168 km. Transportation is carried out by 12-ton trucks, with a fuel efficiency of 2.5 km/L of diesel, and storage is in a horizontal silo with a capacity of 870 t.

The HBremer LIGNODYN-40 boiler generates 37,390 kg/h of saturated steam at 45 kgf/cm², with automated feed and combustion controlled by primary and secondary air. Fuel consumption is 9,170.2 kg/h (12% moisture), producing 1,834 kg/h of ash. Gas emissions are controlled by a multiclone and bag filter, with periodic monitoring of CO_2, NOx, CO, and particulate matter concentrations.

The generated steam is supported by three integrated systems: Water Treatment Plant (WTP), Effluent Treatment Plant (ETP), and Demineralization System (DESMI). The WTP provides 540 m³/day of industrial water; the ETP treats 170 m³/day of effluents, allowing water reuse; and the DESMI removes salts from water, preventing scaling and corrosion. Demineralized water is used in the boiler, with chemical additives to protect the equipment.

After energy generation, the steam is cooled in a cooling tower and condensed, allowing its reuse and reducing the demand for treated water. The cycle is continuous, with replacement of losses due to evaporation and prevention of scaling through chemical additives.

After storage of boiler ash in horizontal silos, the plant disposes of the residue on agricultural properties in São Sepé, holding an environmental license for this purpose. Transportation is carried out daily by a third-party company, and the property owners are responsible for ash distribution.

Electricity generation also depends on the efficient operation of various production chain equipment, such as conveyors, screws, elevators, exhausters, and hydraulic pumps, powered by electric motors of different capacities. Internal energy consumption is predominantly from these motors, and their efficiency directly impacts the amount of electricity available for export.

3 RESULTS AND DISCUSSION

3.1 INVENTORY OF CHEMICAL PRODUCTS

Based on operating hours, treatment flow rates, and standard dosages, it was possible to calculate the amount of chemical inputs used in the water and effluent treatment systems, relating them to the functional unit of interest. The inventory of chemical inputs for the thermal power plant is presented in Table 2.

Table 2

Inventory of Chemicals

Unidade	Insumo	Valor	Unidade
WTP	Polyaluminum Chloride and Aluminum Sulfate	$2{,}083 \times 10^{-4}$	$kg \cdot kWh^{-1}$
	Sodium Hydroxide	$7{,}81 \times 10^{-5}$	$kg \cdot kWh^{-1}$
	Polymer	$2{,}60 \times 10^{-6}$	$kg \cdot kWh^{-1}$
	Sodium Hypochlorite	$1{,}56 \times 10^{-4}$	$kg \cdot kWh^{-1}$
ETP	Polyaluminum Chloride	$3{,}12 \times 10^{-4}$	$kg \cdot kWh^{-1}$
	Polymer	$1{,}56 \times 10^{-6}$	$kg \cdot kWh^{-1}$
Reverse Osmoses	Citric Acid	$6{,}93 \times 10^{-7}$	$kg \cdot kWh^{-1}$
	Sodium Hydroxide	$1{,}72 \times 10^{-7}$	$kg \cdot kWh^{-1}$
	Glycol; 2,2-dibromo-3-nitrilpropionamide; Sodium bromide	$4{,}32 \times 10^{-7}$	$kg \cdot kWh^{-1}$
	Sodium Chloride	$1{,}30 \times 10^{-5}$	$kg \cdot kWh^{-1}$
Demineralization System	Hydrochloric acid	$1{,}67 \times 10^{-4}$	$kg \cdot kWh^{-1}$
	Sodium Hydroxide	$3{,}90 \times 10^{-4}$	$kg \cdot kWh^{-1}$
Cooling Tower	Phosphoric Acid	$2{,}08 \times 10^{-5}$	$kg \cdot kWh^{-1}$
	Carboxylic Acid Polymer; Maleic Acid	$2{,}08 \times 10^{-5}$	$kg \cdot kWh^{-1}$
	Trichloroisocyanuric acid	$2{,}5 \times 10^{-5}$	$kg \cdot kWh^{-1}$
Boiler and turbine	Carbohydrazide	$2{,}60 \times 10^{-5}$	$kg \cdot kWh^{-1}$
	Ammonium Hydroxide	$9{,}37 \times 10^{-6}$	$kg \cdot kWh^{-1}$
	Unspecified polymer	$9{,}37 \times 10^{-6}$	$kg \cdot kWh^{-1}$

Source: Author.

