Energy Valorization of Cashew Nut Shells: Characterization of Volatile Organic Compounds and Quantitative Health Risk Assessment in Pyrolysis and Direct Combustion Processes

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Abstract—This study evaluates the health risks associated with exposure to atmospheric emissions from energy recovery of cashew nut shells through pyrolysis and combustion processes. The analysis focuses on two risk categories: carcinogenic risks, assessed by the Individual Risk Excess (ERI), and non-carcinogenic risks, estimated by the Hazard Quotient (HQ). Samples were collected at the source (industrial chimney) using isokinetic sampling on activated carbon tubes and subsequently analyzed by gas chromatography coupled with mass spectrometry to identify and quantify Volatile Organic Compounds (VOCs). These concentrations were then modelled at 500 meters using an atmospheric dispersion model of the Screening Modelling in Air Quality Assessment type. The results show that benzene and 1,3-butadiene are the primary contributors to carcinogenic risks, with a total ERI exceeding the acceptable threshold of 10^5. For benzene, direct combustion poses approximately 1.7 times the risk compared to pyrolysis. Similarly, 1,3-butadiene shows a risk reduction with pyrolysis (about 1.3 times lower). Overall, pyrolysis reduces the total carcinogenic risk by 26.9% when compared to direct combustion. Regarding non-carcinogenic risks, the Hazard Quotients (HQ) for toluene (4.38×10^{-5} for combustion and 4.03×10^{-5} for pyrolysis) and styrene (5.8×10^{-4} for combustion and 1.9×10^{-4} for pyrolysis) remain below 1, indicating limited short-term health effects. Comparing the two recovery processes, the overall hazard quotients show a slight reduction of 11.1% between direct combustion and pyrolysis of cashew nut shells. The study recommends technological improvements and strict regulatory measures to sustainably manage emissions sustainably, thereby protecting public health and the environment.

Keywords—energy valorization, cashew nut shells, Volatile Organic Compounds (VOCs), health risks, modelling in air quality assessment, pyrolysis and combustion

I. INTRODUCTION

Pollutant emissions resulting from the energy recovery of agricultural biomass or agro-industrial residues pose more than just a technical challenge. They have a significant environmental impact and public health implications, particularly by degrading air quality and exposing local populations to hazardous substances [1].

In recent decades, agricultural residues have emerged as a promising source of sustainable energy, accounting for approximately 13% of global biomass usage and meeting up to 30% of energy needs in rural areas of developing countries [2, 3]. Among these residues, cashew nut shells, a by-product of cashew processing units, stand out for their high energy potential. With a lower heating value (LHV) of around 24.838 MJ/kg [4], raw cashew nut shells are increasingly regarded as a viable alternative fuel for industrial applications. In countries such as Côte d'Ivoire, Burkina Faso, and Benin, these shells are used in industrial boilers through direct combustion or pyrolysis [5–7], thereby reducing dependence on fossil fuels and contributing to more effective solid waste management. This viable option is underscored by the fact that, in addition to presenting energy potential, the carbon released during the combustion of biomass originates from short-term photosynthesis cycles. Such characteristics render them biogenic and often carbon neutral, unlike fossil fuels, which emit additional CO_2 accumulated over millions of years [8].

However, the energy recovery of cashew nut shells also leads to the release of pollutant emissions that raise serious environmental and health concerns. The smoke emitted is typically thick, black, and acrid. Studies have reported the presence of several pollutants, including Carbon Monoxide (CO), Carbon Dioxide (CO_2), Nitrogen Oxides (NOx), Sulfur Oxides (SO_2), Particulate matter and Polycyclic Aromatic Hydrocarbons (PAHs) [9]. This characteristic of the emissions could result from the thermal degradation of phenolic compounds naturally present in cashew nut shells, such as anacardic acid, cardol, and cardanol, whose breakdown products include Volatile Organic Compounds (VOCs). These VOCs are known to have irritant, toxic, and, in some cases, carcinogenic properties, capable of affecting the eyes, mucous membranes, and respiratory system and potentially contributing to long-term neurological or pulmonary conditions.

