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Agricultural and Forestry Residues as Sustainable Bioenergy Resources in the Republic of the Congo: Quantification and Energy Potential Assessment

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Abstract

In the context of increasing energy demand and limited access to clean cooking and heating fuels in the Republic of Congo, agricultural and forestry residues represent a promising resource for energy production. This study aims to identify, quantify and assess the energy potential of the residues generated across eight departments of the country. Ten residues were characterized: sugarcane bagasse, peanut shells, corn stalks and cobs, rice husks, cassava stalks and peelings, sawdust, wood chips and wood slabs. Proximate analyses were carried out using a muffle furnace and an oven, while the calorific value was estimated using empirical formulas. Results of the proximate analysis showed that moisture content ranged from 8.80 ± 0.14% to 45.17 ± 1.57%, ash content from 1.00 ± 0.23 to 15.07 ± 0.15%, volatile matter content from 67.86 ± 0.02 to 82.14 ± 0.14% and fixed carbon content from 12.13 ± 0.33 to 19.87 ± 0.37%. The lower calorific value ranged between 14.98 and 18.04 MJ/kg. Approximately 137,921.16 tons of the assessed residues were estimated to be generated in 2025, corresponding to a first-order theoretical energy potential of approximately 1876.78 TJ/year. These findings provide useful evidence for public policies aimed at promoting the sustainable valorization of agricultural, agro-industrial, and forestry residues, diversifying the national energy mix and supporting the development of decentralized bioenergy systems in the Republic of Congo.

Keywords: quantification; energy potential; agricultural residues; forest residues

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1. Introduction

Access to reliable and affordable energy remains a major determinant of socio-economic development, particularly in developing countries where demand is rising rapidly under the combined pressure of population growth, urbanization, and industrial expansion [1]. In many of these countries, conventional energy distribution, whether through electricity grids, petroleum product supply chains, or cooking gas (LPG) pipelines and logistics networks, is capital-intensive and infrastructure-demanding, which slows the extension of centralized

supply systems to remote and low-density areas. Unlike electricity grids, fuel and LPG distribution further depends on continuous transport logistics (road, rail, or pipeline), making supply chains particularly vulnerable to distance, terrain, and infrastructure gaps. As a result, rural and peri-urban communities often remain disconnected from these centralized networks for extended periods, creating a persistent gap in energy access (for electricity, cooking fuel, and motive power alike) that centralized infrastructure alone cannot close in the short or medium term. Diversifying the energy resource base with decentralized, locally available sources therefore offers a practical pathway to bring energy closer to underserved populations without waiting for network expansion.

Biomass constitutes one of the most abundant and geographically accessible resources for this purpose [2]. The Republic of Congo holds substantial biomass reserves, with forests covering approximately 23.5 million hectares, or 69% of the national territory [3,4]. Wood and charcoal already dominate household energy use, supplying an estimated 81% of the population's primary cooking fuel [5–8], a reliance driven in part by the limited reach of LPG distribution networks in rural areas, and one that illustrates the logistical feasibility of biomass-based solutions where other supply chains are absent or unreliable. In parallel, the country's agricultural sector, spanning nearly 10 million hectares of arable land, generates substantial quantities of residues including peanut shells, corn cobs, cassava stalks, rice husks, cocoa pods, coffee stems, bean stalks, and sugarcane bagasse that are largely left unused or burned in the fields after harvest [8]. This open-field burning represents a direct loss of exploitable energy content and a source of particulate and NOx emissions [9], while these residues could be transformed into combustible pellets or briquettes through densification or pyrolysis processes, or converted into energy through combustion or gasification, to supply local energy demand as a substitute for both electricity and imported cooking fuels. Valorizing these residues would support resource efficiency and generate added value from agricultural and forestry by-products [9,10], while offering rural communities an alternative, locally produced energy source that does not depend on the extension of any of these distribution networks.

Despite this potential, few studies in developing countries have quantified residue availability with a view to energy recovery. Francis et al. [11] estimated Nigeria's annual biomass residue generation from agriculture, forestry, municipal solid waste, and animal/human waste at approximately 200 billion kg using the residue/product ratio method with data from national agricultural authorities, the Food and Agricultural Organization of the United Nation (FAO) and the literature. Obed et al. [12] examined timber-industry residues in Ghana and found that most wood-processing operations lack equipment to quantify their waste, resulting in the incineration or decomposition of nearly 930,270 m^3 of wood residue. This study proposes a simple and inexpensive method for quantifying the amounts of sawdust and wood shavings produced in carpentry workshops. This method is based on the daily weighing of sawdust and shavings stored in 50 kg bags, thus allowing for the estimation of weekly, monthly, and annual production.

Beyond quantification, the energy potential of these residues—the amount of usable energy they contain—remains rarely assessed in developing-country contexts. Several studies have applied the residue/product ratio method combined with crop calorific values to estimate this potential at the national or regional scale: Robinson et al. [13] reported approximately 606 PJ/year from crop residues and municipal solid waste in Cameroon; Moonmoon et al. [14] estimated the production of crop residues generated in India at 686 million tons, including rice husks, maize cobs and stalks, pearl millet, barley, small millets, sorghum, ragi, mustard, rapeseed, sesame, soybeans, safflower, sunflower, peanuts, various varieties of chickpeas, beans, pigeon peas, sugarcane bagasse, and residues from coconut, banana, areca, and cotton, of which approximately 234 million tons are considered

surplus and potentially available for bioenergy production. The annual bioenergy potential associated with this surplus biomass is estimated at 4.15 EJ; a significant contribution to India is national primary energy consumption, estimated at 24.91 EJ in 2011. Ömer et al. [15] calculated an average annual bioenergy potential of 19.27 PJ (range 14.36–24.18 PJ) for South Central Texas; Collins et al. [16] estimated the energy potential of residues generated in Uganda between 2008 and 2009, including crop residues (maize stalks and ears, millet straw, sorghum stalks, rice straw and husks, beans, peanuts, shells, bananas, stems and peels, cassava, stems and peels, sweet potatoes, tops and peels, pigeon peas, stems, soybeans, sesame, bagasse, coffee, husks, cotton), animal manure (cattle, goats, sheep, pigs, chickens, ducks and humans), and forestry residues (stumps, roots, branches and sawdust) at approximately 260 PJ/year. Following a comparable approach, Akpahou et al. [17] assessed the potential of agricultural residues produced in Benin, including maize stalks and cobs, rice straw, millet stalks, sorghum stalks, cassava stalks and peels, yam peels, sweet potato peels, potato leaves, trash and shell peanuts, soybean straw and pods, and cotton stalks. The energy potential of these residues was estimated at approximately 142.63 PJ in 2021.

While regional-scale assessment is equally important for siting decentralized energy projects, it remains uncommon. Angesom et al. [18] evaluated 27 residue types across Ethiopian regions (2014–2018), estimating a gross potential of 494.7 PJ, while Tolessa Amsalu [5] broadened the resource base to manure, agricultural residues, forestry residues, and municipal solid waste across 44 crop-derived residues from 30 crops, estimating a substantially higher national potential of 2955 PJ/year (an electricity equivalent of approximately 819.7 TWh), underscoring how the choice of resource scope strongly influences potential estimates. In the Republic of Congo specifically, Maryse et al. [19] characterized six commonly harvested woody biomass species using allometric estimation of above-ground biomass, finding that half a hectare of forest biomass yields 203.1 GJ (about 56,417 kWh, enough to supply around 350 households), while the same area of savanna biomass yields 109.2 GJ (about 30,333 kWh, enough for around 192 households).

