



## Harnessing cocoa waste for biochar production and emission reduction to promote sustainability in West Africa

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### ABSTRACT

West Africa is a key player in cocoa cultivation, accounting for approximately 70% of world cocoa bean production. However, cocoa pod husk (CPH), an important by-product, remains largely underutilized. Therefore, this study provides the first comprehensive, multi-country assessment of CPH generation across seven major West African cocoa-producing countries namely Côte d'Ivoire, Ghana, Nigeria, Sierra Leone, Liberia, Guinea, and Togo over a 20-year period. It further assesses current management pathways and their environmental implications, with an evaluation of biochar as valorization approach. The data used in this study was gathered through field surveys and quantitative secondary data from FAOSTAT. Methane (CH<sub>4</sub>) emissions from decomposition of CPH were estimated based on IPCC methodologies, while biochar potential and carbon sequestration capacity were determined using established equations. The results showed that in 20 years, a total of 578 million tonnes of CPH were produced, with Côte d'Ivoire contributing the largest share with 331 million tonnes, followed by Ghana with 160 million tonnes. At present, on-farm abandonment remains the predominant management practice, emitting an estimated 17 million tonnes of carbon dioxide equivalent (CO<sub>2</sub>-eq) annually representing about 3% of Africa's agricultural CH<sub>4</sub> emissions. Conversion of this biomass into biochar represents a significant mitigation opportunity. The estimated annual production potential of CPH-biochar is 869 thousand tonnes, capable of sequestering about 1.59 million tonnes of CO<sub>2</sub>-eq per year. Adopting this approach could reduce greenhouse gas (GHG) emissions more than 18 million tonnes of CO<sub>2</sub>-eq, including avoided emissions and carbon sequestration. These findings highlight the importance of CPH-biochar production as a promising strategy for sustainable waste management.

### Introduction

Agriculture is an important economic driver in West Africa, contributing 35% of gross domestic product (GDP). Its share varies considerably from around 4% in smaller economies to over 40% in some countries (Our World in Data, 2024). The sector supports over 290 million people and employs about 60% of the region's labor force (Osabohien et al., 2019). Besides, it plays an indispensable role in ensuring food security and maintaining economic stability in West Africa. The majority of countries in the region are heavily engaged in agricultural activities. Among the different crops grown in the region, cocoa is one of the most economically important cash crops.

The cacao tree also known as *Theobroma cacao* L., meaning food of the gods in Greek belongs to the family *Malvaceae* (Baharum et al.,

2016). As illustrated in Fig. 1, the cocoa fruit (cocoa pod) can be found in three distinct varieties depending on their pod color at maturity such as Forastero, Criollo and Trinitario (Micheli et al., 2010; Adabe and Ngo Sannick, 2014; Chumacero de Schawe et al., 2018; Bekele, 2019; Ouattara et al., 2021a). The average size of the fruit is 16.5 cm long and 7.8 cm in diameter with average weight of 400–600 g (mature fruit) containing 35–50 beans (Crozier et al., 2011; Sitohang and Siahaan, 2018). It is mainly composed of pulp or mucilage (8.7–9.9%), beans (21–23%), and pod husk (67–76%) (Campos-Vega et al., 2018). The diversity of cocoa varieties is a crucial factor in the prosperity of the cocoa sector.

The origin of cocoa in West Africa can be traced back to the colonial period. It was introduced to Africa by the Portuguese in 1822 on the island of São Tomé, even though it originated in Latin America (HOWES,