It is observed that the highest consumptions are associated with the water and raw effluent treatment stages, with coagulants and chlorine-based biocides standing out, which are used in the clarification of water and effluents in the WTPs and WWTPs. In the demineralization process, hydrochloric acid and sodium hydroxide are employed for the regeneration of cationic and anionic resins. Other inputs, such as acidic and alkaline solutions and polymers, complement the treatment, ensuring operational efficiency and process water quality.

3.2 TRANSPORT INVENTORY

For the transport inventory, only those with higher operational frequency were considered, such as the transport of biomass and rice husk ash. Table 3 shows the transport inventory considering fuel consumption.

Table 3

Transport Data Inventory

Inputs	Value	Unit
Biomass Transport (truck 7,5 – 16,0 t)	$1{,}00\times10^{-3}$	$tkm.kWh^{-1}$
Diesel Oil (Biomass Transport)	$4{,}70\times10^{-1}$	$kg\cdot kWh^{-1}$
Rice Husk Ash Transport (truck 7,5 – 16,0 t)	$4{,}23\times10^{-3}$	$tkm.kWh^{-1}$
Diesel Oil (Ash Transport)	$1{,}38\times10^{-2}$	$kg\cdot kWh^{-1}$

Source: Author.

3.3 IMPACT ALLOCATION

According to the ABNT ISO 14044 standard (2009), allocation consists of partitioning the input or output flows of a process between the product under study and other related products. In multiproduct systems, the application of allocation procedures is essential to properly distribute materials, energy, and environmental emissions (TRINDADE, 2020).

For the life cycle assessment, an economic allocation of impacts was performed, using the cost or revenue values of each product, allowing the software to distribute the contribution of each item to greenhouse gas (GHG) emissions. Table 4 presents the economic values of the products considered within the system boundary.

Table 4

Life Cycle Economic Data

Products/Inputs	Value	Unit
White Rice	0,414	USD/kg
Rice Bran	0,145	USD/kg
Broken Rice	0,271	USD/kg
Rice Husk	0,017	USD/kg
Paddy Rice	0,244	USD/kg

Source: Author.

3.4 LIFE CYCLE ASSESSMENT AND DISTRIBUTION OF GHG EMISSIONS

The life cycle model of the present study was structured in different stages, allowing the discrimination of greenhouse gas (GHG) contributions from each sector and the identification of the activities with the highest impact. For this purpose, flows were created with the products listed in Table 4 and the processes required for their production, including all inventory inputs and outputs based on the functional unit. Most inputs were obtained from the Ecoinvent database, except for some specific chemicals, such as carbohydrazide and the biocide (Glycol; 2,2-dibromo-3-nitrilopropionamide; Sodium bromide), which are not available in version 3.6 of the database.

The "Product System" integrated all flows and processes according to the life cycle flowchart (Figure 2), enabling the calculation of the global warming potential (GWP100). GHG emissions by stage are presented in Table 5, totaling 3.60×10^{-2} kg CO_2 eq/kWh.