These studies demonstrate the scale of biomass-based energy solutions achievable even at small spatial units, reinforcing their relevance for off-grid rural electrification. However, existing Congolese research has focused almost exclusively on woody biomass and forest resources [19], leaving the quantities, spatial distribution, and energy recovery potential of agricultural and agro-industrial residues largely undocumented. This gap limits the design of evidence-based decentralized energy strategies and constrains investment planning for local biomass valorization initiatives, particularly in rural areas where grid extension is not economically viable in the near term.

To address this gap, this study identifies, quantifies, and assesses the energy potential of agricultural, agro-industrial, and forestry residues generated across eight departments of the Republic of Congo. Specifically, it aims to: (i) identify the major residue streams from agricultural and forestry activities; (ii) quantify their annual production; (iii) characterize their physicochemical and fuel properties through proximate and ultimate analyses; and (iv) evaluate their theoretical energy potential for local bioenergy applications. The findings are intended to provide a scientific basis for diversifying the national energy mix through decentralized biomass valorization, offering rural and underserved communities a locally produced alternative to electricity, fuel, and cooking gas that does not depend on the extension of costly distribution networks.

2. Materials and Methods

The Republic of Congo is subdivided into 15 departments (Figure 1). This study was conducted in eight departments: Pointe-Noire, Kouilou, Niari, Bouenza, Pool, Brazzaville,

Cuvette and Sangha during the months of June, September and October 2025. Lists of agricultural enterprises, agricultural cooperatives, sawmills and timber harvesting and processing companies were obtained from the Ministry of Agriculture and Livestock, as well as the Ministry of Forest Economy and Sustainable Development in order to identify the different companies working in each department. Field surveys were conducted to collect information on the quantities and types of agricultural, agro-industrial and forestry residues generated in each department. A structured technical questionnaire was used to gather data, including company name and location, manager profile, main activities, types of residues, annual production volumes, and seasonality. Collected data were processed and analyzed using Microsoft Excel 2021 (Microsoft Corporation, Redmond, WA, USA), histograms were plotted using OriginPro 2018 (OriginLab Corporation, Northampton, MA, USA), and the departmental map of the Republic of the Congo was created using QGIS 3.40.13 (QGIS Development Team).

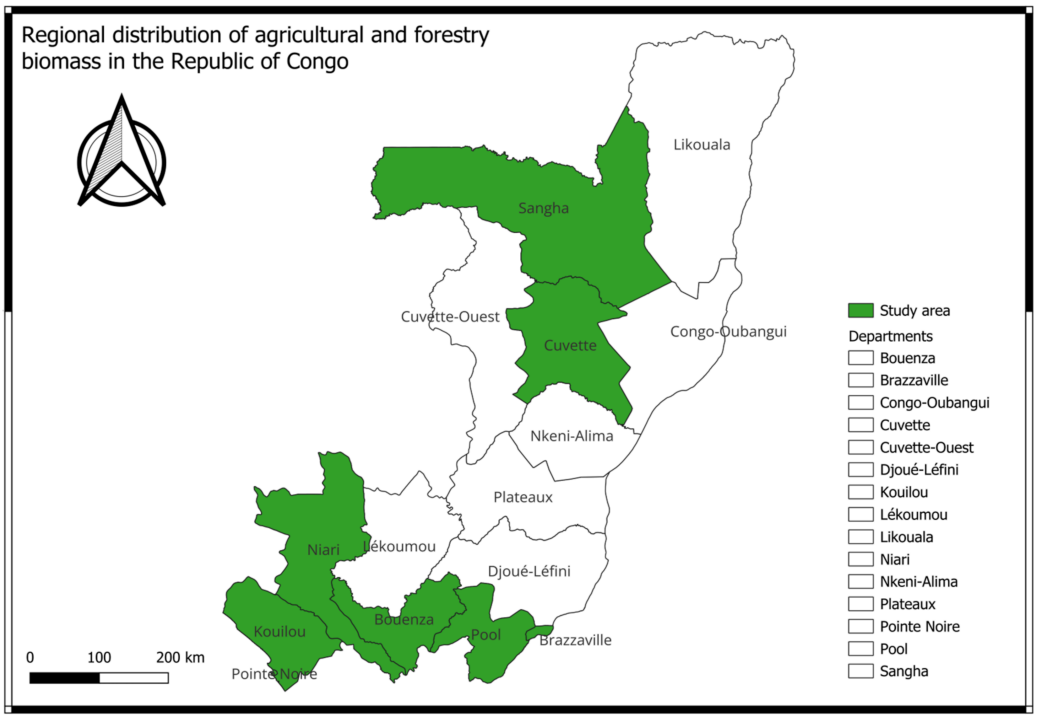


Figure 1. Regional assessment map of the potential of agricultural and forestry residues generated in the Republic of Congo.

Ten types of agricultural, agro-industrial and forestry residues were collected, including: sugarcane bagasse, peanut shells, corn cobs and stalks, cassava stalks and peelings, rice husks, wood slabs, sawdust and wood chips. These residues were quantified in order to assess their potential in each department. The sawdust used in this study is a composite sample from several species. Congolese forests are dominated by several species such as: Okoumé (*Aucoumea klaineana*), Limba (*Terminalia superba*), Sipo (*Entandrophragma utile*), Sapelli (*Entandrophragma cylindricum*), Moabi (*Baillonella toxisperma*), Ayous (*Triplochiton scleroxylon*), Iroko (*Milicia excelsa*), Kossipo (*Entandrophragma candollei*), Padouk (*Pterocarpus soyauxii*), Wengé (*Millettia laurentii*) and Azobé (*Lophira alata*) [20,21]. In this study, two composite samples of sawdust were formed: one composite sample from sawdust collected in the Department of Pointe-Noire, Kouilou, Niari and Brazzaville, consisting of Okoumé (*Aucoumea klaineana*), Limba (*Terminalia superba*), Moabi (*Baillonella toxisperma*) and a composite sawdust sample collected from CODEXO, a surveyed wood-processing company operating in the Cuvette and Sangha study areas, consisting of Sapelli (*Entandrophragma*

cylindricum) and Sipo (*Entandrophragma utile Sprague*). Proximate analysis of these collected residues was conducted at Oyo Centre of Excellence for Renewable Energy and Energy Efficiency, located in Oyo, Republic of Congo.

2.1. Quantification of Biomass Residues

2.1.1. Forest Residues

Three types of forest residues, namely, sawdust, wood chips, and wood slabs were quantified and collected through a sample survey based on technical data sheets in sawmills, carpentry workshops, logging and wood-processing companies. A specific field method was developed to estimate the quantities of sawdust and wood chips stored in bags within carpentry workshops. Fully filled and sealed bags were selected at random to ensure representativeness. Only fully filled and sealed bags were considered. To determine the net mass, three empty bags with a nominal capacity of 50 kg were first weighed to establish a reference tare (M_0). These bags were then filled with sawdust or wood chips as stored in the carpentry workshops. The total mass (M_1) was measured using a TOPMOVE digital portable scale (model HG12836A, TOPMOVE/Lidl Stiftung & Co. KG, Neckarsulm, Germany) (Figure 2a).



