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The Energy Potential of Residual Biomass Gasification Integrated with Internal Combustion Engine in Córdoba, Colombia using Artificial Neural Network Techniques

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ABSTRACT

In this study, the energy potential of waste biomass gasification integrated to internal combustion engine in Cordoba, Colombia was investigated using artificial neural network techniques. A model was trained with proximate and elemental analysis data of different biomasses and this model was used to estimate the gasification potential of the four most abundant biomasses in Cordoba. The model developed achieved an adjusted determination coefficient (R^2) of 0.9293 for validation and 0.9048 for training, demonstrating high predictive accuracy. The results indicate that temperature positively influences energy generation potential, while moisture content and air-to-fuel ratio have a negative impact. Among the biomass types analyzed, cassava stands out with the highest energy potential, exceeding 9 GWh/year, followed by plantain at approximately 3 GWh/year, maize cobs below 2 GWh/year, and rice husk with <0.5 GWh/year. These findings provide critical insights for optimizing biomass gasification processes and harnessing regional biomass resources for energy generation.

Keywords: Renewable Energy Sources, Energy Potential, Gasification, Residual Biomass, Artificial Neural Networks
JEL Classifications: C6, O3, Q3, Q4

1. INTRODUCTION

The growing global energy demand and concerns about climate change have highlighted the urgent need to transition to cleaner and more sustainable energy sources (Peñuelas and Carnicer, 2010). Fossil fuels, such as oil, natural gas, and coal, have been the main contributors to the increase in greenhouse gas emissions and global warming (Moazzem et al., 2012). These fuels, in addition to being finite and non-renewable, generate air pollution and have a negative impact on the environment and human health (Drumm et al., 2014). On the other hand, renewable energy sources, such as solar, wind, hydroelectric, geothermal, and biomass, are essential for reducing dependence on fossil fuels and mitigating the effects of climate change (Lu, 2020). These sources are abundant, renewable, and environmentally friendly, as they do not produce greenhouse gas emissions during their generation (Eitan, 2021). In this context, the use of residual biomass for energy generation through processes like gasification represents a valuable opportunity to diversify the energy mix and reduce the carbon footprint (Shahabuddin et al., 2020). The gasification of residual biomass not only contributes to the transition toward a low-carbon economy but also promotes sustainable waste management and circularity in production systems (Mendoza Martinez et al., 2019).

The study on the energy potential of agricultural residual biomass in the department of Córdoba is highly relevant for multiple reasons. First, it allows for the utilization of abundant local resources that are currently being wasted (Mendoza Fandiño et al., 2021). This would contribute to diversifying the regional energy mix, increasing the security and resilience of the electrical system. Additionally, it promotes sustainable rural development by generating a new source of income for farmers and communities (Rhenals-Julio et al., 2023). From an environmental perspective, it prevents the improper disposal of waste and displaces the use of fossil fuels, contributing to climate change mitigation (Rhenals-Julio et al., 2023). This approach aligns with Colombia's national policies to increase the participation of unconventional renewable energies. Finally, this type of study provides valuable technical and economic information for decision-makers, investors, and communities to assess the feasibility of implementing biomass energy projects in the region (Sagastume et al., 2021).

The research of (Ribeiro and Dalmolin, 2020) highlights energy biomass as a possibility for innovative agricultural initiatives, emphasizing the potential of residual biomass in the energy sector. Likewise, the study of (Kabeyi and Olanrewaju, 2022) proposes strategies for sustainable energy transition that could be applied in electricity generation from renewable sources, such as residual biomass, in line with international commitments to reduce emissions. Furthermore, the research of (Liu et al., 2013) indicates that emissions are a key indicator of sustainability in renewable energy systems, highlighting the importance of considering environmental impact when evaluating alternatives like residual biomass. On the other hand, the work of (Pietrosemoli and Rodríguez-Monroy, 2013) highlights the growing recognition of renewable energies, including biomass, in improving quality of life and supporting sustainable development.

Biomass energy has emerged as a significant renewable resource worldwide, with varying potentials in different regions. For example, studies indicate that biomass accounts for approximately 10.4% of the total primary energy supply globally, with a substantial portion used in developing countries (Tun et al., 2019). In Fiji, the use of sugarcane waste has been highlighted as a means to enhance energy generation, helping to reduce dependence on oil (Chandra and Hemstock, 2015). Similarly, Yunnan Province in China has made progress in converting biomass resources into economic advantages through renewable energy technologies (Zhang et al., 2013) Globally, it is estimated that the potential for sustainable biomass energy will range from 130 to 500 exajoules (EJ) by 2050, depending on agricultural and environmental transformations (Beringer et al., 2011; Meller et al., 2014). In Europe, the balance between climate change mitigation and the land use impacts of bioenergy has been a central focus, emphasizing the need for sustainable practices (Meller et al., 2014). Additionally, the integration of biomass energy systems with carbon capture technologies presents a promising pathway to enhance energy security while mitigating greenhouse gas emissions (Luckow et al., 2010; Rose et al., 2013).