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1946; Wood and Lass, 2008). West Africa is currently the largest cocoa producer in the world thanks to favorable climatic conditions. It accounts for more than 70% of the global supply of cocoa beans, with Côte d'Ivoire representing 40%, followed by Ghana (20%) and Nigeria (5%) (Schroth et al., 2016; Beg et al., 2017; Merem et al., 2020). Most beans are exported to Europe, Asia and North America to be processed into chocolate, cocoa butter and cocoa powder, etc. Cocoa by-products, particularly CPH, are on the other hand left as waste in producing countries. Giving the large volumes of CPH produced each year, limited processing infrastructure and inefficient residue management systems at national and regional levels constrain their effective valorization in West Africa. In most farms, CPH are left at the farm after removing the beans. Compared with major cocoa-growing regions outside Africa, such as Southeast Asia and South America, several studies reported emerging valorization pathways supported by recent technological developments and policy initiatives. Yet, on-farm disposal of CPH remains common (Syamsiro et al., 2012; Picchioni et al., 2020; Meza-Sepúlveda et al., 2021; Rozita et al., 2022; Holguín Posso et al., 2024; Nacua and Lacang, 2024; Salcedo-Puerto et al., 2025). Though this practice can return organic carbon, potassium, and other essential nutrients to the soil, it also introduces several agronomic and environmental risks. The decomposition of CPH releases CH<sub>4</sub> and CO<sub>2</sub>, which contributes to GHG emissions (Mwafulirwa et al., 2024). Accumulating pod husks also

create favorable conditions for pests and pathogens, in particular *Phytophthora palmivora*, the causal agent of black pod disease, which can reduce cocoa yields by 20–30% (Perrine-Walker, 2020; Geroche et al., 2024).

In West Africa, research interest in CPH valorization has been growing in recent years, with studies exploring its use in animal feed, potash production, power generation, biochar and hydrogen production (Gyedu-Akoto et al., 2015; Lu et al., 2018; Ouattara et al., 2020; Zanli et al., 2022; Angbé et al., 2024). However, no comprehensive regional-scale assessment of CPH generation, emissions, and biochar potential across multiple West African countries exists. To address this gap, this study (i) quantifies the amount of CPH generated over a 20-year period in Côte d'Ivoire, Ghana, Nigeria, Sierra Leone, Liberia, Guinea, and Togo; (ii) evaluates the environmental implications of current CPH management practices, particularly GHG emissions associated with on-farm decomposition; and (iii) assesses the potential of converting it into biochar as a sustainable and scalable recovery pathway for soil amendment and emission mitigation.

CPH, rich in cellulose, hemicellulose and lignin, represents a valuable feedstock for biochar production. Biochar is a carbon-rich, porous substance produced through pyrolysis, a thermochemical conversion route of organic materials (Weber and Quicker, 2018; Wang and Wang, 2019; Luo et al., 2023). Unlike anaerobic digestion or biofuels, which