Despite their relevance, VOCs emitted from the combustion of hulls for energy recovery on an industrial scale are not well understood. Their characterization is essential because it allows us to understand their profiles and evaluate the population's exposure risk for sustainable energy valorization.

In rural areas and developing countries, the combustion of cashew nut shells is a prevalent practice across multiple industries, often occurring without the implementation of comprehensive emission control systems or those with limited scope. Consequently, there has been an emission of certain hazardous pollutants, such as Volatile Organic

Compounds (VOCs), which have been shown to deteriorate air quality and potentially compromise the respiratory health of nearby populations, as well as elevate the risk of long-term cancer development.

Previous studies [5, 9] on emissions from the energy recovery of cashew nut shells have primarily been conducted under laboratory conditions, focusing on combustion gases such as Carbon Monoxide (CO), Carbon Dioxide (CO_2), and Nitrogen Oxides (NOx), as well as the toxicity of particulate matter and Polycyclic Aromatic Hydrocarbons (PAHs). However, these studies overlooked the analysis of VOCs present in emissions. Additionally, the complex reality of industrial combustion processes in terms of toxicity wasn't reflected by them either.

Our study addresses this gap by collecting in-situ samples from industrial chimneys and applying Gas Chromatography Coupled with Mass Spectrometry (GC-MS) to characterize Volatile Organic Compounds (VOCs). We then integrate the results into atmospheric dispersion models, enabling us to assess the health risks for populations residing nearby with greater precision. We incorporated the measured concentrations into the Gaussian dispersion model to simulate the transport and dilution of Volatile Organic Compounds (VOCs) emitted from the chimney, extending up to a radius of 500m and encompassing nearby residential areas. These modelled concentrations were further used in exposure equations to estimate inhaled doses and to evaluate both carcinogenic and non-carcinogenic health risks.

The insights gained from this research will enhance our understanding of the environmental and health risks associated with biomass energy recovery, guiding policy and technological improvements toward more sustainable waste management practices.

II. LITERATURE REVIEW

Energy recovery of cashew nut shells has been the subject of numerous studies aimed at understanding the mechanisms of pyrolysis and combustion, as well as the resulting emissions of pollutants. Tsamba *et al.* [10] examined the pyrolysis of cashew nut shells at various heating rates (10, 30, and 100 K/min) using a thermogravimetric analyzer coupled with Fourier-transform infrared spectroscopy (TG-FTIR). Their analysis enabled the identification of a wide range of volatile species, including carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), ethylene (C_2H_4), and water vapor (H_2O), formic acid (HCOOH), formaldehyde (CH_2O), methanol (CH_3OH), ammonia (NH_3), hydrogen cyanide (HCN), isocyanic acid (HCNO), acetone, phenol, acetic acid, and acetaldehyde. Tar yields were estimated by gravimetric difference. The presence of these light hydrocarbons and oxygenated compounds, especially CH_4, C_2H_4, CH_3OH, CH_2O, HCOOH, and acetaldehyde, reflects the high volatile content of cashew nut shells. Compared to other biomasses, such as wood pellets and Miscanthus giganteus, CNS show a greater release of volatiles, highlighting their potential for thermal valorization.

Abrego *et al.* [5] conducted a pyrolysis study of cashew nut shells in a fixed-bed batch reactor operated between 400°C and 600°C. The composition of the pyrolysis gases was analyzed using an online micro-gas chromatograph (micro-GC), which revealed a clear predominance of non-combustible gases—Carbon Dioxide (CO_2) accounted for approximately 68% of the total gas mass, followed by Carbon Monoxide (CO) at 15%, and Methane (CH_4) at 12%, with only trace amounts of other combustible gases such as Hydrogen (H_2) and Ethylene (C_2H_4). Similarly, Moreira *et al.* [11] performed pyrolysis under nitrogen in a batch tubular reactor and found that the gas fraction, analyzed by GC with TCD and FID detectors, was mainly composed of CO_2 and CO at lower temperatures ($\leq$400 °C), further confirming the limited production of combustible gases.