The province of Córdoba, Colombia, is not unfamiliar with this imperative. With a rich tradition in agricultural and forestry activities, the region holds a significant amount of residual biomass, ranging from crop waste to forestry by-products (Sagastume Gutiérrez et al., 2022). This biomass, mostly unused, represents a valuable resource that could be harnessed for energy generation while contributing to the reduction of organic waste and mitigating the negative environmental impacts associated with its conventional disposal (Gomez et al., 2021). The Figure 1 shows the landscape of production of four agricultural products in the department of Córdoba.

In this context, the gasification of residual biomass emerges as a key technology (Gómez-Vásquez et al., 2021). Gasification is a thermochemical process that converts biomass into a combustible gas rich in hydrogen and carbon monoxide, known as synthesis gas (Basu, 2018). This gas can be used to generate electricity and heat, as well as to produce liquid fuels and chemicals. The gasification of residual biomass in Córdoba can not only help diversify the local energy mix but also reduce greenhouse gas emissions, in line with climate change mitigation goals (Mendoza Fandiño et al., 2021).

However, the accurate assessment of the energy potential of residual biomass gasification in Córdoba is a complex challenge that requires a multidisciplinary approach and advanced modeling tools (Das and Hoque, 2014). In this regard, artificial neural network (ANN) techniques have proven to be effective tools in predicting and optimizing energy and environmental processes (Huang et al., 2016; Safa and Samarasinghe, 2011). By employing ANNs in the analysis of the potential for residual biomass gasification in Córdoba, it is expected to obtain more precise and detailed results that allow for more informed decision-making in the planning and development of renewable energy projects in the region.

This article aims to deeply explore the energy potential of residual biomass gasification in the province of Córdoba, using advanced artificial neural network techniques. It will provide a holistic view of its viability and contribution to energy sustainability in the region. Additionally, it will highlight the importance of collaboration among the scientific community, industry, and government authorities to promote the development of innovative and environmentally friendly energy solutions in Córdoba and other regions of the country.

2. MATERIALS AND METHODS

Figure 2 shows the methodology used to develop the artificial neural network (ANN) model, from data analysis to final model validation. The process begins with the analysis of the model's training database. Subsequently, an ANN model is trained, adjusting its hyperparameters until satisfactory performance criteria are met. Once these criteria are fulfilled, the model moves to the testing phase and is finally validated. If the results are not satisfactory at any stage, the process is adjusted until an adequate model is obtained.

2.1. Data Description

In this work, the database collected by (Safarian et al., 2020) which consists of 12 columns and 1,032 rows. The columns contain information on the elemental analysis compositions (C, O, H, N, and S), proximate analysis (moisture, ash, volatile matter, and fixed carbon), and the operational parameters of the gasification process (temperature and air-fuel ratio). On the other hand, the

Figure 1: Historical production in tons of four crops in Córdoba (Agronet, 2021)

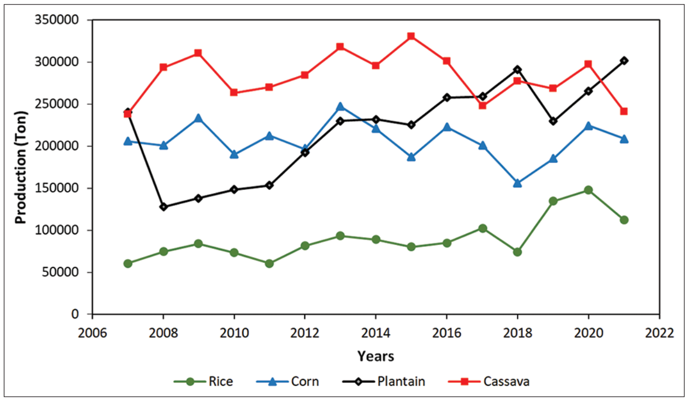
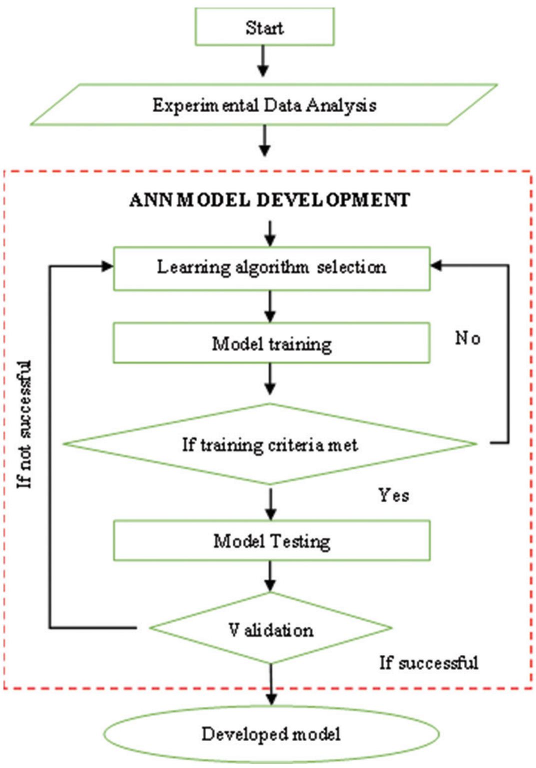