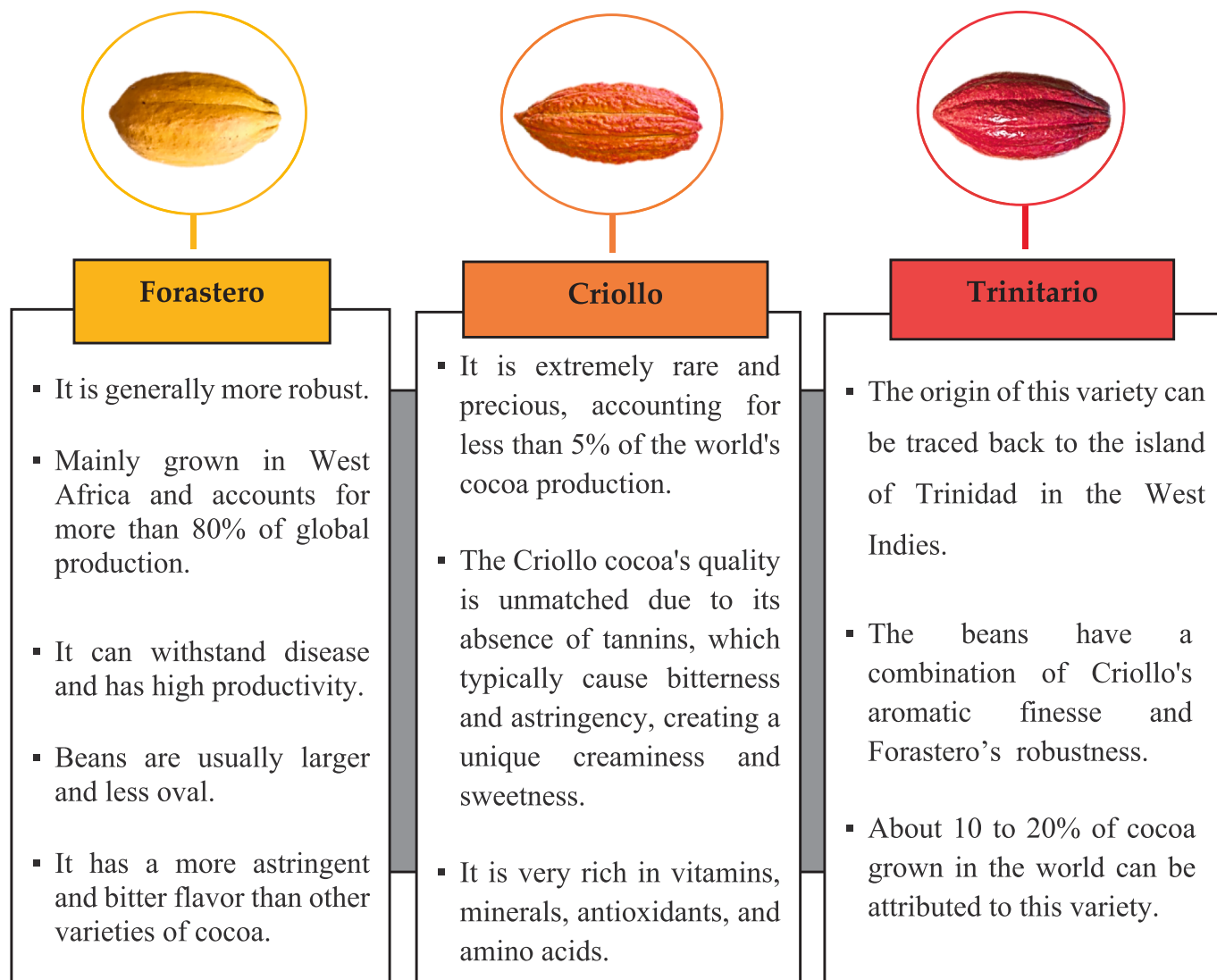


Fig. 1. Varieties of cocoa pods and their characteristics.

require extensive infrastructure, biochar can be produced using small-scale, low-cost equipment. In addition, the porous nature of biochar can help soils retain water and nutrients, reducing the impact of water stress on crops. Simultaneously, the use of biochar can lock carbon in the soil into a stable form, thus reducing GHG emissions. In this context, the conversion of CPH to biochar is not only an effective waste management strategy but also a low-cost, climate-smart solution.