These findings underscore the predominance of non-combustible gases during the thermal degradation of cashew nut shells and suggest that the raw material's oxygen-rich composition (typical of lignocellulosic biomass) leads to high CO_2 yields. Consequently, improving the energy recovery potential from CNS pyrolysis requires enhanced process control, particularly of temperature, residence time, and carrier gas atmosphere, to maximize the formation of valuable fuel gases, such as CH_4 and H_2.

Furthermore, Nam *et al.* [12] identified several technological challenges during their parametric study of cashew nut shell pyrolysis under conditions representative of industrial applications. One of the key difficulties lies in the decomposition of cashew nut shell liquid (CNSL), which occurs within the same temperature range as the thermal degradation of hemicellulose and cellulose. This overlap results in multiple competing reactions—such as volatilization, cracking, and secondary reforming coinciding. The combined effect of temperature, heating rate, and residence time makes it challenging to control the formation and composition of gaseous products precisely.

In industrial conditions where real-time control and fine-tuning of thermal parameters are limited, this complexity results in variability in emission profiles. Therefore, Nam *et al.* [12] emphasize the need for the development of advanced pyrolysis technologies that provide better regulation of operating conditions to ensure consistent and cleaner gas emissions.

Previous studies on combustion from cashew nut shells have reported the emission of hazardous pollutants, including CO, NOx, SOx, CH_4, fine particulate matter (PM_{10}, $PM_{2.5}$), PAHs, and various phenolic compounds. These pollutants were detected using multiple analytical techniques, including Gas Chromatography-Mass Spectrometry (GC-MS), X-ray fluorescence spectrometry, real-time particle monitoring, scanning electron microscopy with Energy-Dispersive X-ray Spectroscopy (SEM-EDS), and High-Performance Liquid Chromatography with Diode Array Detection (HPLC-DAD). These findings highlight the potential respiratory and carcinogenic risks associated with the uncontrolled combustion of cashew nut shells [13–18].

The literature review reveals that most studies on the energy recovery of cashew nut shells have been conducted under controlled laboratory conditions, which limits their applicability to real-world industrial contexts. Crucially, few of these studies have characterized volatile organic compounds (VOCs) or quantified the associated health risks based on actual population exposure. This gap is particularly concerning given the known toxicity and irritant properties of VOCs, as well as their potential long-term health effects. Conducting industrial-scale studies is therefore essential to accurately assess real exposure conditions, better understand the behavior of pollutants under operational constraints, and

inform both technological innovation and environmental regulation. Our study aims to fill this gap by characterizing VOC emissions directly at the industrial chimney and assessing the corresponding health risks through atmospheric dispersion modelling and quantitative risk analysis.

III. MATERIALS AND METHODS

A. Energy Recovery Processes

For the energy recovery of cashew nut shells, two main energy recovery processes are generally used in the raw cashew nut processing industry: direct combustion and pyrolysis. In direct combustion, the shells are burned directly in a combustion chamber to produce energy. In contrast, the pyrolysis process involves first thermally decomposing the shells with reduced oxygen, generating pyrolysis gases that are subsequently burned in a post-combustion chamber to produce the necessary energy.

Fig. 1 below illustrates the combustion of cashew nut shells, resulting in harmful black and acidic smoke.

Fig. 1. Combustion of cashew nut shells.

B. Sampling and Analysis of VOCs

Volatile Organic Compounds (VOCs) are emitted from various industrial sources and have a significant impact on both air quality and human health. To assess emissions from an industrial chimney, a rigorous sampling protocol was implemented, combining field sampling and laboratory analysis using Gas Chromatography coupled with Mass Spectrometry (GC-MS).

Sampling was conducted on-site with the NF EN 15259 standard, titled *"Measurement of emissions from stationary sources – Requirements for measurement sections and sites, and for the measurement objective, plan and report"* This standard defines the criteria for selecting representative sections in the chimney, ensuring homogeneous flow and optimal sampling conditions.

The sampling system consisted of a regulated-flow pump, a heated stainless steel sampling probe, and adsorbent tubes filled with activated charcoal. A dedicated sampling port was prepared at the identified measurement location on the chimney, as prescribed by the standard.