Figure 2: Methodology for the development and validation of the artificial neural network model



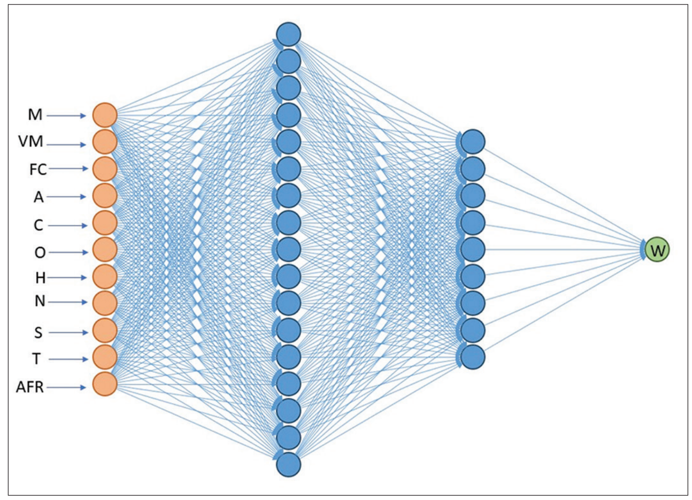
rows represent 1,032 different biomasses that were used to train the model.

Figure 3 presents a diagram of the multilayer network used to predict the energy potential (w) during biomass gasification, based on various fuel characteristics and process conditions. The input variables include moisture (m), volatile matter (VM), fixed carbon (FC), ash (a), and the elemental composition of the fuel (C, O, H, N, S), as well as process temperature (t) and air-fuel ratio (AFR). During the training process, the parameters are adjusted, allowing for the prediction of the impact of the input variables on the energy potential.

2.2. Model Structure and Model Training

In this study, a neural network with three hidden layers was used, configured with 300, 500, and 250 neurons, respectively.

Figure 3: Multilayer neural network for predicting net power in biomass gasification



For training, 70% of the data was used to adjust the weights and biases of the network, while the remaining 30% was allocated for validation, allowing for the assessment of its ability to predict unknown data. The model was developed in Python using the scikit-learn library. Figure 4 presents the overall operation of the neural network. First, it receives the input data and transforms it through mathematical operations, applying linear regression and activation functions. In this study, the sigmoid function was used as the activation function in all layers.

2.3. Case Study

In this study, four types of biomasses that are most generated in the department of Córdoba, Colombia, were selected: Plantain, corn cob, cassava, and rice husk (Sagastume et al., 2021). The high agricultural production of these crops makes them ideal for utilization in bioenergy processes, ensuring a constant source of agricultural waste supply. Table 1 provides information on the elemental composition and physical properties of the selected biomasses.

2.4. Influence of Variables

A parametric analysis was conducted to evaluate the influence of temperature, air-fuel ratio, and moisture on the energy potential of each of the studied biomasses, in order to determine the optimal configuration of the generation system. Table 2 presents the maximum, minimum, and nominal values for each variable considered in the analysis.

3. RESULTS AND DISCUSSION

3.1. Database Analysis

The correlation analysis shown in Figure 5 reveals significant interactions between the physicochemical properties of the biomass and the energy variables of the gasification process. Weak correlations indicate that variables such as sulfur, nitrogen, carbon, and moisture have a moderate statistical impact on volatile matter, while power shows a moderate effect on the percentages of carbon, hydrogen, and temperature. These relationships reflect that, although present, they are not decisive in the overall behavior of

Table 1: Elemental composition and physical properties of different biomasses for energy analysis

Biomass	M (%)	VM (%)	FC (%)	A (%)	C (%)	O (%)	H (%)	N (%)	S (%)	Reference
Plantain	10.20	88.80	0.20	11.00	37.93	55.37	4.46	1.87	0.37	(Abdullah et al., 2014)
Corn Cob	10.52	72.89	18.48	8.62	44.16	50.59	4.48	0.67	0.10	(Mogaji et al., 2020)
Cassava Stem	8.00	66.30	29.35	4.35	49.50	39.50	10.40	0.60	0.00	(Foong et al., 2020)
Rice Husk	10.18	71.99	18.73	9.27	39.27	55.13	4.91	0.59	0.10	(Bonilla Gracia, 2023)

