International Journal of Innovation and Applied Studies
ISSN 2028-9324 Vol. 44 No. 1 Nov. 2024, pp. 216-227
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http://www.ijias.issr-journals.org/

Development of sustainable biofuels from agricultural residue blends available in rural areas for electricity generation in Côte d'Ivoire

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ABSTRACT: As part of the global energy transition towards more sustainable solutions, it is crucial to reduce dependence on fossil fuels by exploring renewable alternatives. This study focuses on the optimization of agricultural residues to develop biofuels for thermal power plants in Côte d'Ivoire. The raw materials studied come from rice, coffee and cocoa crops, which are abundant in rural areas of the country. The aim is to assess the feasibility of creating energy-efficient biofuels that are compatible with power plant boilers, while meeting environmental sustainability criteria. To achieve this, a linear programming model was used to determine the optimum proportions of the various agricultural residues to produce usable blends. The model considers higher heating value, the reduction of pollutant emissions and the preservation of combustion equipment. The energy performance of the fuels is then analyzed using a biomass power plant model. The results led to the development of two types of sustainable biofuel: the first, made up of 68% rice husk and 32% coffee husk, has a higher heating value of 13.79 MJ/kg; the second, made up of 60% rice husk and 40% cocoa pod husk, has a higher heating value of 13.49 MJ/kg. These biofuels stand out for their ability to reduce pollutant emissions and preserve combustion equipment. Rice straw is added to these two fuels to form the matrix of sustainable biofuels to produce electricity from a biomass power plant in Côte d'Ivoire. This study shows that it is possible to make effective use of agricultural residues to create sustainable biofuels, thereby contributing to a transition towards a more sustainable energy mix.

KEYWORDS: Agricultural residue mixtures, Sustainable biofuels, Biomass, Agricultural residues, Power plant.

1 INTRODUCTION

The growing demand for energy, coupled with global environmental concerns, is driving many countries to explore sustainable alternative energy sources. This initiative aims to increase the share of renewable energy in the energy mix. To achieve this, the planet can also rely on its biomass potential. Currently, at the heart of several sustainable development projects, biomass is considered an alternative energy source to fossil fuels. Its use contributes to meeting energy needs, combating climate change, and preserving the natural resources of planet. Additionally, biomass combustion for electricity generation is a well-developed and competitive technology (Lakovou et al., 2012). However, biomass combustion in boilers faces several issues, including reduced thermal efficiency and the emission of acidic pollutants and harmful particles. Indeed, elements such as N, S, Cl, and inorganic compounds present in biofuels contribute to the formation of acidic pollutants and micro-particles, and are also responsible for ash fusion, leading to fouling and corrosion of boiler walls (Obernberger et al., 2006).

Moreover, the transport of biomass to power plants increases greenhouse gas emissions (Zinla et al., 2021 and 2022).

To address the technical and environmental constraints associated with biomass combustion technologies, this study examines the possibility of developing more sustainable biofuels from agricultural residue blends. According to Edmunds et al.

(2018), blending different types of biomass to produce homogeneous raw materials offers a solution to problems related to the variability of physicochemical properties, seasonal and geographical availability of biomass, and allows for better control over raw material specifications. In this context, determining the optimal proportions of each biomass in the blend would ensure the effectiveness of this approach.

To identify the best ratios of raw materials in the production of high-quality briquettes from cashew nut industry waste, Sawadogo et al. (2018) conducted a series of experimental tests on 15 briquette samples with varying proportions of water, binder, and biochar. These tests analyzed the physical, chemical, and energy characteristics of the produced briquettes. By evaluating properties such as calorific value, mechanical strength, and density, the researchers identified optimal formulations that produced a fuel with performance like charcoal. Gomez et al. (2021) assessed the energy potential of various agricultural residue blends using a commercial gasifier, testing 32 different configurations. Their study revealed that increasing the proportion of a specific element in the blend reduced the quality of the synthesis gas and the efficiency of the gasification process. Specifically, a high concentration of this element led to less favorable conditions for gas production. Nevertheless, the study also identified optimal configurations where the efficiency of gasifier was maximized. Castro et al. (2023) analyzed blends of brewery spent grains and eucalyptus wood chips to optimize steam production in a cogeneration system. By experimenting with 6 combinations with varying proportions, the study identified the optimal blend, which improved the energy performance of the system compared to the exclusive use of wood chips.

These various studies have employed iterative methods to characterize fuels from different agricultural residue blends. However, these approaches are often limited by empirical testing, which may not always precisely define the sought-after optimal proportions. This study proposes an innovative analytical method to accurately determine the optimal ratios of the main components of a biofuel intended for biomass thermal power plants. This method is particularly suited to complex agricultural residue blends, offering a more effective and precise approach to optimizing biofuel formulations.

2 METHODOLOGY

2.1 MATERIALS

2.1.1 CHARACTERISTICS OF AGRICULTURAL RESIDUES

The agricultural residues studied in this research include rice husks, rice straw, coffee husks, and cocoa pod husk. These materials were selected due to their abundance in rural areas and their potential as sustainable resources for electricity generation in Côte d'Ivoire. The average energy potential of these crop residues is approximately 54.03 PJ per year, distributed as follows: cocoa pod husk (30.18 PJ/year), rice straw (18.82 PJ/year), rice husk (4.54 PJ/year), and coffee husk (0.49 PJ/year) (Koua et al., 2022). The thermochemical characteristics of these residues are detailed in the literature, providing essential information for their energy utilization and management. Table 1 summarizes data on their elemental and proximate compositions, as well as the Higher Heating Value (HHV). Table 2 presents a detailed analysis of the residual ash, including the distribution of chemical elements (Zinla et al., 2021).