Table 5

Carbon Footprint by Production Stage

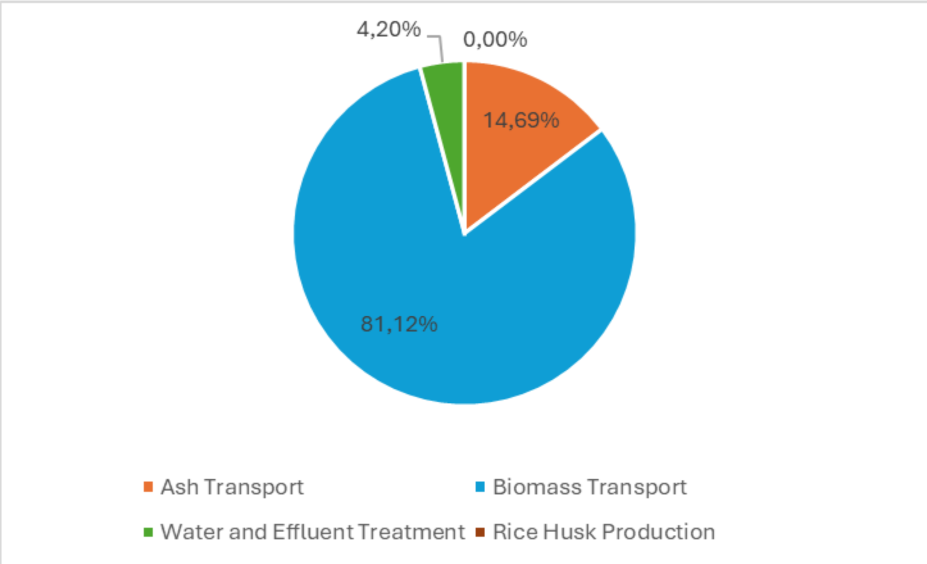
Stage	Source	Global Warming Potential (GWP100) kg CO_2-eq·kWh^{-1}
Rice Cultivation and Milling	-	ND
Biomass Transport	Truck Fuel (Diesel)	$2,92\text{x}10^{-2}$
	Truck Transport/Freight 7.5–16 t	$3,69\text{x}10^{-6}$
Water and Effluent Treatment	Sodium Hydroxide	$6,10\text{x}10^{-4}$
	Sodium Hypochlorite	$4,10\text{x}10^{-4}$
	Aluminum Polychloride	$3,70\text{x}10^{-4}$
	Hydrochloric Acid	$8,22\text{x}10^{-5}$
	Phosphoric Acid	$2,88\text{x}10^{-5}$
	Trichloroisocyanuric Acid	$5,38\text{x}10^{-6}$
	Citric Acid	$4,33\text{x}10^{-6}$
	Sodium Chloride	$1,17\text{x}10^{-6}$
Ash Transport and Disposal	Truck Fuel (Diesel)	$1,16\text{x}10^{-3}$
	Truck Transport/Freight 7.5–16 t	$4,13\text{x}10^{-3}$
Total		**$3,60\text{x}10^{-2}$**

Source: Author.

The results show that the transport of biomass and residues is the largest contributor to GHG emissions, accounting for 81.12% of the total. Factors such as the number of trips, distance traveled, volume of residues, and vehicle efficiency directly influence this impact, with diesel consumption by the fleet being the main contributor to the carbon footprint (Figure 3).

Figure 3

Comparison of Contributions to GHG Emissions



Source: Author.

According to Shen et al. (2015), the low energy density of lignocellulosic biomass makes transportation a critical factor in the economic and environmental viability of plants, also influencing operational scale and site selection. In the case of the São Sepé plant, it's central location in Rio Grande do Sul, near rice processing companies, favors the logistical supply of biomass. Regarding the disposal of rice husk ash (RHA), the company prioritized properties close to the plant (average distance of 18.5 km), reducing costs and emissions.

The water and effluent treatment stage occurs continuously, supporting steam generation, and environmental impacts were estimated based on the chemical inputs used. The electricity consumed internally by equipment, such as centrifugal pump motors, was not accounted for as an external source, as it is generated internally from rice husk combustion. Additional simulations indicated that if the energy came from an external source, it would represent approximately 72.5% of the system's total emissions (~0.1254 kg CO_2 eq/GWP100), reinforcing the environmental advantage of the model adopted by the plant.