Figure 4: General operation of a neural network

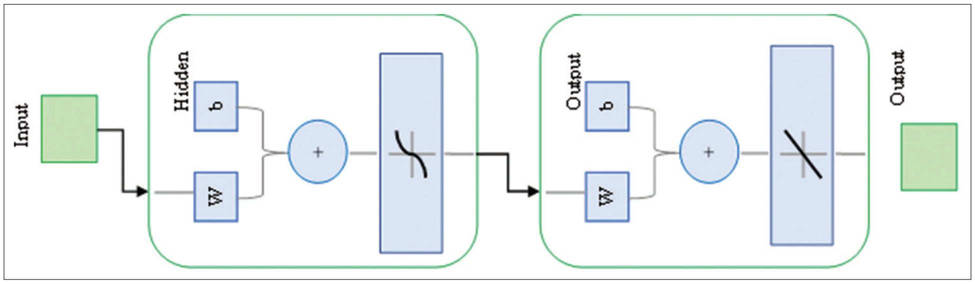


Figure 5: Database correlation matrix

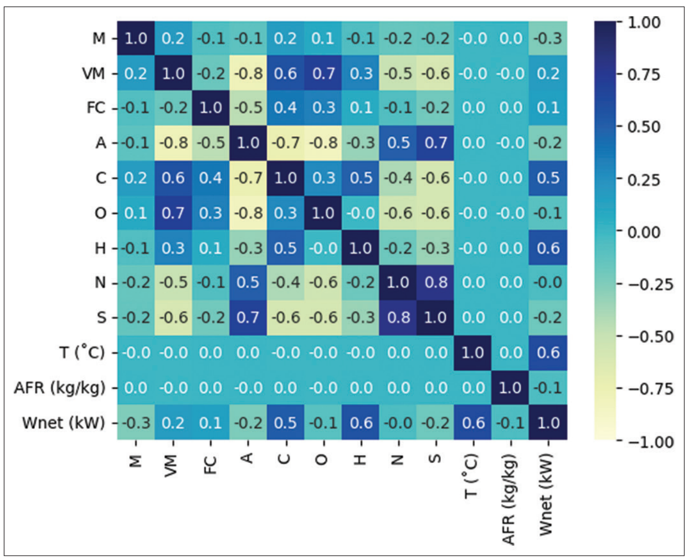
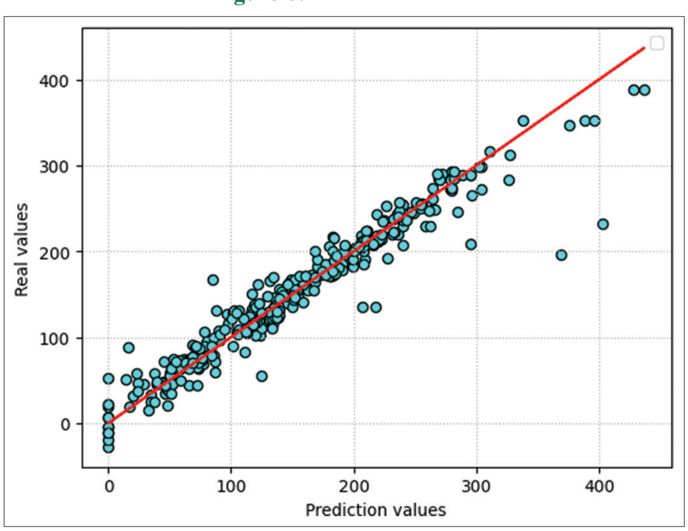


Figure 6: Model validation



the process. On the other hand, strong correlations indicate that ash content, which is strongly related to volatile matter, as well as the percentages of sulfur, carbon, and oxygen, have a high impact on residual composition and the gasification process. Additionally, the relationship between sulfur and nitrogen highlights the importance of these elements in emission generation, emphasizing the need to control these compounds to optimize efficiency and minimize environmental impacts.

3.2. Model Training and Validation

Figure 6 shows the fit between the actual values and the values predicted by the neural network, achieving an adjusted coefficient of determination of 0.9293 for validation and 0.9048 for training, indicating that the model has a high level of fit in both cases.

3.3. Parametric Analysis

Figure 7 shows the behavior of power per unit mass generated with respect to temperature in the gasification process for three types of air-fuel mixtures, namely 1.8, 2.0, and 2.3, for the biomass generated from plantain (a), corn cob (b), cassava (c), and rice husk (d), respectively. The results indicate that higher temperatures lead to greater energy potential, which is consistent with the findings reported by (Atnaw et al., 2014). Therefore, it is highlighted that a gasification temperature of 900°C is the most suitable for the process, along with an air-fuel ratio of 1.8. Under these conditions, the specific power of plantain is above 16 kW/kg, corn cob shows values >28 kW/kg, cassava waste exceeds 100 kW/kg, and rice husk is above 11 kW/kg. This emphasizes that the residual biomass of cassava generates the highest power, which is consistent due to its fixed carbon content and percentage of carbon established in its characterization through proximate and elemental analysis.