The heated probe was connected to the pump, allowing for the controlled aspiration of flue gas through the sampling line. The emissions were passed through the charcoal tubes, allowing VOCs to be adsorbed of over one hour, with continuous monitoring of temperature, flow rate, and operational stability.

After sampling, the tubes were hermetically sealed, labelled, and transported in an isothermal cooler to preserve the integrity of the samples. In the laboratory, VOCs were desorbed using carbon disulfide (CS_2) and then analyzed using gas chromatography-mass spectrometry (GC-MS).

C. Atmospheric Dispersion Modelling

Screening Modelling in the air quality Assessment method was used to estimate VOC concentrations in residential areas near industrial sites.

We used a Gaussian dispersion modelling approach (screening modelling) to estimate the atmospheric concentrations of VOCs emitted by industrial facilities in nearby residential areas. This method allowed us to simulate the dispersion and dilution of pollutants in ambient air, taking into account several key parameters: the concentration of each VOC at the emission source, the stack height, gas temperature, ejection velocity, wind speed, and local topography.

The model was applied to estimate VOC concentrations at a distance of 500m, corresponding to the proximity of neighboring residential zones. These simulated concentrations were then integrated into exposure equations to perform a quantitative health risk assessment for populations potentially exposed to the emissions.

D. Quantitative Health Risk Assessment (QHRA)

The QHRA of the energy recovery from cashew nut shells aimed to quantify both carcinogenic and non-carcinogenic risks for the surrounding population of industrial sites through the following steps.

- Toxicological Characterization:

Toxicological Reference Values (TRVs) are used to establish a relationship between exposure to a pollutant and its health effects in humans. They are specific to a substance, an exposure pathway, and a duration. The TRVs applied in this study were selected from [19] and [20], a structured database organized by exposure duration and inhalation pathways. Only compounds for which TRVs were available were considered in the Quantitative Health Risk Assessment (QHRA). Only compounds with available target release values (TRVs) were considered for the QHRA.

- Exposure Estimation:

Modelled VOC concentrations were integrated into exposure equations to calculate the average inhaled dose (CI) as in Eq. (1):

$$CI = Ci \times \frac{ti}{T} \qquad (1)$$

where:

CI: Average inhaled concentration (mg/m³)
Ci: Pollutant concentration in the air (mg/m³)
ti/T: Fraction of exposure time (8h/24h)

- Risk Indices Calculation

To assess the potential health risks associated with VOC exposure, two key risk indexes were calculated. Non-carcinogenic risks were evaluated using the Hazard Quotient (HQ), which compares the estimated exposure to a reference toxicological value. An HQ ≥ 1 suggests a potential health concern. Carcinogenic risks were calculated through the Individual Risk Excess (ERI), which quantifies the

probability of additional cancer cases based on a threshold-free toxicological value specific to each compound.

Non-Carcinogenic Risks: Assessed via Hazard Quotient (HQ) as in Eq. (2):

$$HQ = \frac{CI}{VTRAS,inh} \qquad (2)$$

Carcinogenic Risks: Estimated through Individual Excess Risk (ERI) as in Eq. (3):

$$ERI = (CIi \times \frac{Ti}{Tm}) \times VTRss, inh \qquad (3)$$

IV. RESULT AND DISCUSSION

A. Characterization of Volatile Organic Compounds (VOCs)

The analysis of smoke emissions from the combustion of cashew nut shells was conducted on samples collected directly from the industrial chimney and subsequently analyzed using gas chromatography coupled with mass spectrometry (GC-MS). This method enabled the precise characterization of the VOC composition present in the smoke emitted by a pyrolysis technology for cashew nut shells, allowing for a direct comparison with the results obtained from a direct combustion technology (see Table 1).