(**a**) (**b**)

Figure 2. (**a**) Collection of sawdust or wood chips from carpentry workshops; (**b**) Storage of sawdust and wood chips in 50 kg bags in the carpentry workshops.

The mass (M_2) of sawdust or wood chips contained in each bag was determined by the difference between the total mass (M_1) of the bag containing the residue and the mass of the empty bag (M_0).

An average of three measurements was calculated to represent the mass of sawdust or wood chips per bag. This value was then multiplied by the average number of bags produced per week in each workshop. Finally, an annual estimate was derived, taking into account periods of high and low production.

The quantity of sawdust and wood chips generated in sawmills and wood-processing companies was initially measured in cubic meters. Annual production in tons was determined using the bulk density of the residues. The collected samples consisted of mixtures of different wood species. Sawdust and wood chips samples were collected from each site and stored in hermetically sealed containers. A composite sample was prepared from samples collected from each carpentry shop, sawmill, and wood-processing facility.

Because sawdust and wood-chip streams consisted of mixtures of several wood species, the composite samples were considered representative of the residues generated under actual operating conditions rather than of individual species. Annual quantities derived

from field measurements, facility production information and bulk-density conversion are therefore subject to uncertainty associated with species heterogeneity, variations in processing activity, bulk-density variability and extrapolation to annual production. As the original field survey did not include sufficient repeated measurements across all sites and production periods to establish a statistically robust confidence interval, no numerical margin of error was assigned retrospectively. The reported annual quantities should therefore be interpreted as field-based estimates.

Wood-slab quantities were obtained from information provided directly by managers of the surveyed forestry and wood-processing companies. The reported annual quantities were based on the companies' production records and/or operational estimates. Unlike sawdust and wood chips, wood slabs were not systematically quantified through direct field weighing or bulk-density conversion. No additional theoretical conversion coefficient was retrospectively applied to these reported quantities. Therefore, the annual wood-slab quantities reported in this study should be considered company-reported survey estimates rather than direct experimental measurements.

2.1.2. Agricultural and Agro-Industrial Residues

Seven types of agricultural residues (sugarcane bagasse, peanut shells, corn cobs and stalks, rice husks, cassava stems and peels) from five agricultural crops were identified. The annual quantity of agricultural and agro-industrial residues was estimated using the residue/product ratio (RPR) method, as described by Miguel et al. [22], Mohamedeltayib et al. [23], Angesom et al. [18], and Jesus et al. [24] using Equation (1).

$$Q_{\text{annual,residues}} = \sum_{i=1}^{n} (RPR)_i \left(Q_{\text{annual,products}}\right)_i \quad (1)$$

$Q_{\text{annual,residues}}$: Annual quantity of residues generated;
RPR: Crop residue/product ratio;
$Q_{\text{annual,products}}$: Annual quantity of crops produced;
i: Crop index;
n: Total number of crops considered.

RPR values were obtained from published studies where direct local measurements were unavailable. These ratios should not be considered universal constants, as they may vary with crop variety, cultivation and harvesting practices, moisture conditions and processing methods. Their use therefore introduces uncertainty into the estimated residue quantities. Locally determined RPR values based on repeated measurements would improve the precision of future assessments.

The selected departments encompass important agricultural, agro-industrial, forestry and wood-processing areas of the country. However, the survey was not designed as a probability-based nationally representative sampling campaign. The field component should therefore be interpreted as a targeted assessment of the principal residue streams identified in the surveyed areas rather than an exhaustive national inventory. Where production statistics and residue-to-product ratios were used, the resulting estimates reflect the scope and assumptions of the corresponding data sources.

2.2. Physicochemical Characterization Methods

2.2.1. Bulk Density Determination

The bulk density (ρ) of the composite sample of wood chips or sawdust collected in sawmills was determined according to ISO 17828:2015 [25], using a container of known

volume and a TOPMOVE digital portable scale (model HG12836A, TOPMOVE/Lidl Stiftung & Co. KG, Neckarsulm, Germany), according to Equation (2).

$$\rho = \frac{m}{V} \quad (2)$$

ρ: bulk density of collected forest residues (kg/m^3);
m : mass of sawdust or wood chips (kg);
V : volume of the container used (m^3).

2.2.2. Proximate Analysis

The proximate analysis can give the amount of moisture, ash, volatile matter and fixed carbon of the biomass sample.

- Moisture content

The moisture content (MC) was determined according to ISO 18134-1:2022 [26]. Approximately 2 g of each powdered biomass sample was weighed using a semi-microbalance (PX225D, OHAUS Corporation, Parsippany, NJ, USA) and dried at 105 °C to constant mass using a laboratory oven (UF750, Memmert GmbH + Co. KG, Schwabach, Germany). After cooling in a desiccator, the sample was reweighed and the moisture content was calculated from the mass loss during drying using Equation (3).

$$MC\ (\%) = \frac{M_4 - M_5}{M_4 - M_3} \times 100 \quad (3)$$

M_3: mass of the empty crucible after heating to 105 °C and cooling in the desiccator (g);
M_4: mass of the crucible + wet sample before drying (g);
M_5: mass of crucible + sample after drying in the oven at 105 °C for 4 h and re-cooling in the desiccator (g);
MC (%) : Moisture content.

- Volatile matter content

The volatile matter content (VM) was determined according to ISO 18123:2015 [27]. Approximately 2 g of dried powdered sample was placed in a covered crucible and introduced into a muffle furnace (LT 9/13, Nabertherm GmbH, Lilienthal, Germany) maintained at 900 ± 10 °C for 7 min ± 5 s. After cooling in a desiccator, the remaining residue was weighed and the volatile matter content was calculated using Equation (4).

$$VM\ (\%) = \frac{M_7 - M_8}{M_7 - M_6} \times 100 \quad (4)$$

M_6: mass of empty crucible + lid after heating to 900 °C ± 10 °C for 7 min ± 5 s and cooling in the desiccator for 30 min (g);
M_7: mass of crucible + dry sample + lid before heating in the muffle furnace (g);
M_8: mass of crucible + lid + residue after heating at 900 °C ± 10 °C for 7 min ± 5 s and cooling in the desiccator for 30 min (g);
VM (%): volatile matter content.

- Ash content

The ash content (Ash) was determined according to ASTM E1755 [28]. Approximately 2 g of dried powdered biomass sample was heated in the same muffle furnace at 575 ± 25 °C until complete ashing. After cooling in a desiccator, the residual ash was weighed and the ash content was calculated using Equation (5).

$$Ash\ (\%) = \frac{M_{11} - M_9}{M_{10} - M_9} \times 100\% \quad (5)$$

M_9: mass of the crucible after pretreatment at 575 °C ± 25 °C for 4 h (g);
M_{10}: mass of the crucible + sample before heating in the muffle furnace (g);
M_{11}: crucible mass + Ash after heating at 575 °C ± 25 °C for 4 h (g);
Ash (%): ash content.

- Fixed carbon content

The fixed carbon content (FC) of the collected samples was determined on a dry basis by difference, according to Equation (6):

$$FC\ (\%) = 100\% - (Ash\ (\%) + VM\ (\%)) \quad (6)$$

FC (%) : fixed carbon content.