In Figure 8, the proposed model analyzed the relationship between the moisture content of the biomasses and the energy potential generated for the studied case. This variable was considered because, in biomass gasification, moisture content can negatively affect the efficiency of the process (Abdalla et al., 2022). The trend for all biomasses is that higher moisture content significantly reduces energy potential, as noted by authors such as (Yakan à Nwai and Patel, 2023) moisture content of 20%, it decreases to <10 kW/kg at the same process temperature. It is also noteworthy that at 1200°C, power generation is nearly 30 kW/kg even with

Figure 7: Power (kW/kg) versus temperature (°C) for (a) plantain, (b) corn stover, (c) cassava and (d) rice husk

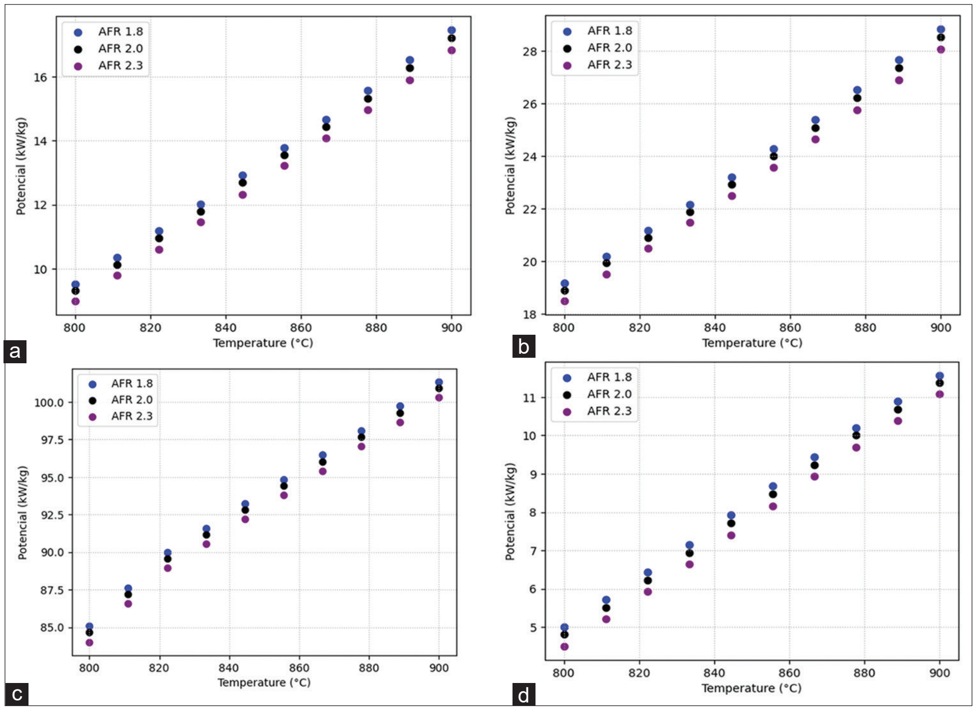


Figure 8: Power (kW/kg) versus humidity (%) for (a) plantain, (b) corn stover, (c) cassava and (d) rice husk