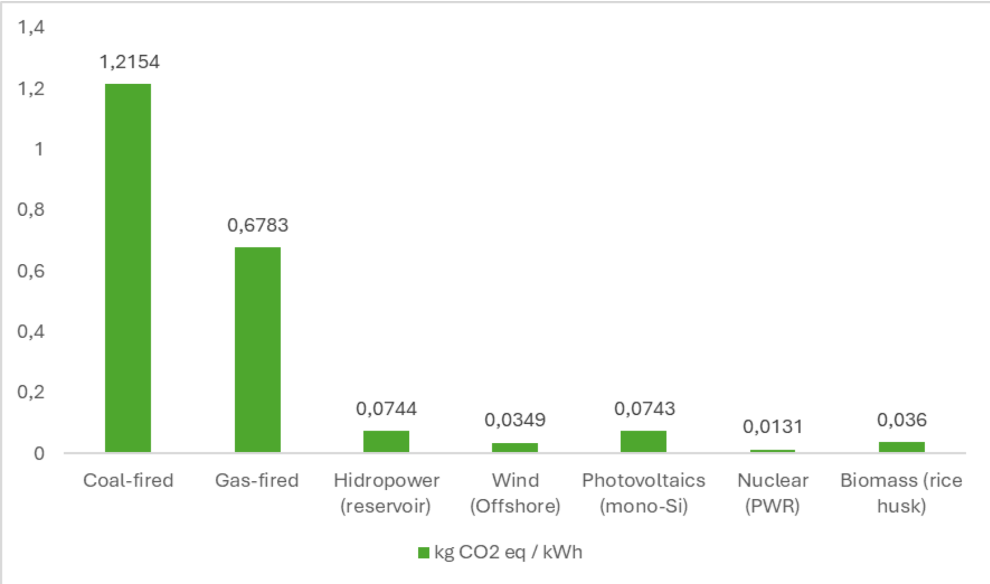
Regarding rice cultivation and processing, no GHG emissions were attributed to the husk due to economic allocation, which concentrates the environmental burden on the higher-value commercial products (Table 9). Moreover, emissions from husk combustion are not included in GHG accounting, as the released CO_2 is considered biogenic and reabsorbed by subsequent crops. Finally, it was not possible to estimate GHG emissions associated with the application of RHA to agricultural soil, due to the scarcity of specific data and the lack of robust inventories on the subject.

3.5 COMPARISON OF GHG EMISSIONS WITH OTHER ENERGY TECHNOLOGIES

The carbon footprint obtained in this study was compared with results from Life Cycle Assessments (LCAs) of other electricity generation technologies. Guidi et al. (2023) consolidated data from different energy matrices, providing a comparative overview. As shown in Figure 4, energy generation from rice husk exhibits significantly lower greenhouse gas (GHG) emissions compared to conventional and non-renewable sources, such as coal and natural gas, highlighting it as a low-environmental-impact energy alternative.

Figure 4

Comparison of emissions across different electricity generation technologies

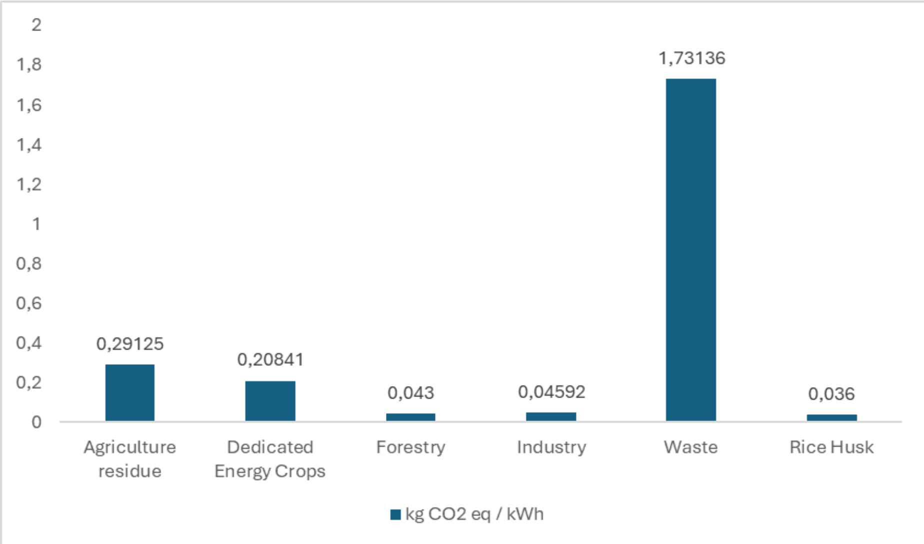


Source: Author.