2.2.3. Estimation of Ultimate Analysis

Ultimate analysis was not experimentally performed using a CHNS/O elemental analyzer in this study. Instead, carbon (C), hydrogen (H), and oxygen (O) contents were estimated from the experimentally determined proximate-analysis parameters using the empirical correlations proposed by Daya Ram [29]. These calculated values should therefore be interpreted as estimated elemental compositions rather than direct elemental measurements, as shown in Equations (7)–(9) presented below:

$$\text{C}\ (\%) = 0.9671\ FC\ (\%) + 0.4097\ VM\ (\%) - 0.0348 Ash\ (\%) \quad (7)$$

$$\text{H}\ (\%) = 0.0215\ FC\ (\%) + 0.0708\ VM\ (\%) - 0.0063 Ash\ (\%) \quad (8)$$

$$\text{O}\ (\%) = 0.0061\ FC\ (\%) + 0.5147\ VM\ (\%) - 0.0097 Ash\ (\%) \quad (9)$$

C (%): carbon content;
H (%): hydrogen content;
O (%): oxygen content.
Sulphur (S) and nitrogen (N) contents were not measured or estimated in this study.

2.2.4. Estimation of Heating Value

The higher heating value of the collected samples was estimated using the empirical correlation developed by Parikh et al. [30] for solid fuels, as shown in Equation (10):

$$\text{HHV (MJ/kg)} = 0.3536\ FC\ (\%) + 0.1559\ VM\ (\%) + 0.0078 Ash\ (\%) \quad (10)$$

HHV: high heating value (MJ/kg).
The heating value (*LHV*) was subsequently calculated from the estimated *HHV* using the estimated hydrogen content and measured moisture content according to Equation (11):

$$(LHV)_{dry} = (HHV)_{dry} - 2.442\left(8.9\ \frac{H\ (\%)}{100}\right) \quad (11)$$

2.3. Energy Potential Assessment

2.3.1. Energy Potential of Forest Residues

The energy potential of forest residues was calculated according to the method proposed by Miguel et al. [22] and Giordano et al. [31] using Equation (12).

$$(E_n R_F) = \sum_{i=1}^{n} (Q^R_{annual})i.(LHV)i.(1 - (MC\ (\%))i) \quad (12)$$

$(E_n R_F)$: energy potential of collected waste (TJ);
LHV: lower heating value of each type of collected residue (MJ/kg);
Q^R_{annual}: annual quantity of sawdust and wood chips generated (Kg);
MC (%): moisture content;
In this study, the mass of sawdust and wood chips generated per year corresponds to the annual quantity produced in the sawmills and the carpentry workshops.

2.3.2. Energy Potential of Agricultural and Agro-Industrial Residues

The energy potential of these residues was evaluated using the method proposed by Miguel et al. [22] and Bill Vanneck et al. [32], as described in Equation (13). This method proposes first estimating the quantity of residue potentially available for energy production. Thus, the residue/product ratio of certain crops was determined based on results published in the literature. Equation (13) was then used to determine the energy potential of the collected agricultural residues.

$$(E_n R_t) = \sum_{i=1}^{n} (Q_{annual})i.(LHV)i.(1 - (MC\ (\%))i) \quad (13)$$

$(E_n R_t)$: energy potential of agricultural residues (TJ);
LHV: lower heating value (MJ/kg);
MC (%): moisture content.

2.3.3. Uncertainty and Methodological Limitations

This biomass resource assessment combines different quantification and estimation approaches, each associated with specific sources of uncertainty. Agricultural and agro-industrial residue quantities were estimated using crop-production data and literature-derived residue-to-product ratios (*RPR*s), whereas forestry-residue quantities were derived from field surveys, direct measurements, facility production information and, where applicable, bulk-density conversion. *RPR*-based estimates may be affected by variations in crop variety, agricultural and harvesting practices, moisture conditions, and processing methods. Forestry-residue estimates may also be influenced by wood-species heterogeneity, bulk-density variability, differences in processing activity, and the extrapolation of field observations to annual residue production. For wood slabs specifically, annual quantities were based on production information and operational estimates reported by the surveyed forestry and wood-processing companies rather than systematic direct field measurements. Their reliability therefore depends on the accuracy and consistency of the companies' production records and reporting practices, introducing an additional source of uncertainty. Consequently, the different residue-quantification approaches do not necessarily have equivalent uncertainty ranges.

Additional uncertainty arises from the empirical estimation of fuel properties. Carbon (C), hydrogen (H), and oxygen (O) contents were not directly measured by CHNS/O elemental analysis but were estimated from experimentally determined proximate-analysis parameters using the empirical correlations of Nhuchhen [29]. The higher heating value (HHV) was estimated directly from proximate-analysis parameters using the empirical correlation of Parikh et al. [30], whereas the lower heating value (LHV) was subsequently calculated using the estimated hydrogen content and measured moisture content. Thus, although HHV was not calculated from the estimated C, H, and O values, uncertainty associated with the empirical estimation of hydrogen content and HHV propagates into the calculated LHV and subsequently into the theoretical energy potential estimate.

A formal numerical propagation of the combined uncertainty would require uncertainty distributions and sufficiently replicated spatial and temporal measurements for the different input parameters and residue-quantification pathways. Such information was not available for all residue categories because the original field campaign was not specifically designed for probabilistic uncertainty analysis. Therefore, a retrospective numerical confidence interval was not assigned, as this would imply unsupported precision. Instead, the principal sources and pathways of uncertainty are explicitly acknowledged, and the resulting energy potentials are interpreted as first-order theoretical estimates for biomass resource screening rather than precise estimates of technically recoverable energy. Future studies should incorporate expanded field replication, locally validated *RPR* values, direct

CHNS/O elemental analysis, bomb calorimetry, and formal uncertainty propagation to improve the precision of these estimates.

3. Results

3.1. Assessment of the Potential of Agricultural, Agro-Industrial and Forestry Residues

The survey covered eight departments of the Republic of the Congo: Pointe-Noire, Kouilou, Niari, Bouenza, Pool, Brazzaville, Cuvette and Sangha. In the Pool Department, particularly in Kinkala and the Louingui District, only very limited quantities of the targeted agricultural and forestry residues were identified. Consequently, no sufficiently representative quantities were retained for inclusion in the quantitative energy potential assessment.

In the Pointe-Noire Department, the study covered four boroughs (Lumumba, Mongo-Poukou, Loandjili and Ngoyo). Five neighborhoods were covered (Grand Marché, Makayabou, Mpaka, Siafoumou and Ngoyo). A total of twenty-seven carpentry workshops, three sawmills (Scierie de la Plage site 1, MIRAF Scierie and MGP Service), one rice mill (PESA AGRI) and one wood-processing company (SICOFOR) were surveyed. As shown in Figure 3a, wood-related residues dominate this urban area, with approximately 767.48 tons of wood chips and 741.34 tons of sawdust produced in 2025. In contrast, the Kouilou Department (Figure 3b) has more limited industrial activity, producing 88.52 tons of sawdust and 13.6 tons of wood shavings, mainly from small-scale carpentry workshops. The difference is mainly attributed to the higher concentration of industrial and artisanal wood-processing activities in Pointe-Noire Department.