Table 1. Elemental and proximate composition (% wt.), and HCV (MJ/kg) of rice husk, rice straw, coffee husk and cocoa pod husk (Zinla et al., 2021)

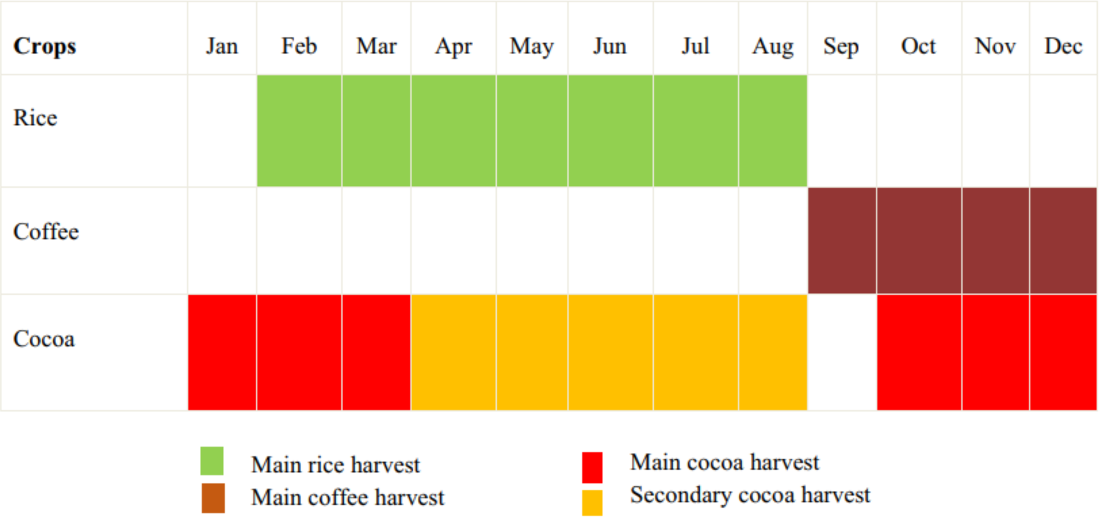
	Elemental composition							Immediate composition			
Residues	**C**	**H**	**N**	**S**	**O**	**Cl**	**HHV**	**Moisture**	**Volatile matter**	**Ash**	**Fixed carbon**
Rice husk	37.02	5.56	0.95	0.21	56.26	0.02	13.35	7.82	64,02	14,96	13,2
Rice straw	33.51	4.73	0.50	0.26	61.00	0.30	10.49	9.52	64,86	23,7	1,92
Coffee husk	39.68	5.41	3.01	0.32	51.58	0.27	14.71	11.3	72,94	8	7,76
Cocoa pod husk	37.36	5.60	1.59	0.22	55.23	0.07	13.70	12.33	66,32	10,77	10,61

Table 2. Composition (wt.%) of the ashes of the rice husk, rice straw, coffee husk and cocoa pod husk (Zinla et al., 2021)

Residues	K_2O	CaO	MgO	P_2O_5	SO_3	SiO_2	CuO	Cl	PbO	CoO	Fe_2O_3	MnO	Na_2O	WO_3	ZnO	NiO	Al_2O_3
Rice husk	6.98	0.67	2.25	4.95	0.15	74.78	0.35	0.15	--	0.22	0.3	0.2	0.1	8.68	0.1	0.12	--
Rice straw	13	4.33	1.95	1.48	0.95	64.45	0.72	1.27	--	0.16	0.9	0.6	0.67	8.74	0.32	--	0.46
Coffee husk	72.05	9.76	3.02	2.55	3.54	1.65	0.59	3.35	1.67	0.17	0.73	0.14	0.26	--	0.12	0.4	--
Cocoa pod husk	77.53	6.82	5.5	2.81	2.56	1.35	1.18	0.65	0.6	0.35	0.3	0.23	0.12	--	--	--	--

A thorough understanding of the crop production seasons could not only facilitate storage operations but also significantly reduce transport costs associated with the residues (Koua et al., 2022). Indeed, this would optimize logistical planning by synchronizing harvest periods with available storage capacities. Additionally, precise management of agricultural seasons would help minimize delays and transport costs, while ensuring better preservation of agricultural residues throughout the supply chain.

In Côte d'Ivoire, there are two annual harvest periods for cocoa beans and paddy rice, as well as one period for green coffee beans. The main cocoa harvest runs from October to March, followed by an intermediate harvest from April to August. For rice, the production season typically extends from February/March to August. Green coffee beans are harvested exclusively from September to December. Figure 1 illustrates the harvest periods for rice, coffee, and cocoa in Côte d'Ivoire (Koua et al., 2022). Additionally, Figure 2 shows the production trends for cocoa beans, green coffee beans, and paddy rice in Côte d'Ivoire from 2013 to 2022 (FAO, 2024). This period highlights distinct dynamics for each product. Since 2017, cocoa bean production in Côte d'Ivoire has shown a generally positive trend. It increased from approximately 2,030,000 tons in 2017 to 2,200,000 tons in 2020, before stabilizing around 2,230,000 tons from 2021. This stable growth can be attributed to several factors, such as improved agricultural practices, the introduction of disease-resistant cocoa varieties, and political and economic support from donors (Bockel et al., 2021).



Crops	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rice		🟩	🟩	🟩	🟩	🟩	🟩	🟩				
Coffee									🟫	🟫	🟫	🟫
Cocoa	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟨		🟥	🟥	🟥

🟩 Main rice harvest
🟫 Main coffee harvest
🟥 Main cocoa harvest
🟨 Secondary cocoa harvest

Fig. 1. Harvest periods for rice, coffee and cocoa crops (Koua et al., 2022)

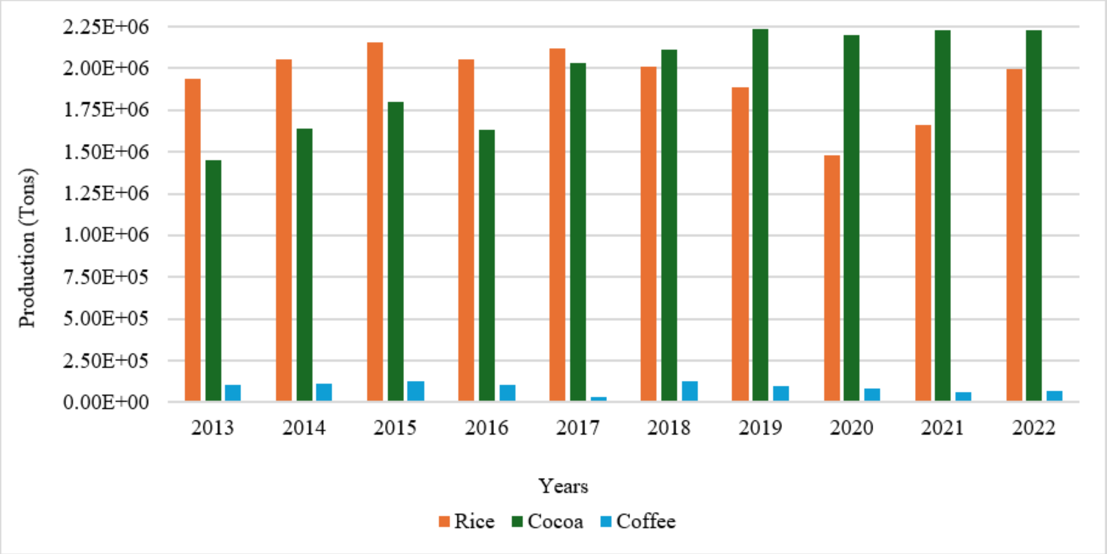


Fig. 2. Trends in production of cocoa beans, green coffee beans and paddy rice in Côte d'Ivoire from 2013 to 2022

In contrast, paddy rice production has experienced a fluctuating trend over the same period, with an average annual production of about 1,860,000 tons. This variability is due to various factors, including climatic conditions, limited access to advanced agricultural technologies and storage infrastructure, and insufficient support for producers (Ouedraogo et al., 2021). Lastly, green coffee bean production has shown a declining trend since 2019, dropping from 95,200 tons in 2019 to approximately 70,000 tons in 2022. This decrease can be explained by several factors, such as reduced cultivated areas due to the expansion of more profitable cocoa crops, ageing coffee plantations, and less government support compared to other agricultural sectors.