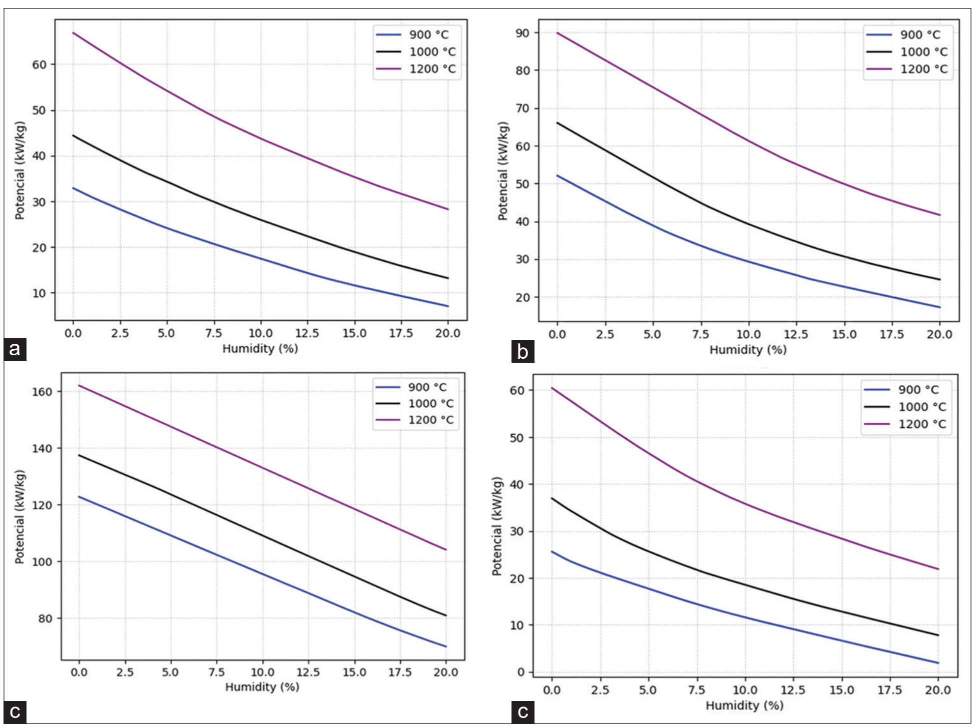
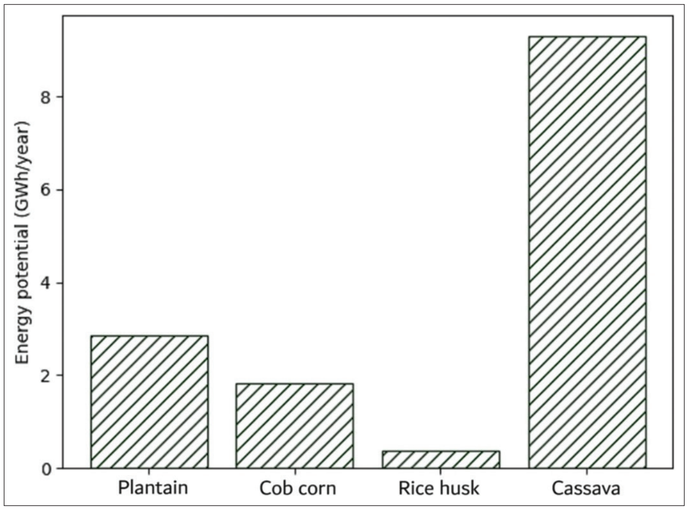


Table 2: Maximum, minimum, and nominal values of variables for biomass energy potential analysis

Variable	Máximo	Mínimo	Nominal
Temperatura	1200	800	900
Humedad	20	0	--
Relación aire-combustible	2.3	1.8	2.0

higher moisture content. For corn cob, at a temperature of 900°C, the generated power is >50 kW/kg with 0% moisture, and for moisture contents of 20%, it drops to nearly 15 kW/kg; however, at 1200°C with 20% moisture, the power is above 40 kW/kg. In the case of cassava, the power at 0% moisture with 900°C is over 120 kW/kg, and with 20% moisture at that temperature, it is below 70 kW/kg; for 1200°C, the power generation at 20% moisture exceeds 100 kW/kg. For rice husk, the lowest power generation values are obtained, with above 25 kW/kg at 900°C and 0% moisture, while at 20% moisture, values fall below 5 kW/kg; at 1200°C, generation with 20% moisture is above 20 kW/kg. These

Figure 9: Energy potential (GWh/year) for different types of biomasses



results highlight the importance of implementing drying processes prior to gasification, especially for biomasses with high moisture content, such as cassava and plantain.

3.4. Gasification Potential

In Figure 9 the results obtained by the model for the energy potential of each of the four studied biomasses, considering the analyzed gasification process factors, are observed. Cassava stands out with the highest generation potential, exceeding 9 GWh/year, followed by plantain with values close to 3 GWh/year, corn cob with values below 2 GWh/year, and finally rice husk with values under 0.5 GWh/year. These results are lower than the potentials reported by (Sagastume et al., 2021) for the energy potential of the same biomasses in the combustion process, which is due to the fact that the efficiency of the gasification process integrated with internal combustion engines is much lower than that of combustion. However, gasification represents a more flexible process in terms of technologies for utilizing syngas (Devi et al., 2020; Singh Siwal et al., 2020).

4. CONCLUSION

The artificial neural network-based model developed in this study proved to be a robust tool for predicting the gasification potential integrated with internal combustion engines for various biomasses with high accuracy, as demonstrated by the adjusted coefficients of determination obtained during the training and validation stages. This model is adaptable to any geographic region and can be applied to different types of biomass, which expands its utility for energy planning in various contexts.

The four studied biomasses (cassava, plantain, corn cob, and rice husk) exhibit significant potential for energy generation. Cassava stands out as the biomass with the highest energy capacity, exceeding 9 GWh/year, making it a particularly viable option for bioenergy projects in the Córdoba region. Plantain and corn cob also show considerable values, while rice husk, although with lower potential, can be utilized in combinations with other sources to maximize system efficiency.

The results of this study provide fundamental data to enhance energy planning in the department of Córdoba, allowing for better integration of residual biomass resources into local energy generation strategies. Furthermore, the developed approach can significantly contribute to the diversification of the regional energy matrix, promoting the transition to renewable and sustainable energy sources, with positive impacts on emission reduction and agricultural waste management.