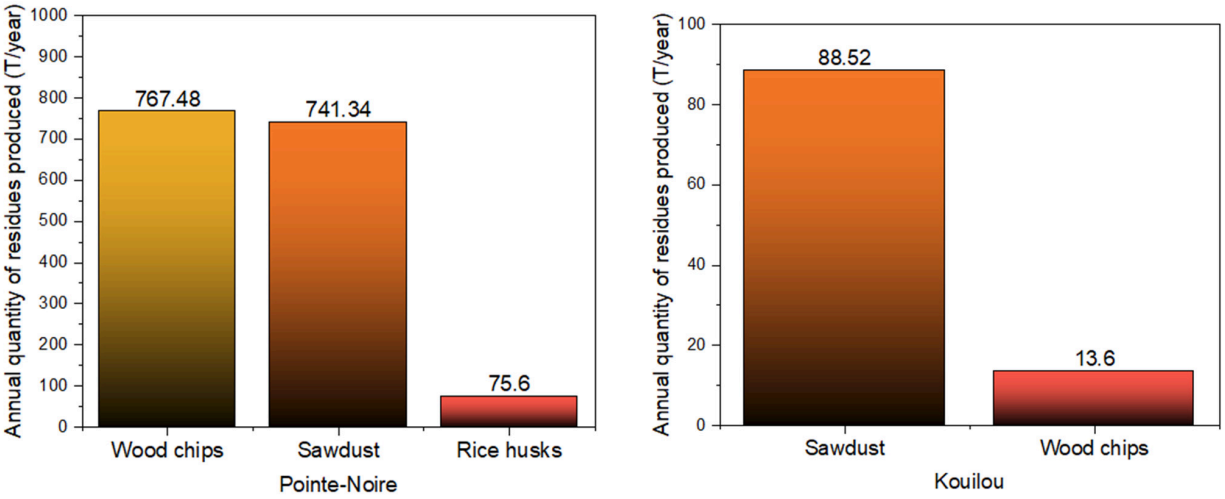
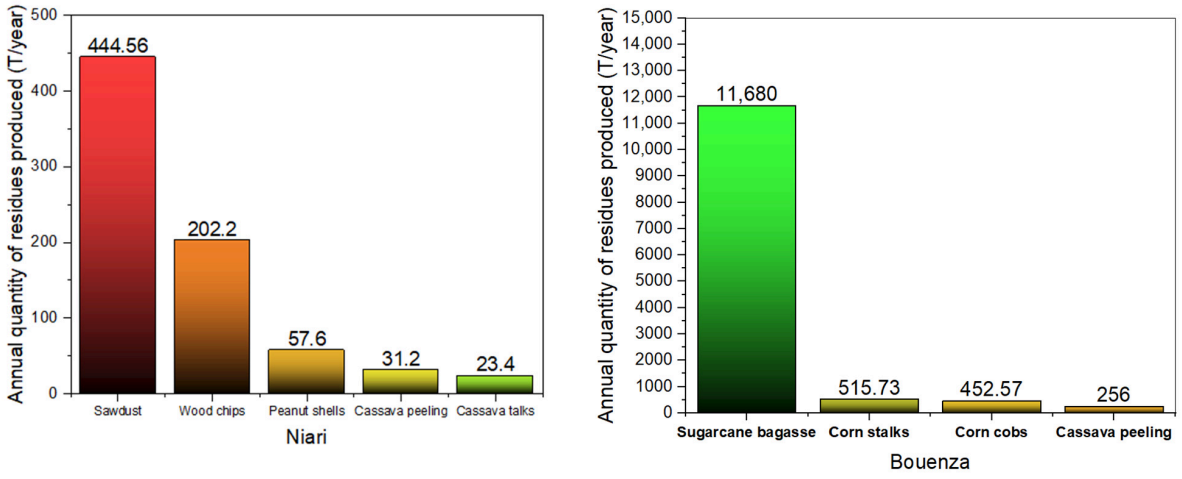


Figure 3. (**a**) Potential of agricultural and forestry residues generated in the Department of Pointe-Noire; (**b**) Potential of agricultural and forestry residues generated in the Department of Kouilou.

In the Niari Department, the survey focused on five carpentry workshops, three peanut shelling units, and two wood production and processing companies (SICOFOR Parc Matsende and XIANGTAO), located in Dolisie. A Protected Agricultural Zone (ZAP) was also identified in Malolo 2, in the Louvakou District.

However, the Bouenza Department, primarily dominated by agricultural crops, included three agricultural enterprises (SARIS, SHENG SHENG, and TOLONA), a sugarcane wine production workshop, a Protected Agricultural Zone and an agricultural cooperative. The results of this survey showed that approximately 444.56 tons of sawdust, 202.2 tons of wood chips, 57.6 tons of peanut shells, 31.2 tons of cassava peelings and 23.4 tons of cassava stalks were assessed in the Niari Department (Figure 4a). However, sugarcane bagasse was the most

dominant residue in Bouenza Department, with approximately 11,680 tons (Figure 4b). Similarly, approximately 515.73 tons of maize stalks, 452.57 tons of maize cobs and 256 tons of cassava peelings were produced (Figure 4b). The Bouenza Department is primarily dominated by agricultural crops due to its very fertile soil. The forestry residues are less frequently generated.

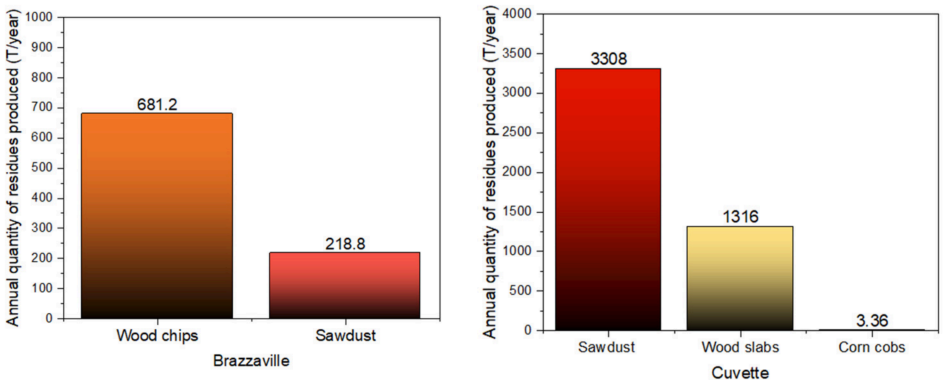


(**a**) (**b**)

Figure 4. (**a**) Potential of agricultural and forestry residues generated in the Niari Department; (**b**) Potential of agricultural and forestry residues generated in the Bouenza Department.

In the Brazzaville Department, the survey was conducted in three boroughs (Makélékélé, Bacongo and Madibou). The neighborhoods covered by the study were: Moukoundzi-Ngouaka, Centre Sportif, Cinq Chemins and Massissia. Approximately twenty carpentry workshops were surveyed. In the Cuvette Department, two wood-processing and logging companies (CODEXO and WANG SAM), as well as one Protected Agricultural Zone, were surveyed in Makoua. The survey results revealed that approximately 681.12 tons of wood chips and 218.8 tons of sawdust, mainly generated by carpentry workshops, were produced in the Brazzaville Department. In contrast, the Cuvette Department was characterized by a predominance of sawdust, estimated at about 3308 tons, followed by 1316 tons of wood slabs and 3.36 tons of corn cobs.

In contrast, the Cuvette Department was characterized by a predominance of sawdust, estimated at approximately 3308 tons, followed by 1316 tons of wood slabs and 3.36 tons of corn cobs (Figure 5a,b).