Crop residues are omnipresent in production areas throughout the harvest periods (Koua et al., 2022). Figure 3 presents a detailed map of the main production regions for cocoa beans, green coffee beans, and paddy rice in Côte d'Ivoire. This map reveals that residues from all three crops are particularly abundant in five regions: Tonkpi, Guémon, Haut-Sassandra, Cavally, and Lôh-Djibouah. Additionally, waste from cocoa and rice crops is also found in large quantities in six other key regions: Marahoué, Gôh, Nawa, San-Pedro, Gbôklé, and Agnéby-Tiassa. Cocoa residues are also present in three southeastern regions: Indénié-Djuablin, Moronou, and La Mé. Finally, rice cultivation also results in a high concentration of residues in the northern regions of the country (Esso, 2009; FAO et al., 2019; Koua et al., 2022).

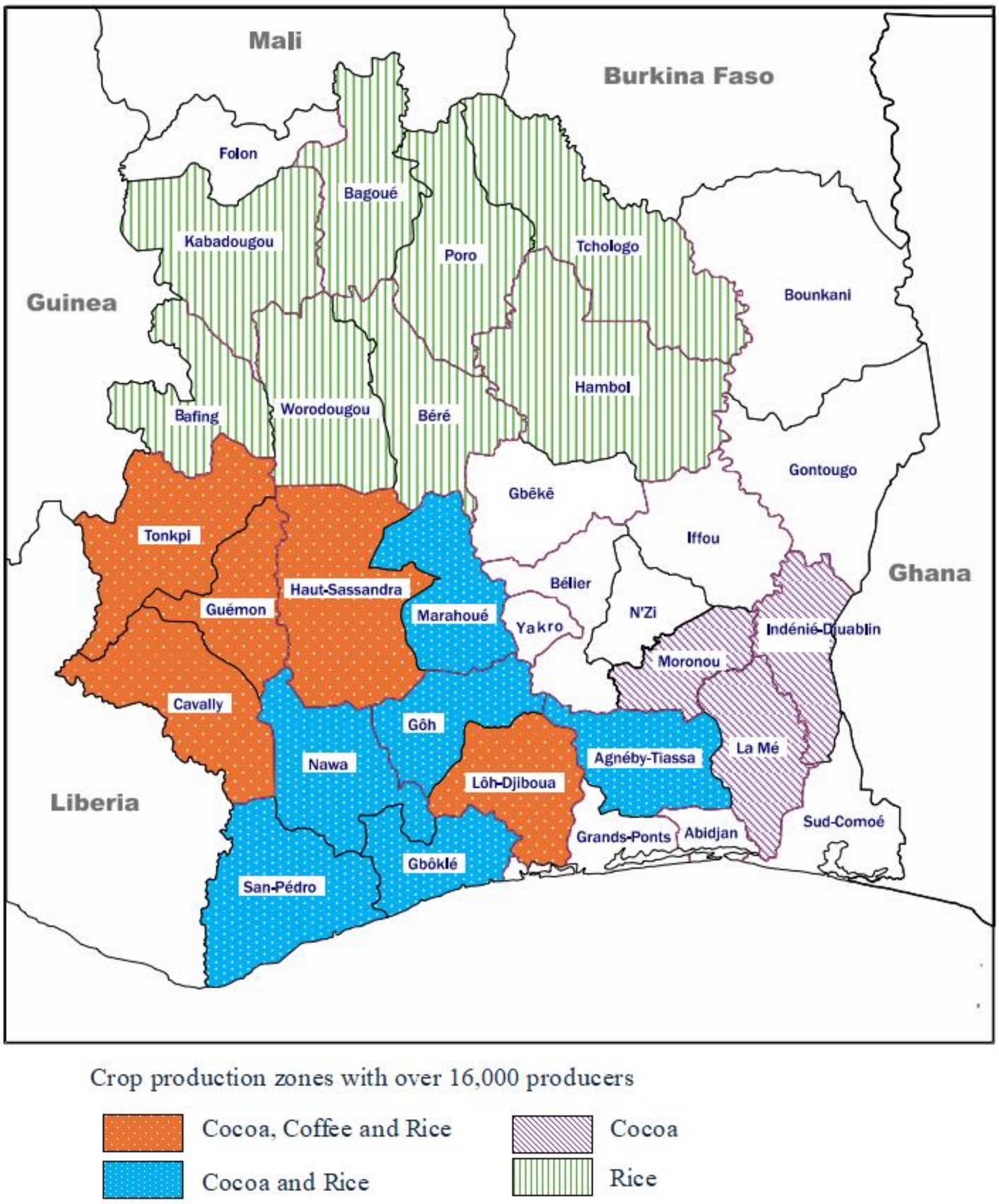


Fig. 3. Main regions producing cocoa beans, green coffee beans and paddy rice in Côte d'Ivoire

2.1.2 MODELLING A BIOMASS THERMAL POWER PLANT

To evaluate the energy efficiency of biofuels, a model of a 5 MW biomass thermal power plant was developed based on the Hirn steam cycle, a technology known for its high efficiency. This model is built on the precise data from the study by Sahoo et al. (2016), allowing for a thorough analysis of the energy performance of the biofuels. The layout of the plant is illustrated in Figure 4. The installation comprises 5 main components: a biomass boiler, a two-stage steam turbine, a condenser, two pumps (low and high pressure), and a Feed Water Heater equipped with a deaerator.