5. ACKNOWLEDGMENT

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REFERENCES

Abdalla, M.E., Abdalla, S.A., Taqvi, S.A.A., Naqvi, S.R., Chen, W.H. (2022), Investigation of biomass integrated air gasification regenerative gas turbine power plants. Energies, 15(3), 741.

Abdullah, N., Sulaiman, F., Miskam, M.A., Taib, R.M. (2014), Characterization of banana (*Musa* spp.) pseudo-stem and fruit-bunch-stem as a potential renewable energy resource. International Journal of Biological, Veterinary, Agricultural and Food Engineering, 8, 712-716.

Agronet. (2021), Sistema de Estadísticas Agropecuarias. Agronet COL. Available from: https://www.agronet.gov.co

Atnaw, S.M., Sulaiman, S.A., Yusup, S. (2014), Influence of fuel moisture content and reactor temperature on the calorific value of syngas resulted from gasification of oil palm fronds. The Scientific World Journal, 2014(1), 121908.

Basu, P. (2018), Biomass gasification, pyrolysis and torrefaction: Practical design and theory. In: Biomass Gasification, Pyrolysis and Torrefaction: Practical Design and Theory. United States: Academic Press.

Beringer, T., Lucht, W., Schaphoff, S. (2011), Bioenergy production potential of global biomass plantations under environmental and agricultural constraints. GCB Bioenergy, 3(4), 299-312.

Bonilla Gracia, S.I. (2023), Evaluacion Termoenergetica De La Co-Digestión De La Mezcla Cascarilla De Arroz Y Estiercol Bovino En [Universidad De Córdoba]. Available from: https://repositorio.unicordoba.edu.co/handle/ucordoba/6947

Chandra, V.V., Hemstock, S.L. (2015), A biomass energy flow chart for Fiji. Biomass and Bioenergy, 72, 117-122.

Das, B.K., Hoque, S.M.N. (2014), Assessment of the potential of biomass gasification for electricity generation in Bangladesh. Journal of Renewable Energy, 2014(1), 429518.

Devi, G.S., Vaishnavi, S., Srinath, S., Dutt, B., Rajmohan, K.S. (2020), Energy recovery from biomass using gasification. In: Current Developments in Biotechnology and Bioengineering: Resource Recovery from Wastes. Netherlands: Elsevier. p363-382.

Drumm, F.C., Gerhardt, A.E., Fernandes, G.D., Chagas, P., Sucolotti, M.S., Kemerich, P.D.C. (2014), Air pollution from the burning of fuels derived from petroleum in motor vehicles. Revista Eletrônica Em Gestão, Educação e Tecnologia Ambiental, 18(1), 66-78.

Eitan, A. (2021), Promoting renewable energy to cope with climate change-policy discourse in Israel. Sustainability, 13(6), 3170.

Foong, S.Y., Abdul Latiff, N.S., Liew, R.K., Yek, P.N.Y., Lam, S.S. (2020), Production of biochar for potential catalytic and energy applications via microwave vacuum pyrolysis conversion of cassava stem. Materials Science for Energy Technologies, 3, 728-733.

Gomez, R.D., Palacio, M., Arango, J.F., Avila, A.E., Mendoza, J.M. (2021), Evaluation of the energy generation potential by an experimental characterization of residual biomass blends from Córdoba, Colombia in a downdraft gasifier. Waste Management, 120, 522-529.

Gómez-Vásquez, R.D., Castiblanco, E.A., Zapata Benabithe, Z., Bula Silvera, A.J., Camargo-Trillos, D.A. (2021), CaCO3 and air/steam effect on the gasification and biohydrogen performance of corn cob as received: Application in the Colombian Caribbean region. Biomass and Bioenergy, 153, 106207.

Huang, C., Bensoussan, A., Edesess, M., Tsui, K.L. (2016), Improvement in artificial neural network-based estimation of grid connected photovoltaic power output. Renewable Energy, 97, 838-848.

Kabeyi, M.J.B., Olanrewaju, O.A. (2022), Sustainable energy transition for renewable and low carbon grid electricity generation and supply. Frontiers in Energy Research, 9, 743114.

Liu, G., Baniyounes, A.M., Rasul, M.G., Amanullah, M.T.O., Khan, M.M.K. (2013), General sustainability indicator of renewable energy system based on grey relational analysis. International Journal of Energy Research, 37(14), 1928-1936.

Luckow, P., Wise, M., Dooley, J.J., Kim, S.H. (2010), Large-scale utilization of biomass energy and carbon dioxide capture and storage in the transport and electricity sectors under stringent CO_2 concentration limit scenarios. International Journal of Greenhouse Gas Control, 4(5), 865-877.

Meller, L., Thuiller, W., Pironon, S., Barbet-Massin, M., Hof, A.F., Cabeza, M. (2014), Balance between climate change mitigation benefits and land use impacts of bioenergy: Conservation implications for European birds. GCB Bioenergy, 7(4), 741-751.