(**a**) (**b**)

Figure 5. (**a**) Potential of agricultural and forestry residues generated in the Department of Brazzaville; (**b**) Potential of agricultural and forestry residues generated in the Department of Cuvette.

The Sangha Department is largely covered by forest and traversed by the vast equatorial rainforest. Timber exploitation constitutes the main economic activity in this department. Three timber harvesting and processing companies were surveyed: Congolaise Industrielle de Bois (CIB), located in Pokola, Société d'Exploitation Forestière Yuang Dong (SEFYD) located in Souanke and Industrie Forestière de Ouesso (IFO) located in Ngombe. The results showed that approximately 80,124 tons of sawdust and 36,920 tons of wood slabs were produced in 2025 (Figure 6). This department is characterized by a strong predominance of forest residues.

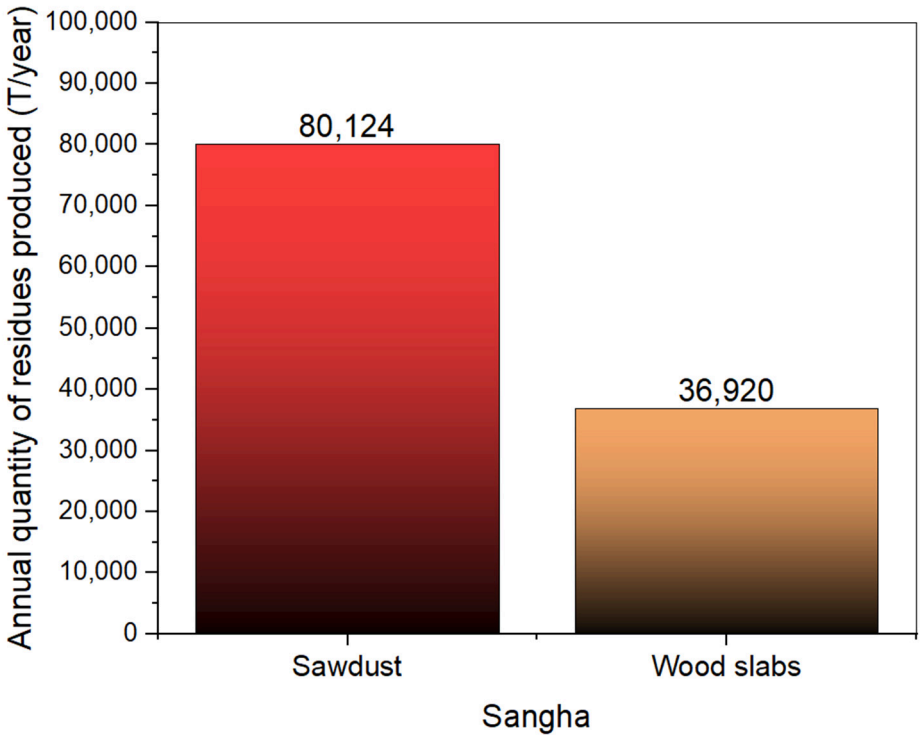


Figure 6. Potential of agricultural and forestry residues generated in the Sangha Department.

3.2. Physicochemical Properties

3.2.1. Bulk Density

The bulk density of the composite sample of sawdust varied between 181.52 and 230.13 kg/m^3. The bulk density of the composite sample of sawdust collected in the departments of Pointe-Noire, Kouilou, Niari and Brazzaville was 181.52 kg/m^3, whereas that of the composite sawdust sample collected in the departments of Cuvette and Sangha was 230.13 kg/m^3. The wood chips had a substantially lower bulk density than the sawdust, with the composite wood-chip sample exhibiting a bulk density of 81.12 kg/m^3.

3.2.2. Proximate and Ultimate Analysis

The proximate and estimated ultimate-analysis results are presented in Table 1. Moisture content varied from 8.80 ± 0.14% to 45.17 ± 1.57%, with the highest value observed for sugarcane bagasse and the lowest for corn stalks. Volatile matter contents were generally high, ranging from 67.86 ± 0.02% to 82.14 ± 0.14%, while ash content ranged from 1.00 ± 0.23% to 15.07 ± 0.15%. The highest ash values were observed for rice husks and cassava peel, whereas the sawdust samples exhibited comparatively low ash contents. Fixed carbon ranged from 12.13 ± 0.33% to 20.03 ± 0.17%.

The estimated elemental composition also varied among residue types, with carbon contents ranging from 41.44 ± 0.36% to 51.60 ± 0.26%, hydrogen from 5.12 ± 0.01% to

6.16 ± 0.01%, and oxygen from 34.91 ± 0.01% to 42.36 ± 0.07%. Detailed values for each biomass residue are reported in Table 1.

Table 1. Proximate and ultimate analysis of agricultural, agro-industrial and forestry residues.

Biomass Residues	Proximate Analysis (%)				Ultimate Analysis (%)		
	MC	*VM*	*AC*	*FC*	C	H	O
Sugarcane bagasse	45.17 ± 1.57	82.07 ± 0.25	5.64 ± 0.27	12.28 ± 0.37	45.31 ± 0.37	6.04 ± 0.02	42.26 ± 0.13
Corn cobs	9.47 ± 0.01	81.77 ± 0.17	1.99 ± 0.01	16.24 ± 0.17	49.14 ± 0.17	6.12 ± 0.01	42.16 ± 0.08
Corn stalks	8.80 ± 0.14	79.73 ± 0.09	4.82 ± 0.36	15.45 ± 0.37	41.44 ± 0.36	5.94 ± 0.01	41.08 ± 0.04
Cassava peel	21.00 ± 0.47	67.86 ± 0.02	13.51 ± 0.32	18.63 ± 0.32	45.35 ± 0.31	5.12 ± 0.01	34.91 ± 0.01
Peanut shells	10.94 ± 0.22	74.82 ± 0.11	5.15 ± 0.13	20.03 ± 0.17	49.84 ± 0.17	5.69 ± 0.01	38.58 ± 0.05
Cassava stems	10.58 ± 0.13	79.58 ± 0.30	8.29 ± 0.14	12.13 ± 0.33	44.05 ± 0.34	5.84 ± 0.02	40.95 ± 0.15
Sawdust	18.08 ± 0.14	82.14 ± 0.14	1.49 ± 0.01	16.37 ± 0.14	49.43 ± 0.15	6.16 ± 0.01	42.36 ± 0.07
Sawdust (CODEXO composite sample)	27.58 ± 0.17	79.13 ± 0.29	1.00 ± 0.23	19.87 ± 0.37	51.60 ± 0.26	6.02 ± 0.01	40.84 ± 0.01
Wood chips	12.27 ± 0.14	81.13 ± 0.10	3.31 ± 0.36	15.56 ± 0.37	48.17 ± 0.36	6.06 ± 0.01	41.82 ± 0.05
Rice husks	9.62 ± 0.14	69.81 ± 0.01	15.07± 0.15	15.12 ± 0.15	42.69 ± 0.14	5.17 ± 0.01	35.87 ± 0.01

MC (%): Moisture content; *AC* (%): Ash content; *FC* (%): Fixed carbon content; *VM* (%): Volatile matter content; C (%): Carbon content; H (%): Hydrogen content; O (%): Oxygen content.