Kadiyala et al. (2016) compiled equivalent CO_2 emission values from various biomass-fired power plants based on Life Cycle Assessment (LCA) studies. Figure 6 presents a comparison between the plant analyzed, which uses rice husk as fuel, and the average emissions of other plants powered by different types of biomass. The results indicate that the rice husk plant exhibits lower CO_2-equivalent emissions per kWh generated compared to the average of plants using agricultural residues, highlighting its higher environmental efficiency in the context of biomass-based thermal power generation.

Figure 6

Comparative Chart of Different Biomass Types



Source: Author.

3.6 CARBON FOOTPRINT OF RICE HUSK-BASED ENERGY GENERATION

In the present study, the São Sepé Thermoelectric Plant (TEP) exhibited a carbon footprint of 0.036 kg CO_2 eq/kWh for electricity generation from rice husk. The Life Cycle Assessment (LCA) was developed based on detailed primary data from the plant's operation, complemented by secondary data from the Ecoinvent 3.6 database, considering a "cradle-to-gate" boundary. This approach included rice cultivation and processing, biomass and ash transport, plant operation, water and effluent treatment, and the use of chemical inputs, with economic allocation applied among the co-products.

The use of emission factors updated by the IPCC (2021), combined with the inclusion of auxiliary processes and accounting for emissions related to average transport distances, resulted in a value lower than that reported by Shafie et al. (2011), who estimated 0.217 kg CO_2 eq/kWh. In Shafie et al.'s study, the inventory was less comprehensive, with shorter transport distances, exclusion of support stages, and the use of emission factors prior to IPCC 2021. On the other hand, the study by Chungsangunsit et al. (2010) reported 0.0172 kg CO_2 eq/kWh, due to a restricted boundary focused only on combustion and immediate biomass transport, with short distances and possible exclusion of agricultural and processing stages, as well as the use of older data and emission factors.

These differences highlight that the scope, quality, and origin of data, as well as the methodological assumptions adopted, decisively influence the results and must be clearly stated to allow consistent comparisons among studies.

When analyzing stage-specific contributions, biomass transport remains the main source of emissions, followed by ash transport and disposal, which accounts for approximately 10% of the total—an aspect not considered in some comparative studies. Emissions from boiler operation and chemical input use are low (<10%), while cultivation and processing stages have a marginal contribution, in agreement with Chungsangunsit et al. (2010).

These results indicate that, even with a low overall carbon footprint, mitigation opportunities are concentrated in the logistics chain, highlighting strategies such as route optimization, the use of more efficient transport modes, and local utilization of ash.

4 CONCLUSIONS

The study demonstrated that electricity generation from rice husk exhibits a significantly reduced carbon footprint compared to fossil fuels, reinforcing the potential of this biomass as a strategic alternative for diversifying Brazil's energy matrix. The analyzed plant presented a value of 0.036 kg CO_2 eq/kWh, a competitive result compared to other biomass technologies reported in the literature. The main contribution to emissions was associated with the transport of biomass and ash, confirming the importance of logistics in the environmental and economic viability of such plants. Strategies such as route optimization, reducing transport distances, and local utilization of agricultural ash emerge as effective measures for impact mitigation. Thus, the use of rice husk in thermoelectric plants not only contributes to reducing greenhouse gas emissions but also represents a sustainable solution for the utilization of agro-industrial residues, aligning with the country's energy transition and circular economy goals.

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