**Materials and methods**

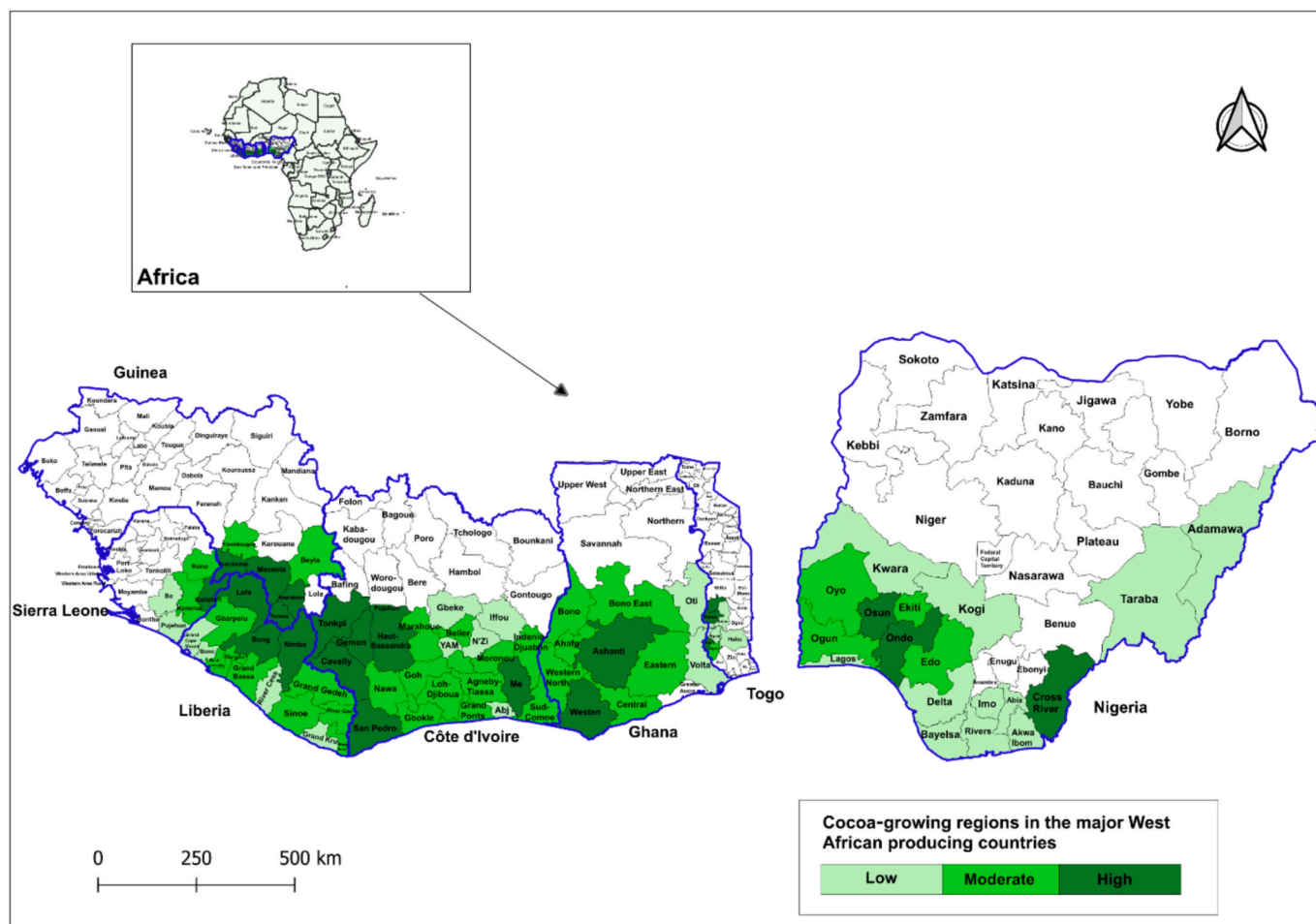
*Study area*

This study focuses on West Africa, located between latitudes 4°N and 28°N and between longitudes 15°E and 16°W. The region is dominated by tropical climate and favorable agro-climatic conditions (Blein et al., 2008). The annual average temperature is between 24–32 °C with rainfall ranging between 1,000–3,000 mm, making it a conducive environment for cocoa farming. Seven main cocoa producing countries, including Côte d'Ivoire, Ghana, Nigeria, Togo, Sierra Leone, Liberia and Guinea, where cocoa farming is one of the biggest drivers of land use, are considered for this study. For example, in 2022, Côte d'Ivoire and Ghana allocated about 32% and 27% of their total cultivated land to cocoa farms respectively (Merem et al., 2020; FAOSTAT, 2024). Their cocoa-growing areas (Fig. 2) were mapped in QGIS 3.30 using datasets from multiple sources (Milbrandt, 2009; Oro et al., 2011; AFOLAYAN, 2020; Abu et al., 2021; Attioghé et al., 2022; Moinina et al., 2023). This delimitation is based on reported data and should be interpreted as an

indication of the dominant cocoa growing regions. Due to the limited availability of data at the regional level, some smaller or dispersed areas of cocoa cultivation may not be fully represented.

*Data collection and processing*

The study utilized a mix of primary and secondary data sources. In Côte d'Ivoire, a purposive sampling approach was applied, where farms located in the southern cocoa belt were visited based on accessibility and the predominance of cocoa cultivation. In Togo, a convenience sampling method was used in collaboration with the local cocoa cooperative, ensuring inclusion of both small and large producers. This non-probabilistic approach was adopted due to logistical constraints in remote rural areas. Although such a sampling strategy does not permit statistical generalization to all cocoa farms, it provides representative insights into key cocoa-growing contexts. Field data collection was conducted in the remote village of Kpadapé, located near Kpalimé (6.8417° N; 0.5939° E), in the Plateaux Region, about 120 km from Lomé, the capital of Togo. The Kobo tool was used to collect data via structured and predefined response options that excluded free text entries in order to mitigate ambiguity. In addition to the close supervision of the interviewer for clarification of inconsistencies, the tool was programmed with range restrictions and required fields to minimize implausible responses. In case of language barrier, an agronomist and also member of the cocoa cooperative with extensive experience in agricultural projects able to speak both French and the local dialect helped translate the questions and answers. Prior to the interview,