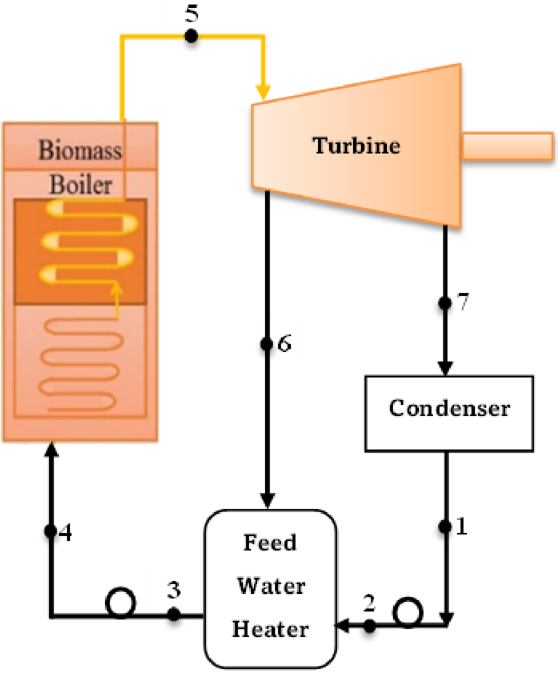


Fig. 4. Schematic diagram of the steam power plant

The boiler generates steam at a pressure of 60 bars and a temperature of 500°C, which drives the turbine at a flow rate of 5 kg/s. After passing through the turbine, the steam is condensed in the condenser; the condensed water is then pumped to a pressure of 5 bars and mixed with the purge steam before being returned to the boiler. Table 3 provides the efficiency ratings of the turbine, pumps, and boiler.

Table 3. Turbine, pump and boiler efficiencies (Sahoo et al., 2016)

Equipments	efficiencies (%)
Turbine	96
Pumps	88
Boiler	80

2.2 METHODS

2.2.1 CHARACTERIZATION OF BIOFUELS

The authors (Cozzani et al., 1995; Skodras et al., 2009; Danias et al., 2018) have revealed that the interactions between components of lignocellulosic biomass blends are negligible. The studies by Heikkinen et al. (2004) and Farrow et al. (2013) also demonstrated that the thermochemical characteristics of these blends can be determined by taking a weighted sum of the properties of the individual constituents.

This research opens the way to a new method for optimizing biofuels. Therefore, to design sustainable biofuels from agricultural residue blends, this study proposes a linear programming model to determine the ideal proportions of these residues. The objective is to maximize the energy content while adhering to regulatory limits for elements N, S, Cl, K, Ca, and Zn. This approach ensures not only optimal energy performance but also contributes to the sustainability of the biofuels by minimizing environmental and technological impacts. The objective function of the linear programming is defined by relation (1).

Maximize: $$\boldsymbol{HHV_{Blend} = \sum_{i=1}^{n} X_i(\llbracket HHV)\rrbracket_i} \qquad (1)$$

Where: $\boldsymbol{HHV_{Blend}}$ is the Higher Heating Value (MJ/kg) of the blend, $\boldsymbol{X_i}$ is the proportion (%) of the *i-th* residue in the blend and ($\boldsymbol{\llbracket HHV)\rrbracket_i}$ is the Higher Heating Value of the *i-th* residue.

According to Nussbaumer et al. (1997), Obernberger (2003), and Nussbaumer (2003), the emissions of acidic pollutants such as NOx, SOx, HCl, and PCDD/F during combustion in a boiler are directly related to the concentrations of the elements N, S, and Cl in the biofuel. Specifically, high concentrations of chlorine (exceeding 0.1%) lead to emissions of HCl and PCDD/F. Similarly, concentrations of sulphur above 0.2% generate SOx emissions, while NOx is produced when the nitrogen concentration exceeds 0.6%. Furthermore, corrosion issues can occur in the boiler when chlorine and sulphur concentrations exceed 0.1% respectively (Obernberger et al., 2006). The requirements for S, Cl, and N concentrations in the biofuel to ensure clean and trouble-free combustion are specified by relations (2), (3), and (4).

$$\boldsymbol{\sum_{i=1}^{n} X_i(S)_i \le 0.001} \qquad (2)$$

$$\boldsymbol{\sum_{i=1}^{n} X_i(Cl)_i \le 0.001} \qquad (3)$$

$$\boldsymbol{\sum_{i=1}^{n} X_i(N)_i \le 0.006} \qquad (4)$$

Where: $\boldsymbol{(S)_i}$, $\boldsymbol{(Cl)_i}$ and $\boldsymbol{(N)_i}$ are the concentrations (%) of S, Cl and N in the *i-th* residue in the blend.

Ashes produced undergo various thermal and chemical transformations. The main inorganic components of ash play a crucial role in influencing the melting temperature, agglomeration in the boiler, and corrosion of metal surfaces (Van et al., 2002; Spiegel, 2004). Potassium (K) is particularly significant as a primary catalyst in these processes. Due to its low melting temperature, potassium reacts with silicates or refractory materials in the combustion bed, forming eutectic mixtures that melt at temperatures lower than those of their individual constituents. These compact mineral aggregates can suffocate combustion and obstruct ash removal, thereby exacerbating the corrosion of metal surfaces (Mikkanen et al., 1999; Nielson et al., 2000; Armesto et al., 2002).

The presence of alumina (Al_2O_3), magnesium oxide (MgO), calcium oxide (CaO), iron oxide (Fe_2O_3), or silicon dioxide (SiO_2) in the ash increases its melting point, while the presence of phosphorus pentoxide (P_2O_5), sodium oxide (Na_2O), or potassium oxide (K_2O) decreases it (Obernberger et al., 2006; Armesto et al., 2002; Du et al., 2014). Generally, a potassium concentration in the ash above 7% significantly lowers its melting temperature. However, this temperature can be elevated when the calcium concentration exceeds 15%. Ashes can also lead to the emission of fine particles or be recycled or reused, if potassium and zinc concentrations remain below certain indicative limits (Obernberger et al., 2006). The constraints related to the concentrations of K_2O, ZnO, and CaO in the biofuel ash for clean and trouble-free combustion are defined by equations (5), (6), and (7).

$$\boldsymbol{\frac{\sum_{i=1}^{n} X_i Ash_i \llbracket (K\rrbracket_2 O)_i}{\sum_{i=1}^{n} X_i Ash_i} \le 0.07} \qquad (5)$$

$$\boldsymbol{\frac{\sum_{i=1}^{n} X_i Ash_i (ZnO)_i}{\sum_{i=1}^{n} X_i Ash_i} \le 0.0008} \qquad (6)$$

$$\boldsymbol{\frac{\sum_{i=1}^{n} X_i Ash_i (CaO)_i}{\sum_{i=1}^{n} X_i Ash_i} \le 0.15} \qquad (7)$$

Where: $\boldsymbol{Ash_i}$ is the concentrations (%) of Ash in the *i-th* residue in the blend, $\boldsymbol{\llbracket (K\rrbracket_2 O)_i}$, $\boldsymbol{(CaO)_i}$, $\boldsymbol{\llbracket (Z\rrbracket_n O)_i}$ are the concentrations (%) of $\boldsymbol{K_2O}$, $\boldsymbol{CaO}$ and $\boldsymbol{Z_nO}$ in the ash of the *i-th* residue in the blend.