Table 1. VOC concentrations in smoke emissions (mg/Nm³)

Compound	Pyrolysis	Direct Combustion
Benzene	79.33	246.60
1,3-Butadiene	3.87	22.50
Toluene	18.83	99.27
Styrene	2.71	20.54
Ethyl Cyclopropane	1.72	7.44
2-Methyl-1-propene	2.00	9.63
Propene	2.63	2.58
m+p-Xylene	0.97	9.90
Fluorene	0.25	0.70

The total VOC concentration measured during pyrolysis was 283.17 mg/Nm³, indicating a significant presence of these compounds in the emitted gases. Among the primary VOCs identified, benzene was the most abundant (79.33 mg/Nm³), followed by toluene (18.83 mg/Nm³) and 1,3-butadiene (3.87 mg/Nm³). These three compounds, recognized for their toxicity and potential carcinogenicity, serve as key indicators in assessing health risks.

Additional volatile compounds were detected at lower concentrations. For instance, styrene was measured at 2.71 mg/Nm³, propene at 2.63 mg/Nm³, and cyclopentene at 1.92 mg/Nm³. Furthermore, certain hydrocarbons, such as 2-methyl-1-propene (2.00 mg/Nm³) and ethyl cyclopropane (1.72 mg/Nm³), were identified. Trace levels of aromatic compounds, including m+p-xylene (0.97 mg/Nm³) and polyaromatic compounds, exemplified by fluorene (0.25 mg/Nm³), were also detected.

Based on the analysis of VOC emissions, the results show that pyrolysis generally emits lower levels of both carcinogenic and non-carcinogenic compounds compared to direct combustion. In particular, the emissions of benzene, 1,3-butadiene, toluene, and styrene are significantly lower under pyrolysis conditions (benzene: 79.33 mg/Nm³ for pyrolysis versus 246.60 mg/Nm³ for direct combustion). The results indicate that pyrolysis may significantly lower carcinogenic and non-carcinogenic health risks linked to the energy recovery of cashew nut shells.

These findings demonstrate the diversity and significant concentration of VOCs emitted, thereby highlighting potential risks to air quality and public health. This data provides a foundation for the quantitative evaluation of health risks, taking into account the specific toxicological properties of each identified compound.

B. Modelling Concentrations of Volatile Organic Compounds (VOCs)

The concentrations of volatile organic compounds (VOCs) measured in both pyrolysis and direct combustion processes demonstrated distinct variations (Fig. 2). Notably, the modelled concentrations of benzene, 1,3-butadiene, and toluene were significantly higher in direct combustion as compared to pyrolysis, indicating the direct influence of technological performance on atmospheric pollutant emissions. This finding underscores the importance of process selection, as direct combustion tends to release greater quantities of hazardous compounds into the environment. In contrast, the pyrolysis method demonstrated the ability to reduce these emissions, suggesting the potential for a cleaner energy recovery of the cashew nutshell option.
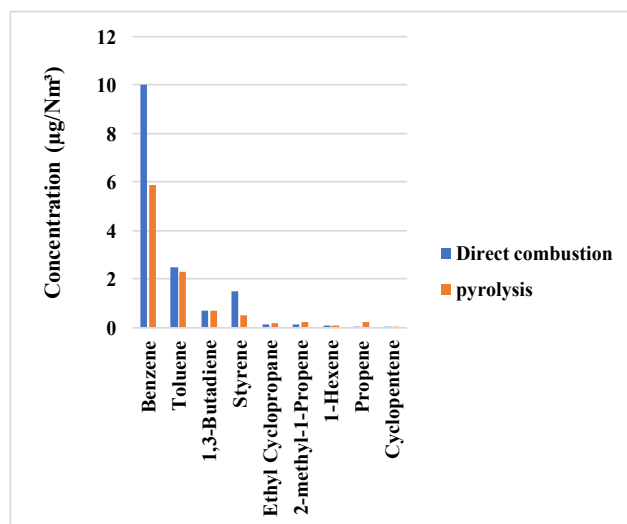

Fig. 2. Concentrations of volatile organic compounds (VOCs).

C. Result in Quantitative Health Risk Assessment (QHRA)

1) Non-carcinogenic risks

The hazard quotient (HQ) results for the three studied compounds, based on the processing method used, are presented in Table 2.