**Fig. 2.** Cocoa-growing regions in seven West African countries, classified according to the relative extent of cocoa cultivation based on available cultivated area or production data.

crucial concepts such as waste management, biochar and sustainable agriculture were clearly elucidated to ensure a common understanding before answers are recorded. The survey aimed to determine the major challenges of cocoa farming, including waste management practices, and farmers' perception of the use of biochar for soil amendment. In total 10 cocoa farms were visited and 16 farmers (12 males and 4 females) participated in the survey and agreed to provide accurate responses based on their long-term observations.

In addition, secondary quantitative data on cocoa bean production from 2003 to 2022 were obtained from FAOSTAT (accessed 5–6 August 2024). According to (Bannor et al., 2024), based on previous work by (Campos-Vega et al., 2018), the average ratio of dry cocoa beans to fresh CPH is about 1:10, indicating that for 1 tonne of dry cocoa beans (with about 6–8% moisture), generally 10 tonnes of fresh CPH (post-harvest byproduct with high moisture content) are generated. Although it is commonly used as average ratio it can vary (around 1:9 to 1:7) depending on different conditions such as the variety of the fruit and its weigh. In this study, this average rate was applied as a conversion factor to estimate the total production of CPH in the seven countries.

#### Estimation of emissions from cocoa pod husk decomposition

CPH are generally unprocessed across the major cocoa producing countries in West Africa. While no specific study has quantified the exact proportion of valorized versus neglected CPH, numerous peer-reviewed publications consistently report that a large share of these residues is discarded in the field without further use (Campos-Vega et al., 2018; Antwi et al., 2019a; Ouattara et al., 2020). These pod husks are often piled up, with the upper layers decomposing under aerobic conditions and the lower layers undergoing anaerobic or semi-anaerobic degradation (Doungous et al., 2018; Lu et al., 2018; Ouattara et al., 2021a). Moreover, based on field observations in Côte d'Ivoire and Togo and farmer interviews (Table S1), this study assumes that approximately 20% of CPH are subject to valorization. This assumption is important to prevent any competitions or conflicts arising from the use of CPH. According to the methodology developed by Intergovernmental Panel on Climate Change (IPCC) for National GHG Inventories, the disposal of solid waste produces significant amounts of CH<sub>4</sub>, biogenic CO<sub>2</sub> and some non-methane volatile organic compounds (NMVOCs), small amounts of nitrogen oxides (NO<sub>x</sub>) and carbon monoxide (CO) (IPCC, 2006; Ortiz-Rodríguez et al., 2016). Thus, CPH's CH<sub>4</sub> emission is estimated and converted to CO<sub>2</sub> equivalent using Eq. (1).

#### Estimation of biochar potential and its impact

Based on the above assumption, the average potential of CPH-derived biochar from the seven countries in West Africa is estimated using Eq. (2). Maniscalco et al. (2021); Almeida et al. (2022) suggest the biochar fraction in the slow pyrolysis process to be ranging from 20 to 35%, however (Quansah, 2021) showed that the yield of biochar in the Kon-tiki kilns is typically around 25%. Given the local aspect in West African countries, external energy input to operate the system and associated cost is critical and could constitute a potential barrier. Therefore, Kon-tiki kilns are promoted because the operation of such systems is simple and does not require external energy (Vriesmann et al., 2011; Dzelagha et al., 2020).