The constraints related to the optimal ratios are defined by equations (8) and (9).

$$\boldsymbol{\sum_{i=1}^{n} X_i = 1} \qquad (8)$$

$$\boldsymbol{X_1, X_2, \dots, X_n \ge 0} \qquad (9)$$

The residues from rice, coffee, and cocoa crops exhibit nitrogen (0.95%–3.01%), sulphur (0.21%–0.32%), and potassium (13%–77.53%) concentrations that exceed permissible thresholds. Consequently, these constraints cannot be incorporated into the linear programming model used to determine the optimal ratios in the formulation of sustainable biofuels from these mixtures. However, technical solutions available in the literature can be implemented to reduce NOx and SOx emissions.

2.2.2 ANALYSIS OF THE ENERGY PERFORMANCE OF BIOFUELS

In the analysis of performance and optimization of energy systems, several authors rely on the laws of thermodynamics. Researchers such as Singh et al. (2000), Beerbaum and Weinrebe (2000), Kaushik et al. (2001), Kosugi and Pak (2003), Montes et al. (2009), Kalogirou (2009), and Morin et al. (2012) have applied the first law of thermodynamics for the energy analysis of hybrid power plants. This law, also known as the principle of conservation of energy, states that the total energy of an isolated system remains constant. By applying this law, researchers have been able to quantify the incoming energy, compare it to the energy produced, and assess the losses. This has allowed for the measurement of system efficiency, identification of areas needing improvement, and development of strategies to optimize energy production while minimizing losses.

Exergy analysis, on the other hand, relies on the second law of thermodynamics to evaluate the efficiency of processes by identifying exergy losses and deviations from an ideal state. This approach helps to pinpoint the least efficient stages, understand the impact of thermodynamic phenomena, and propose the best solutions for system optimization (Szargut et al., 1988). To assess the energy performance of biofuels, the energy and exergy efficiencies of the biomass thermal power plant model are the two key parameters considered. These efficiencies are determined following the energy and exergy analyses of the steam thermal plant. Table 4 provides the thermodynamic properties of the steam in the installation required for the calculation.

Table 4. Thermodynamic properties of steam in the biomass power plant

Point	Pressure (bar)	Temperature (C)	Enthalpy (kJ/kg)	Entropy (kJ/kg K)	Mass flow rate (kg/s)
1	0.1	45.82	191.8	0.6493	4.269
2	5	45.85	192.4	0.6495	4.269
3	5	98.84	414.5	1.293	5
4	60	99.44	421.1	1.296	5
5	60	500	3422	6.881	5
6	5	204.60	2865	7.079	0.731
7	0.1	45.82	2330	7.352	4.269

2.2.2.1 ENERGY ANALYSIS

The energy efficiency of the thermal power plant is defined by relation (10).

$$\boldsymbol{\eta_{en}} = \frac{W_{net}}{Q_{biom}} \tag{10}$$

Where: $\boldsymbol{\eta_{en}}$ is the energy efficiency of the biomass thermal power plant, $\boldsymbol{W_{net}}$ is the Net power of the biomass thermal power plant (kW) and $\boldsymbol{Q_{biom}}$ is the total heat produced from biomass (kW).

Relations (11), (12), (13), and (14) respectively allow for the determination of the net power of the installation ($\boldsymbol{W_{net}}$), the thermal power produced by the combustion of biomass ($\boldsymbol{Q_{biom}}$), the thermal power of the boiler ($\boldsymbol{Q_{boiler}}$), and the lower heating value ($\boldsymbol{LHV}$) (Sahoo et al., 2016).

$$\boldsymbol{W_{net} = m[\alpha(h_5 - h_6) + (1 - \alpha)(h_5 - h_7)]} \tag{11}$$

$$\boldsymbol{Q_{biom} = m_{biom} * LHV} \tag{12}$$

$$\boldsymbol{Q_{boiler} = m(h_5 - h_4) = \eta_{boiler} * Q_{biom}} \tag{13}$$

$$\boldsymbol{LHV = HHV - (226.04 * H) - 25.82 * w} \tag{14}$$

Where: m is the mass flow rate of steam (kg/s), α is the fraction of steam extracted from the turbine, $\boldsymbol{m_{biom}}$ is the mass flow rate of the biomass feeding the boiler (kg/s), $\boldsymbol{\eta_{boiler}}$ is the energy efficiency of the boiler, H is the hydrogen content of the biomass (%), w is the moisture content of the biomass (%), LHV is the lower heating value of the biomass (kJ/kg) and HHV is the higher heating value of the biomass (kJ/kg).

2.2.2.2 EXERGY ANALYSIS

The exergy efficiency of the biomass thermal power plant is defined by relation (15).

$$\boldsymbol{\eta_{ex} = \frac{W_{net}}{E_{X,biom}}} \quad (15)$$

Where: $\boldsymbol{\eta_{ex}}$ is the exergy efficiency of the biomass thermal power plant, and $\boldsymbol{E_{X,biom}}$ is the Exergy associated with the biomass flow (kW).

The exergy associated with the biomass flow is equal to the sum of its physical exergy and its chemical exergy. The physical exergy of the biomass is neglected as its initial state is the same as the reference environment state. Therefore, its exergy is equal to its chemical exergy, which is determined by relation (16) (Sahoo et al., 2016).

$$\boldsymbol{E_{X,biom} = m_{biom} * \phi * LHV} \quad (16)$$

Where: $\boldsymbol{\phi}$ is a multiplying factor determined by relation (17) (Szargut, 2005).

$$\boldsymbol{\phi = 1.0401 + 0.1728 * \frac{H}{C} + 0.0432 * \frac{N}{C} + 0.2169 * \frac{O}{C} * \left(1 - 0.2062 * \frac{H}{C}\right)} \quad (17)$$

Where: C, H, O and N are the dry biomass weight (%) of carbon, hydrogen, oxygen and nitrogen.