3.3. Heating Value

The High Heating Value (*HHV*) and Lower Heating Value (*LHV*) values of the investigated biomass residues are presented in Table 2. The Lower Heating Value (*LHV*) of agricultural, agro-industrial and forestry residues varied between 14.98 ± 0.05 MJ/kg and 18.04 ± 0.09 MJ/kg. The highest value was observed for the composite sample of sawdust (18.04 ± 0.09 MJ/kg) collected in the departments of Cuvette and Sangha, followed by wood slabs (17.54 ± 0.09 MJ/kg), peanut shells (17.46 ± 0.06 MJ/kg), corn cobs (17.14 ± 0.06 MJ/kg), wood chips (16.80 ± 0.13 MJ/kg), corn stalks (16.56 ± 0.13 MJ/kg), cassava peel (15.94 ± 0.11 MJ/kg) and cassava stalks (15.35 ± 0.13 MJ/kg). The lowest lower heating value was obtained for rice husks, at approximately 14.98 ± 0.05 MJ/kg.

Table 2. Annual residue quantities, residue-to-product ratios, estimated heating values, and theoretical energy potential of agricultural, agro-industrial, and forestry residues by department.

Departments	Biomass Residues	Total Annual Quantity (T/Year)	*RPR*	*HHV* (MJ/kg)	*LHV* (MJ/kg)	Energy Potential (TJ/Year)
Pointe-Noire	Sawdust	741.34	-	18.58 ± 0.05	17.24 ± 0.05	10.47
	Wood chips	767.48	-	18.12 ± 0.13	16.80 ± 0.13	11.31
	Rice husks	75.6	0.27 [18]	16.11 ± 0.05	14.98 ± 0.05	1.02
Kouilou	Wood chips	13.6	-	18.12 ± 0.13	16.80 ± 0.13	0.2
	Sawdust	88.52	-	18.58 ± 0.05	17.24 ± 0.05	1.25
Niari	Wood chips	202.2	-	18.12 ± 0.13	16.80 ± 0.13	2.98
	Sawdust	444.56	-	18.58 ± 0.05	17.24 ± 0.05	6.27
	Peanut shells	57.6	0.37	18.71 ± 0.06	17.46 ± 0.06	0.89
	Cassava peel	31.2	0.2 [33]	17.06 ± 0.11	15.94 ± 0.11	0.39
	Cassava stems	23.4	0.8 [33]	16.63 ± 0.13	15.35 ± 0.13	0.32

Table 2. *Cont.*

Departments	Biomass Residues	Total Annual Quantity (T/Year)	*RPR*	*HHV* (MJ/kg)	*LHV* (MJ/kg)	Energy Potential (TJ/Year)
Bouenza	Sugarcane bagasse	11,680	0.304	17.09 ± 0.14	15.77 ± 0.14	101.04
	Cassava peel	256	0.2 [33]	17.06 ± 0.11	15.94 ± 0.11	3.22
	Corn cobs	452.57	0.174	18.47 ± 0.06	17.14 ± 0.06	7.02
	Corn stalks	515.73	1.5	17.85 ± 0.13	16.56 ± 0.13	7.78
Brazzaville	Sawdust	218.8	-	18.58 ± 0.05	17.24 ± 0.05	3.09
	Wood chips	681.2	-	18.12 ± 0.13	16.80 ± 0.13	10.04
Cuvette	Sawdust (CODEXO composite sample)	3308	-	19.37 ± 0.14	18.04 ± 0.09	43.22
	Wood slabs	1316	-	18.87 ± 0.09	17.54 ± 0.09	21.32
	Corn cobs	3.36	0.174	18.47 ± 0.06	17.14 ± 0.06	0.05
Sangha	Wood slabs	36,920	-	18.87 ± 0.09	17.54 ± 0.09	598.17
	Sawdust (CODEXO composite sample)	80,124	-	19.37 ± 0.14	18.04 ± 0.09	1046.73
	Total	137,921.16				1876.78

HHV: High Heating Value; *LHV*: Lower Heating Value; TJ: Terajoule; T: tons.

3.4. Assessment of Energy Potential

This study was conducted in eight departments of the Republic of the Congo. The energy potential of the various types of waste collected per department ranged from 0.05 TJ/year to 1046.73 TJ/year. Consequently, the distribution of energy potential across the departments ranged from 1.45 TJ/year to 1644.9 TJ/year (Figure 7). The highest energy potential was estimated in the Sangha Department, at approximately 1644.90 TJ/year. Furthermore, the energy potential of the waste collected is estimated at 119.06 TJ/year in the Department of Bouenza, 64.59 TJ/year in the Department of Cuvette, 22.8 TJ/year in the Department of Pointe-Noire, 13.13 TJ/year in the Department of Brazzaville and 10.85 TJ/year in the Niari Department. However, the lowest energy potential was observed in the Kouilou Department, at approximately 1.45 TJ/year.

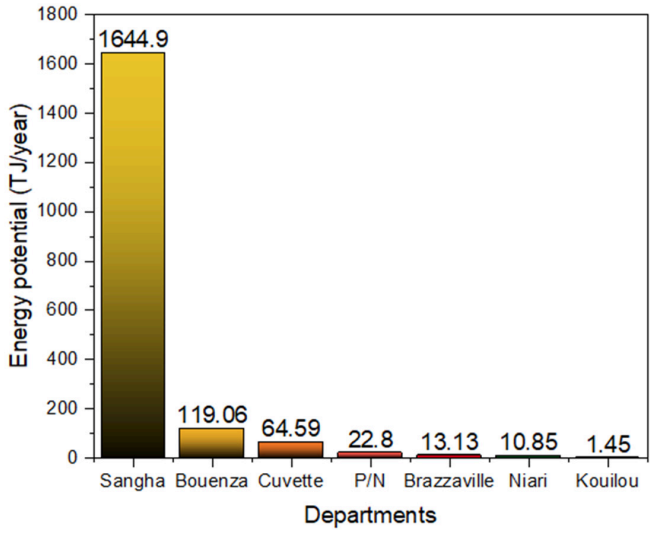


Figure 7. Distribution of the energy potential of residues generated by department in the Republic of Congo.

4. Discussion

This study identified, quantified, characterized and assessed the potential of biomass generated in eight departments in the Republic of the Congo. Ten types of agricultural, agro-industrial and forestry residues were identified (sugarcane bagasse, maize stalks and cobs, cassava stalks and peels, peanut shells, rice husks, wood chips, wood slabs and sawdust). The conversion of these residues into solid biofuels or bioenergy faces several constraints, including heterogeneous moisture content, seasonal availability, storage requirements, logistical difficulties related to collection and transportation competing uses of biomass resources. Approximately 137,921.16 tons of agricultural, agro-industrial and forestry residues were generated in the Republic of the Congo in 2025. The largest quantity of agricultural and agro-industrial residues was estimated in the Bouenza Department. This department has vast areas of arable land, particularly in the great Niari valley, which offer great potential for the development of agricultural activities. However, the departments of Pointe-Noire, Kouilou, Niari, Brazzaville, Cuvette and Sangha are mainly characterized by the predominance of forest residues. The amount of residues generated in the Pool Department, specifically in Kinkala and the Louingui District, are very low and no significant agricultural or forestry residues were identified.