Table 2. Quotient Hazard (HQ)

Compound	HQ Combustion	HQ Pyrolyse	Variation (Combustion-Pyrolysis)
Toluene	4.38×10^{-5}	4.03×10^{-5}	7.9 %decrease
Styrene	5.8×10^{-4}	1.9×10^{-4}	67.2 %decrease
m+p-xylene	8.3×10^{-5}	7.7×10^{-4}	9.3-fold increase
$\sum HQ$	9×10^{-3}	8×10^{-3}	11%decrease

The hazard quotient (HQ) values for the three compounds studied, based on the processing method, are presented in Table 1. Our analysis indicates that pyrolysis decreases the HQ for both toluene and styrene compared to direct combustion, with reductions of 7.9% and 67.2%, respectively. These results imply that pyrolysis is more effective in

degrading hazardous pollutants, leading to a reduction in related health risks. Conversely, a significant increase in the HQ for m+p-xylene was noted with pyrolysis, escalating from $8.3×10^{-5}$ to $7.7×10^{-4}$(9.3-fold), which may suggest enhanced formation or reduced degradation of this compound during the process. Overall, the total HQ experienced a modest reduction of 11%, demonstrating only a slight improvement in the non-carcinogenic risk profile when transitioning from direct combustion to pyrolysis.

2) Carcinogenic risks

The carcinogenic risk evaluation was conducted by estimating the Individual Risk Excess (ERI) for direct combustion and pyrolysis processes, with a focus on benzene and 1,3-butadiene emissions, as presented in Table 3.

Table 3. Individual Risk Excess (ERI)

Compound	Direct Combustion ERI	Pyrolysis ERI
Benzene	$4.29.10^{-6}$	$2.53×10^{-6}$
1,3-Butadiene	$1.43×10^{-5}$	$1.11×10^{-5}$
Total ERI	$1.86×10^{-5}$	$1.36×10^{-5}$

The results demonstrate that the direct combustion of cashew nut shells poses a significantly higher carcinogenic risk compared to pyrolysis, with a total ERI of $1.86×10^{-5}$ for combustion versus $1.36×10^{-5}$ for pyrolysis, reflecting a reduction of approximately 26.9%. Benzene emissions from direct combustion posed roughly 1.7 times higher risk than from pyrolysis, while 1,3-butadiene exhibited a more minor risk reduction (about 1.3 times lower with pyrolysis). The significant decrease in carcinogenic risk highlighted by pyrolysis supports the notion that pyrolysis could be a safer alternative in terms of minimizing exposure to carcinogenic compounds like benzene and 1,3-butadiene.

While pyrolysis significantly reduces carcinogenic risks, it is essential to note that the remaining levels still exceed the widely accepted threshold of 1.10^{-6}.

The diversity of Volatile Organic Compounds (VOCs) detected reflects the complex chemical transformations that occur during the energy recovery of cashew nut shells. These shells are rich in phenolic compounds, such as anacardic acid, cardanol, and cardol [21], which are intrinsic to their chemical composition. The thermal degradation of these compounds likely contributes to the formation of smaller aromatic molecules. The phenolic compounds naturally present in cashew nut shells, such as anacardic acid, cardol, and cardanol, contribute significantly to VOC formation. Under high-temperature conditions, these molecules undergo thermal decomposition mechanisms such as decarboxylation and dealkylation. For instance, anacardic acid, with its carboxyl group, phenolic ring, and aliphatic side chain, can fragment into benzene and toluene. These reactions are initiated by the heat-induced cleavage of the carbon side chains and the removal of functional groups, leading to the formation of volatile, toxic aromatic compounds [22]. Similarly, cardanol and cardol may undergo thermal decomposition and rearrangements, generating compounds such as 1,3-butadiene as well as xylene isomers.

Furthermore, the detection of polyaromatic compounds, such as fluorene, suggests that secondary condensation reactions among low-molecular-weight aromatics occur under high-temperature pyrolysis conditions. The observation suggests that some VOCs originate directly from the initial phenolic compounds, whereas others are formed through complex secondary reactions that alter the overall emission profile ([11, 12]).