The exergy efficiency of the thermal power plant can also be defined based on the energy efficiency and the factor ϕ according to relation (18).

$$\boldsymbol{\eta_{ex} = \frac{1}{\phi} * \eta_{en}} \quad (18)$$

3 RESULTS AND DISCUSSION

3.1 CHARACTERIZATION OF BIOMASS FUELS

The characterization study of biomass fuels reveals that only two types of sustainable biofuels can be produced from blends of rice, coffee, and cocoa residues. The first biofuel (B1) consists of 68% rice husk and 32% coffee husk, while the second biofuel (B2) contains 60% rice husk and 40% cocoa pod husk. Table 5 presents the nitrogen (N), sulfur (S), chlorine (Cl) concentrations, ash content, and the higher heating value (HHV) of these biofuels. The analysis indicates a significant improvement in the concentrations of certain chemical elements and the heating values of the blends compared to the base residues. However, the concentrations of nitrogen and sulfur remain above the permissible limits, raising concerns about the corrosion of heat exchangers caused by acidic pollutants (NOx and SOx), especially when flue gases reach their acid dew point in the exhaust ducts (Ghysel et al., 2010).

Table 5. Elemental composition (% wt.) of N, S, Cl, Ash and HHV (MJ/kg) of biofuels

			Composition		
Biofuels	N	S	Cl	HHV	Ash
B1	1.61	0.25	0.10	13.79	12.73
B 2	1.21	0.21	0.04	13.49	13.28

3.2 ASH COMPOSITION

An improvement is also noted in the ash composition of the biofuels. The ashes produced contain a greater proportion of refractory materials (SiO_2, CaO, MgO, Fe_2O_3) compared to alkaline materials (K_2O). Figure 5 shows the distribution of the main inorganic components in the ashes. Nonetheless, problems related to ash agglomeration and ash-related corrosion may occur, especially at high combustion temperatures. During combustion, alkaline oxides or salts can react with refractory compounds to form eutectic mixtures (e.g., $K_2O{\cdot}CaO{\cdot}6SiO_2$, $K_2O{\cdot}4SiO_2$, $K_2Fe_2O_4$), whose melting points exceed 740°C (Mikkanen et al., 1999; Nielson et al., 2000; Armesto et al., 2002). These phenomena may intensify during the combustion of coffee and cocoa residues, as these residues generate ashes with higher potassium oxide concentrations, with a melting temperature around 350°C (Bardeau, 2009).

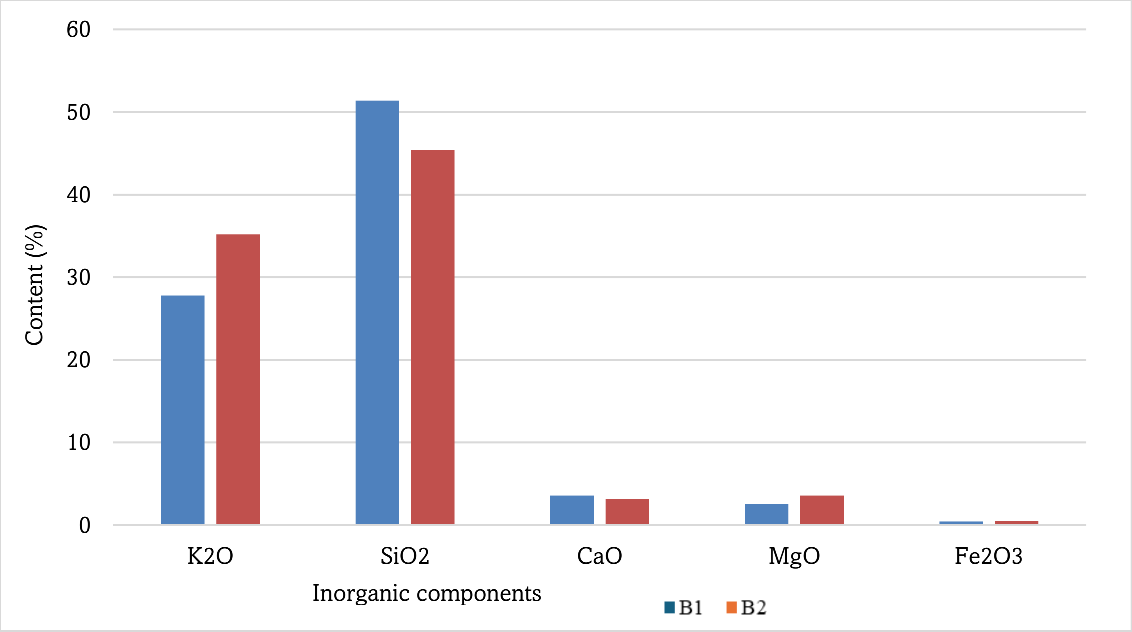


Fig. 5. Distribution of the main inorganic components in the ashes of biofuels

3.3 ENERGY AND EXERGY ANALYSIS

The energy analysis shows that the combustion of these fuels provides an energy efficiency of approximately 27% for the steam thermal plant. This indicates that nearly 73% of the thermal energy produced by biomass combustion is lost. In contrast, the exergy efficiency ranges between 18.64% and 20.13%, depending on the type of biofuel used in the boiler. Therefore, between 18.64% and 20.13% of the energy from the combustion of biofuels is converted into mechanical work to drive the electric generator. Figure 6 illustrates the exergy efficiencies of the biofuels in the thermal plant. The lowest exergy efficiency is observed with rice straw, while the highest is achieved with coffee husks.