The bulk density of the composite sample of sawdust collected in the departments of Pointe-Noire, Kouilou, Niari and Brazzaville ($\rho = 181.52$ kg/m^3) is lower than that of the composite sample of sawdust collected in the departments of Cuvette and Sangha ($\rho = 230.13$ kg/m^3). This difference is due to the species collected: Sipo and Sapelli are the most dominant species in the departments of Cuvette and Sangha, whereas the departments of Pointe-Noire, Kouilou, Niari, Brazzaville are dominated by Okoumé, Moabi and Limba. The bulk density of the composite sample wood chips obtained was very low, $\rho = 81.12$ kg/m^3. These results for sawdust are almost corroborated by those reported by Kewir et al. [34] ($\rho = 184.64$ kg/m^3).

Regarding the characterization, the sugarcane bagasse had a very high moisture content: the result obtained in this study ($45.17 \pm 1.57\%$) was higher than that obtained by Muhammad et al. [35] (8.77%). The rice husks have a low moisture content, but their ash content is very high. This increase in ash content may be due to the presence of silica Dinh et al. [21], which reduces their lower heating value. These results are almost identical to those obtained by Muhammad et al. [35] and Dinh et al. [21]. This high ash content is a disadvantage for the recovery of pellets as solid biofuels. In addition, the sawdust collected has very low ash content and a high lower heating value. These results are consistent with those obtained by Muhammad et al. [35]. The peanut shells, corn stalks and corn cobs collected had a very low ash content and very high heating value. These results are similar to those obtained by Ayşegül et al. [36]. Singh et al. [37] reported that biomass samples with higher ash contents may lead to increased combustion-related operational constraints, including greater ash handling and equipment-cleaning requirements.

The residue/product ratio for peanut shells (0.35) obtained by Ezekiel et al. [7] is almost identical to that obtained in this study (0.37) but remains lower than the value of 0.447 obtained by Robinson et al. [12]. However, the residue/product ratio for maize stalks (1.15) obtained by Ezekiel et al. [7] is much lower than that obtained in this study (1.50). This value is almost identical to that of 1.59 obtained by Angesom et al. [18]. Furthermore, the residue/product ratio of corn cobs (0.57) reported by Angesom et al. [18] is significantly higher than that determined in this study (0.174). This difference could be explained by the variability of species, agronomic and climatic conditions. Regarding sugarcane bagasse, the residue/product ratio estimated in this study (0.304) is close to that obtained by Angesom et al. [18] (0.33), but is higher than the value of 0.25 obtained by Collins et al. [16] and Maw et al. [38]. The energy potential of unused agricultural, agro-industrial and forestry residues

generated in the Republic of the Congo is approximately 1876.78 TJ/year. These residues can be used to generate electricity, particularly in cogeneration plants. In the Republic of the Congo, national electricity production relies mainly on thermal and hydroelectric power stations. However, the country faces significant load-shedding problems in large cities, particularly Brazzaville and Pointe-Noire, due to growing demand for electricity caused by high population density. To better illustrate the significance of this resource, the estimated energy potential of 1876.78 TJ/year corresponds to an electricity equivalent of approximately 521 GWh/year. Although this figure represents a theoretical potential, it highlights the considerable contribution that agricultural, agro-industrial and forestry residues could make to the national energy sector. Such an amount of energy could support decentralized electricity generation systems, particularly in rural and peri-urban areas where access to reliable electricity remains limited [39].

The spatial distribution of biomass resources also reveals important regional opportunities. The Sangha Department accounts for the largest share of the national biomass energy potential, mainly due to the concentration of forestry industries and timber processing activities. Furthermore, the contribution of biomass to electricity production in this department remains very limited. Approximately 4.1 MW are produced by Congolaise Industrielle de Bois from biomass residues. In contrast, the Bouenza Department exhibits the highest agricultural biomass potential, particularly through sugarcane bagasse, maize stalks and maize cobs. These findings suggest that future biomass energy projects should adopt a regional approach that takes into account local resource availability and existing industrial infrastructure.

Beyond electricity generation, the valorization of agricultural and forestry residues can generate important environmental and socio-economic benefits. The utilization of residues that are currently burned, abandoned or underutilized would contribute to reducing greenhouse gas emissions, limiting open-field burning practices, promoting circular economy principles and creating new employment opportunities along biomass supply chains. Consequently, biomass energy development could support efforts in the Republic of the Congo to achieve its Nationally Determined Contributions (NDCs), improve energy security and accelerate progress toward Sustainable Development Goals 7 (Affordable and Clean Energy) and 13 (Climate Action).

The interpretation of these findings should nevertheless consider the methodological limitations of the assessment. Residue quantities were derived using different field and literature-based approaches depending on residue type, while elemental composition and heating values were partly estimated using empirical correlations. Consequently, the reported energy potentials should be considered first-order theoretical estimates intended to support resource screening and regional planning rather than exact predictions of technically recoverable energy.

5. Conclusions

This study assessed the availability, physicochemical characteristics, and energy potential of selected agricultural, agro-industrial, and forestry residues in the Republic of the Congo. The findings demonstrate that diverse lignocellulosic residues are available across the country and could constitute a relevant resource for bioenergy development. However, their availability, characteristics, and geographical distribution vary considerably according to residue type and department, emphasizing the importance of locally adapted biomass energy strategies.

A clear geographical complementarity was observed in residue availability. Agricultural and agro-industrial residues were particularly important in Bouenza, reflecting the concentration of agricultural and agro-industrial activities in this department, whereas forestry residues predominated in several forest- and wood-processing areas, particularly

Sangha and Cuvette. Only limited quantities of the targeted residues were identified in Pool. This spatial variability indicates that future biomass valorization strategies should be designed according to the type, quantity, and local availability of residues rather than through a uniform national approach.

The physicochemical and energy characteristics of the investigated residues indicate potential opportunities for their valorization as solid biofuels, including pellets and briquettes, as well as through appropriate thermochemical conversion pathways. Where sufficient and sustainable residue supplies can be secured, these resources could also contribute to decentralized heat and electricity production, particularly in rural and peri-urban areas. Their valorization could therefore contribute to diversifying the national energy mix while promoting the productive use of agricultural, agro-industrial, and forestry residues.

From a public-policy perspective, the findings support the integration of locally available biomass residues into national renewable-energy and rural-electrification strategies. Priority measures could include support for decentralized biomass energy projects in residue-rich areas, the development of organized residue collection and supply chains, incentives for investment in small- and medium-scale biomass conversion technologies, and the establishment of appropriate technical and sustainability standards for biomass-derived fuels. Such measures could facilitate the development of locally adapted bioenergy value chains while contributing to improved energy access, particularly in rural and peri-urban areas.

The findings should nevertheless be interpreted within the methodological scope of the study. The estimated energy potentials represent first-order theoretical estimates of the available biomass resource rather than technically or economically recoverable energy potential. Further research should therefore focus on improving the quantification of residue availability and associated uncertainties, experimentally validating estimated fuel properties where applicable, assessing seasonal and spatial variability, and conducting detailed techno-economic and environmental assessments of the most promising biomass conversion pathways. Such investigations will be essential to determine the practical feasibility and sustainability of biomass-based energy systems in the Republic of the Congo.

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Abbreviations

The following abbreviations are used in this manuscript:

CIB	Congolaise Industrielle de Bois
SEFYD	Société d'Exploitation Forestière Yuang Dong
IFO	Industrie Forestière de Ouesso
SICOFOR	Sino-Congo Forêt

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