Overall, the substantial concentrations and diversity of VOCs, including both primary aromatic compounds and those potentially derived from phenolic degradation, underscore the need for a deeper understanding of the thermal transformation mechanisms during the pyrolysis or combustion of cashew nut shells. This knowledge is essential for developing effective mitigation strategies to control harmful emissions in industrial applications of cashew nut shell energy recovery, thereby reducing the associated environmental and health risks.

Building on the insights into the formation and nature of VOCs, our study further demonstrates that pyrolysis represents a promising alternative to direct combustion for the energy recovery of cashew nut shells, as it generally results in lower emissions of both non-carcinogenic and carcinogenic pollutants. Despite the overall reduction in toxic emissions, pyrolysis unexpectedly led to higher levels of m+p-xylene compared to direct combustion. A probable explanation involves the breakdown of phenolic compounds during pyrolysis, where limited oxygen availability favors the formation of VOCs like m+p-xylene over complete oxidation. These findings suggest that although pyrolysis offers advantages in reducing most health-related risks, additional emission control strategies, such as optimizing airflow and adopting staged combustion systems, are necessary to ensure a broader reduction of all harmful compounds [11]. Despite an overall 26.9% reduction in carcinogenic risk, the residual risk levels remain above the acceptable threshold of 1.10^{-6}, underscoring the indispensable need for additional emission reduction measures to minimize adverse health impacts [23].

V. CONCLUSION

This study highlights the challenges and potential benefits of recovering energy from cashew nut shells, with particular attention to atmospheric emissions and associated health risks. Volatile organic compounds (VOCs) were collected using an isokinetic smoke sampling system installed at industrial chimneys. Samples were adsorbed onto activated charcoal tubes and subsequently analyzed using gas chromatography coupled with mass spectrometry (GC/MS). The measured concentrations were modelled and incorporated into a quantitative health risk assessment (QHRA) to estimate exposure levels and potential risks to nearby populations.

Our findings reveal that emission levels of hazardous compounds such as benzene and 1,3-butadiene exceeded recommended safety thresholds, emphasizing the need for improved emission control strategies. When comparing direct combustion with pyrolysis, the latter proves to be a safer alternative for energy recovery from cashew nut shells. A 26.9% reduction in overall carcinogenic risk was observed, primarily due to significantly lower emissions of benzene and 1,3-butadiene. This reduction is attributed to the oxygen-limited conditions and the more stable thermal environment of pyrolysis, which limit the formation of toxic by-products commonly associated with incomplete combustion. As a result, pyrolysis represents a cleaner and less harmful energy recovery pathway. However, some residual emissions remain

concerning, and further technological improvements are needed to achieve consistent control in real-world industrial settings.

In summary, although pyrolysis shows strong potential for reducing harmful emissions from cashew nut shell processing, additional mitigation strategies are essential to bring both carcinogenic and non-carcinogenic risks within acceptable limits. Future research should prioritize the optimization of combustion parameters, such as temperature, residence time, and oxygen supply, particularly in industrial contexts where real-time control is limited. One promising avenue is the development of staged combustion technologies, which improve the oxidation of volatile compounds by controlling primary and secondary airflow inputs. In this regard, the BioStar project currently under development offers an innovative and locally adapted solution. By enhancing combustion stability and air distribution, this technology may significantly reduce residual VOC emissions. Further studies are warranted to assess its effectiveness compared to conventional pyrolysis and direct combustion systems, and to support the development of cleaner, safer, and more sustainable biomass energy recovery practices.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

AUTHOR CONTRIBUTIONS

Anselme BAGORO, Marie SAWADOGO, and Anthony BENOIST conceptualized the study and developed the experimental framework. Anselme BAGORO and Marie SAWADOGO contributed significantly to the study design by performing the data analysis and interpreting the results with a particular focus on atmospheric emissions. Igor W.K. OUEDRAOGO, Sayon dit Sadio SIDIBE, and Anselme BAGORO coordinated the sample collection at the industrial sites and contributed to developing the analytical methodology and interpreting the data. Igor W.K. OUEDRAOGO, Sayon dit Sadio SIDIBE, and Anthony BENOIST supervised the entire project and ensured the integration of interdisciplinary approaches. All authors reviewed and approved the final version of the manuscript.

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