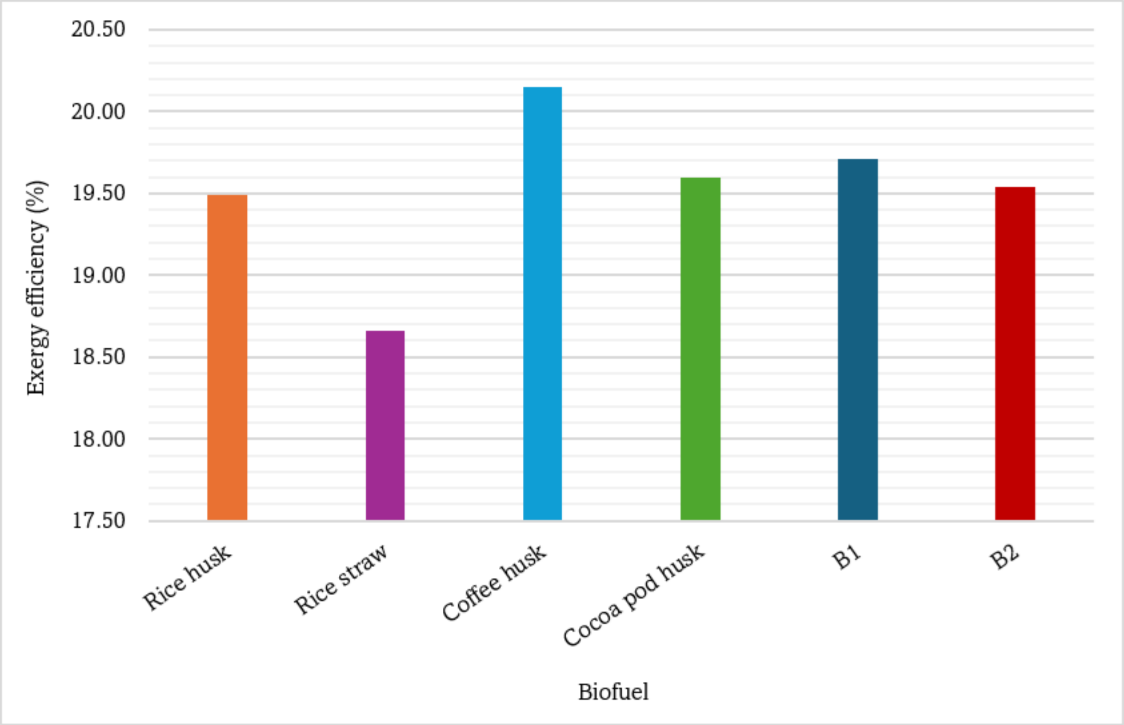


Fig. 6. Exergy efficiency of thermal power plant as a function of biofuel

3.4 ENVIRONMENTAL CONSIDERATIONS

The studied crop residues are found to be sustainable biofuels for environmental protection when used in a biomass thermal power plant (Zinla et al., 2021). The carbon dioxide emitted during their combustion is considered neutral since the amount released equals that absorbed by the plants during their growth (Saidur et al., 2011). Moreover, nitrogen oxides, sulfur oxides, and particulates can be captured or reduced using electrostatic filters or by implementing staged combustion with air or fuel. Chlorine content can also be reduced through leaching (Obernberger et al., 2006; Khan et al., 2009).

In the context of optimizing availability and improving the quality of biomass, rice straw, as well as biofuels B1 and B2, offer a promising basis for sustainable biofuels aimed at efficient energy utilization of residues in a biomass thermal power plant for electricity production in Côte d'Ivoire.

4 CONCLUSION

The study investigates the possibility of developing sustainable biofuels from mixtures of residues from rice, coffee, and cocoa crops with the aim of producing electricity in Côte d'Ivoire, thereby enabling the sustainable utilization of these resources. Based on the results and observations from various experimental studies, this research develops an analytical approach using a linear programming model subject to constraints related to the problematic concentrations of biofuel components, to determine the optimal ratios of the mixture constituents.

The analysis reveals that it is feasible to produce only two types of sustainable biofuels from the residue mixtures of rice, coffee, and cocoa crops. Specifically, rice straw as well as biofuels B1 and B2 form the basis for sustainable biofuels derived from the residues of rice, coffee, and cocoa crops for electricity generation from a biomass power plant in Côte d'Ivoire. However, the study recommends pre-washing the various biofuels before combustion in the boiler to reduce their chlorine content. Additionally, it suggests installing electrostatic filters on the boilers and/or employing staged combustion techniques with the fuel or air to reduce emissions of NOx, SOx, and harmful microparticles.

REFERENCES

[1] Armesto L., Bahillo A., Veijonen K., Cabanillas A., Otero J. (2002). Combustion behaviour of rice husk in a bubbling fluidised bed. Biomass and Bioenergy, 23, 171-179.

[2] Bardeau G. (2009). Etude de la faisabilité de produire des combustibles à partir de mélanges de coproduits agricoles. Rapport de master, ENSTIB.

[3] Beerbaum, S., & Weinrebe, G. (2000). Solar thermal power generation in India—a techno–economic analysis. Renewable energy, 21 (2), 153-174.

[4] Bockel, L.; Ouedraogo, S.A.; Auguste, K.A.; Gopal, P. (2021). Analyse prospective de la filière cacao en Côte d'Ivoire 2020-2030 - Vers une politique commune de marché de cacao en Afrique de l'Ouest. Accra, FAO. https://doi.org/10.4060/cb6508fr.

[5] Cao W., Li J., Martí-Rosselló T., et al. (2019). Experimental study on the ignition characteristics of cellulose, hemicellulose, lignin and their mixtures. Journal of the Energy Institute 92: 1303–1312.

[6] Castro, L. E. N., Sganzerla, W. G., Matheus, L. R., Mançano, R. R., Ferreira, V. C., Barroso, T. L. C. T.,... & Colpini, L. M. S. (2023). Application of brewers' spent grains as an alternative biomass for renewable energy generation in a boiler combustion process. Sustainable Chemistry for the Environment, 4, 100039. https://doi.org/10.1016/j.scenv.2023.100039.

[7] Cozzani V., Petarca L. and Tognotti L. (1995). Devolatilization and pyrolysis of refuse derived fuels: Characterization and kinetic modelling by a thermogravimetric and calorimetric approach. Fuel 74: 903–912.

[8] Danias P. and Liodakis S. (2018). Characterization of refuse derived fuel using thermogravimetric analysis and chemometric techniques. Journal of Analytical Chemistry 73: 351–357.

[9] Du, S., Yang, H., Qian, K., Wang, X., Chen, H. (2014). Fusion and transformation properties of the inorganic components in biomass ash. Fuel 117, 1281–1287. https://doi.org/10.1016/j.fuel.2013.07.085

[10] Edmunds, C.W., Reyes Molina, E.A., André, N., Hamilton, C., Park, S., Fasina, O., Adhikari, S., Kelley, S.S., Tumuluru, J.S., Rials, T.G., Labbé, N. (2018). Blended Feedstocks for Thermochemical Conversion: Biomass Characterization and Bio-Oil Production from Switchgrass-Pine Residues Blends. Front. Energy Res. 6, 79. https://doi.org/10.3389/fenrg.2018.00079.

[11] Esso Loesse Jacques (2009) Dynamique des recettes du café et du cacao en côte d'ivoire. Juillet 2009: 19.

[12] FAO et le ministère de l'Agriculture et du développement rural, Côte d'Ivoire Abidjan (2019) L'atlas des résultats du recensement des exploitants et exploitations agricoles, http://www.fao.org/3/ca311 1fr/CA3111FR.pdf

[13] FAOSTAT, http://www.fao.org, Consulted on: June 30, 2024.