Mendoza Fandiño, J.M., Rhenals-Julio, J.D., Avila Gomez, A.E., Durando Padilla, E.R. (2021), Análise exergoeconômica da gasificação de sabugo de milho integrado em um sistema de geração de energia: Estudo de caso na Colômbia. Revista Virtual de Quimica, 76, 1-7.

Mendoza Martinez, C.L., Alves Rocha, E.P., Oliveira Carneiro, A.C., Borges Gomes, F.J., Ribas Batalha, L.A., Vakkilainen, E., Cardoso, M. (2019), Characterization of residual biomasses from the coffee production chain and assessment the potential for energy purposes. Biomass and Bioenergy, 120, 68-76.

Moazzem, S., Rasul, M.G., Khan, M.M.K., Moazzem, S., Rasul, M.G., Khan, M.M.K. (2012), A review on technologies for reducing CO_2 emission from coal fired power plants. In: Thermal Power Plants. London: IntechOpen.

Mogaji, T.S., Moses, E.O., Idowu, E.T., Jen, T.C., Bonilla, J.A. (2020), Thermal degradation conditions effects on selected biomass wastes and characterization of their produced biochar. Journal of Energy Research and Reviews, 4(3), 46-59.

Peñuelas, J., Carnicer, J. (2010), Climate change and peak oil: The urgent need for a transition to a non-carbon-emitting society. Ambio, 39(1), 85-90.

Pietrosemoli, L., Rodríguez-Monroy, C. (2013), The impact of sustainable construction and knowledge management on sustainability goals. A review of the Venezuelan renewable energy sector. Renewable and Sustainable Energy Reviews, 27, 683-691.

Rhenals-Julio, J.D., Castellar, J.G., Camargo, C.A., Mendoza, J.M. (2023), Technical-economic analysis of power generation with steam cycles fed with residual biomass from rice and corn. International Journal of Energy Economics and Policy, 13(5), 126-131.

Rhenals-Julio, J.D., Galván Castilla, M.K., Jorge, S.P., Mendoza, J.M. (2023), Exergoecological evaluation of power generation in steam cycles fed by biomass. International Journal of Energy Economics and Policy, 13(2), 537-544.

Ribeiro, A.P., Dalmolin, S. (2020), Biomass energy as a possibility for innovative agriculture initiatives. Energy Ecology and Environment, 6(4), 344-352.

Rose, S.K., Kriegler, E., Bibas, R., Calvin, K., Popp, A., Van Vuuren, D.P., Weyant, J. (2013), Bioenergy in energy transformation and climate management. Climatic Change, 123(3-4), 477-493.

Safa, M., Samarasinghe, S. (2011), Determination and modelling of energy consumption in wheat production using neural networks: "A case study in Canterbury province, New Zealand". Energy, 36(8), 5140-5147.

Safarian, S., Saryazdi, S.M.E., Unnthorsson, R., Richter, C. (2020), Dataset of biomass characteristics and net output power from downdraft biomass gasifier integrated power production unit. Data in Brief, 33, 106390.

Sagastume Gutiérrez, A., Mendoza Fandiño, J.M., Cabello Eras, J.J., Sofan German, S.J. (2022), Potential of livestock manure and agricultural wastes to mitigate the use of firewood for cooking in rural areas. The case of the department of Cordoba (Colombia), Development Engineering, 7, 100093.

Sagastume, A., Mendoza, J.M., Cabello, J.J., Rhenals, J.D. (2021), The available waste-to-energy potential from agricultural wastes in the department of Córdoba, Colombia. International Journal of Energy Economics and Policy, 11(3), 44-50.

Shahabuddin, M., Alam, M.T., Krishna, B.B., Bhaskar, T., Perkins, G. (2020), A review on the production of renewable aviation fuels from the gasification of biomass and residual wastes. Bioresource Technology, 312, 123596.

Singh Siwal, S., Zhang, Q., Sun, C., Thakur, S., Kumar Gupta, V., Kumar Thakur, V. (2020), Energy production from steam gasification processes and parameters that contemplate in biomass gasifier - A review. Bioresource Technology, 297, 122481.

Tun, M.M., Juchelková, D., Win, M.M., Thu, A.M., Puchor, T. (2019), Biomass energy: An overview of biomass sources, energy potential, and management in Southeast Asian countries. Resources, 8(2), 81.

Yakan à Nwai, C., Patel, B. (2023), Techno-economic study and environmental analysis for the production of bio-methanol using a solar-aided dual-bed gasifier. Waste and Biomass Valorization, 14(12), 4155-4171.

Zhang, X., Cai, Z.S., Chen, L.H., Ying, C. (2013), Analysis on biomass resources and potential of developing biomass energy in Yunnan province. Advanced Materials Research, 724-725, 212-215.