[14] Farrow T. S., Sun C. and Snape C.E. (2013). Impact of biomass char on coal char burn-out under air and oxy-fuel conditions. Fuel 114: 128–134.

[15] Ghysel F., Godin B., Flamin C., Delfosse P., Delcarte J., et Stilmant D. (2010). « Valorisation énergétique des fourrages : comparaison de trois filières, enjeux et opportunités », p. 13.

[16] 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. https://doi.org/10.1016/j.wasman.2020.10.014

[17] Heikkinen J, Hordijk Jd, de Jong W, et al. (2004). Thermogravimetry as a tool to classify waste components to be used for energy generation. Journal of Analytical Applied Pyrolysis 71: 883–900.

[18] Kalogirou, S. A. (2004). Solar thermal collectors and applications. Progress in energy and combustion science, 30 (3), 231-295.

[19] Kaushik, S. C., Abhyankar, Y. P., Bose, S., & Mohan, S. (2001). Exergoeconomic evaluation of a solar thermal power plant. International journal of solar energy, 21 (4), 293-314.

[20] Khan A.A., de Jong W., Jansens P.J., Spliethoff H., (2009). Biomass combustion in fluidized bed boilers: Potential problems and remedies. Fuel Processing Technology 90, 21–50.

[21] Kosugi, T., & Pak, P. S. (2003). Economic evaluation of solar thermal hybrid H2O turbine power generation systems. Energy, 28 (3), 185-198.

[22] Koua, B. K., Zinla, D. B. T., Koffi, P. M. E., & Gbaha, P. (2022). Assessment of the energy potential of agricultural crop residues in rural areas of Côte d'Ivoire. Biomass Conversion and Biorefinery, 1-14.

[23] Lakovou, E., Vlachos, D., & Toka, A. (2012). Integrating waste biomass into thermal energy production systems: a strategic methodological framework. Civil Engineering and Environmental Systems, 29 (4), 255-272. https://doi.org/10.1080/10286608.2012.710610.

[24] Mikkanen P. et colb. (1999). Alkali salt ash formation in four Finnish industrial recovery boilers. Energy and Fuels, 13, 778–95.

[25] Montes, M. J., Abánades, A., & Martínez-Val, J. M. (2009). Performance of a direct steam generation solar thermal power plant for electricity production as a function of the solar multiple. Solar Energy, 83 (5), 679-689.

[26] Morin, G., Dersch, J., Platzer, W., Eck, M., & Häberle, A. (2012). Comparison of linear Fresnel and parabolic trough collector power plants. Solar energy, 86 (1), 1-12.

[27] Nielsen H. P., Baxter L. L., Sclippab G., Morey, C., Frandsen F. J., Dam-Johansen K. (2000). Deposition of potassium salts on heat transfer surfaces in straw-fired boilers: a pilot-scale study. Fuel, 79, 131-139.

[28] Nussbaumer, T. (2003). Combustion and co-combustion of biomass: fundamentals, technologies, and primary measures for emission reduction. Energy & fuels, 17 (6), 1510-1521.

[29] Nussbaumer, T., & Hasler, P. (1997). Formation and Reduction of Polychlorinated Dioxins and Furans in Biomass Combustion: Dioxin emissions from biomass combustion. Developments in Thermochemical Biomass Conversion: Volume 1/Volume 2, 1492-1506.

[30] Obernberger I., Brunner T., et Barnthaler G. (2006). Chemical properties of solid biofuels—significance and impact. Biomass and Bioenergy, vol. 30, no 11, p. 973 982, doi: 10.1016/j.biombioe.2006.06.011

[31] Obernberger, I. (2003). Physical characteristics and chemical composition of solid biomass fuels. Thermochemical Biomass Conversion. Eindhofen University of Technology.

[32] Ouedraogo, S.A., Bockel, L., Arouna, A., Fatognon, I. et Gopal, P. (2021). Analyse de la chaine de valeur riz en Côte d'Ivoire: Optimiser l'impact socio-économique et environnemental d'un scénario d'autosuffisance à l'horizon 2030. Accra, FAO. https://doi.org/10.4060/cb1506fr.

[33] Raveendran K., Ganesh A. and Khilar K. C. (1996). Pyrolysis characteristics of biomass and biomass components. Fuel 75: 987–998.

[34] Sahoo, U., Kumar, R., Pant, P.C., Chaudhary, R., (2016). Resource assessment for hybrid solar-biomass power plant and its thermodynamic evaluation in India. Solar Energy 139, 47–57. https://doi.org/10.1016/j.solener.2016.09.025

[35] Saidur R., Abdelaziz E.A., Demirbas A., Hossain M.S., Mekhilef S. (2011). A review on biomass as a fuel for boilers. Renewable and Sustainable Energy Reviews 15, 2262–2289.

[36] Sawadogo, M., Tchini Tanoh, S., Sidibé, S., Kpai, N., Tankoano, I. (2018). Cleaner production in Burkina Faso: Case study of fuel briquettes made from cashew industry waste. Journal of Cleaner Production 195, 1047–1056. https://doi.org/10.1016/j.jclepro.2018.05.261

[37] Singh, N., Kaushik, S. C., & Misra, R. D. (2000). Exergetic analysis of a solar thermal power system. Renewable energy, 19 (1-2), 135-143.

[38] Skodras G., Grammelis P., Basinas P., et al. (2009). A thermochemical conversion study on the combustion of residue-derived fuels. Water, Air, Soil Pollution: Focus 9: 151–157.

[39] Spiegel, M. (2004). Salzschmelzenkorrosion an Überhitzern und Verdampfern. In VDI Wissensforum: Beläge und Korrosion in Großfeuerungsanlagen.

[40] Szargut, J., Morris, D. R., & Steward, F. R. (1987). Exergy analysis of thermal, chemical, and metallurgical processes.

[41] Szargut, J., (2005). Exergy Method: Technical and Ecological Applications. WIT press.

[42] Van Loo, S., & Koppejan, J. (2002). Handbook of biomass combustion and co-firing; IEA Bioenergy. Twente University Press: Enschede, The Netherlands.

[43] Zinla D., Gbaha P., Koffi P. M. E., et Koua B. K. (2021). Characterization of rice, coffee and cocoa crops residues as fuel of thermal power plant in Côte d'Ivoire. Fuel, vol. 283, p. 119250.

[44] Zinla, B. T. D., Koua, B. K., Gbaha, P., & Koffi, P. M. E. (2022). Life cycle assessment of power generation using cocoa pod husk in Côte d'Ivoire. Indian Journal of Science and Technology, 15 (19), 914-922.