The production of biochar through Kon-Tiki kilns, especially with the low cost and most suited flame curtain, which involves a combustion of the exhaust gas from the pyrolysis system, tends to reduce emissions compared to traditional practice. However, when not well managed, it can also generate GHG and air pollutants. Experimental studies on Kon-tiki processes done by (Cornelissen et al., 2024) demonstrated that the moisture content of the feedstock, its size and type and the operation of the system (the sequential addition of the feedstock and quenching at the end of the running) are the influencing factors for emissions. Although average emission factors are provided in the literature, there is

nevertheless a lack of explicit mathematical formulas linking these emissions to key influencing factors. Therefore, in this study the formula Eq. (3) is developed to estimate gas emissions as a function of these critical factors. Considering optimal conditions such as adopted biomass size, adjusted operation condition, other factors are neglected. Moisture, indicated as the most influencing factor is only considered. For instance, Cornelissen et al. (2024) showed that at moisture of 15%, emissions in gCO<sub>2</sub>-eq/kg of biochar were 202 and at 25% moisture content of the same feedstock, it increases to 777, indicating that emissions follow an exponential rather than a linear pattern. On the other hand, biochar on the soil could have a positive impact, hence its CO<sub>2</sub> sequestration capacity is carried out by Eq. (4), also employed by (Yang et al., 2021; Lontsi et al., 2024) in their studies. Furthermore, the GHG reduction potential (GHGRP) from the CPH valorization approach is given by Eq. (5). Avoided emissions (AE<sub>CPH</sub>) were quantified as equal to the emissions from CPH disposal in the status quo. This is mainly due to the fact that the valorization approach tends to fully replace the abandonment of CPH on farms. Thus, there is a direct correlation between CPH emissions and avoided emissions. It means that the valorization scenario prevents the occurrence of baseline emissions. The estimated emissions are limited to the system boundary (Fig. 3). Finally, to assess the influence of key assumptions on the GHGRP, a one-at-a-time (OAT) sensitivity analysis was performed (see Table 1).

$$E_{CPH} = m_{CPH} \times DOC \times F_{DOC} \times CF_{CH_4} \times F_{CH_4} \times 1.33 \times R_{CH_4/C} \times GWP_{CH_4} \quad (1)$$

$$m_{Biochar} = m_{CPH} \times \left(1 - \frac{M_X}{100}\right) \times F_{Biochar} \times 0.8 \quad (2)$$

$$EX_{CO_2-eq} = m_{Biochar} \times EF_{CO_2-eq,ref} \times e^{\beta(M_X - M_{ref})} \times 10^{-3} \quad (3)$$

$$m_{CO_2-eq,Seq} = m_{biochar} \times C_{biochar} \times C_{stable} \times R_{CO_2/C} \quad (4)$$

$$GHGRP = AE_{CPH} - (EX_{CO_2-eq} - m_{CO_2-eq,Seq}) \quad (5)$$

## Results and discussion

### Trends of cocoa pod husk generation

Cocoa in West Africa presents a huge opportunity and can be better managed to improve the incomes, livelihoods and well-being of stakeholders, especially local farmers (Ouattara et al., 2021a). Fig. 4 depicts the evolution of CPH generation by country in West Africa over the past 20 years. Despite some differences in waste production, all seven West African countries have substantial quantities of CPH.

The study revealed that over the last 2 decades, the seven countries have collectively produced 578 million tonnes of CPH. Côte d'Ivoire, the world's largest cocoa producer, has the highest potential, accounting for 57% (331 million tonnes) of the total CPH estimated. The country's CPH generation increased from 13 million tonnes in 2003 to 22 million tonnes in 2019 with an average generation of 17 million tonnes. This is relatively due to the growing global demand for cocoa beans and government support (Coulibaly and Erbao, 2019; Kouassi et al., 2023). Despite an increase in cocoa plantation, the CPH per hectare has decreased from 7 tonnes in 2003 to 5 tonnes in 2022, suggesting that high CPH potential do not always lead to high CPH per hectare. Most residues are concentrated in the southwestern, and southern, eastern, central and western part of the country (Abu et al., 2021). Ghana produced a cumulative 160 million tonnes (an average of 8 million tonnes per year), with waste concentrated in the Ashanti, Western and Brong-Ahafo regions. In contrast to Côte d'Ivoire, Ghana's national CPH generation growth is generally consistent with improvements in yields per hectare, likely related to targeted programs such as the Cocoa Disease and Pest Control Project, which improved fertilizer use and pest management (Ntiemoah and Afrane, 2008; Gockowski and Sonwa, 2011). In

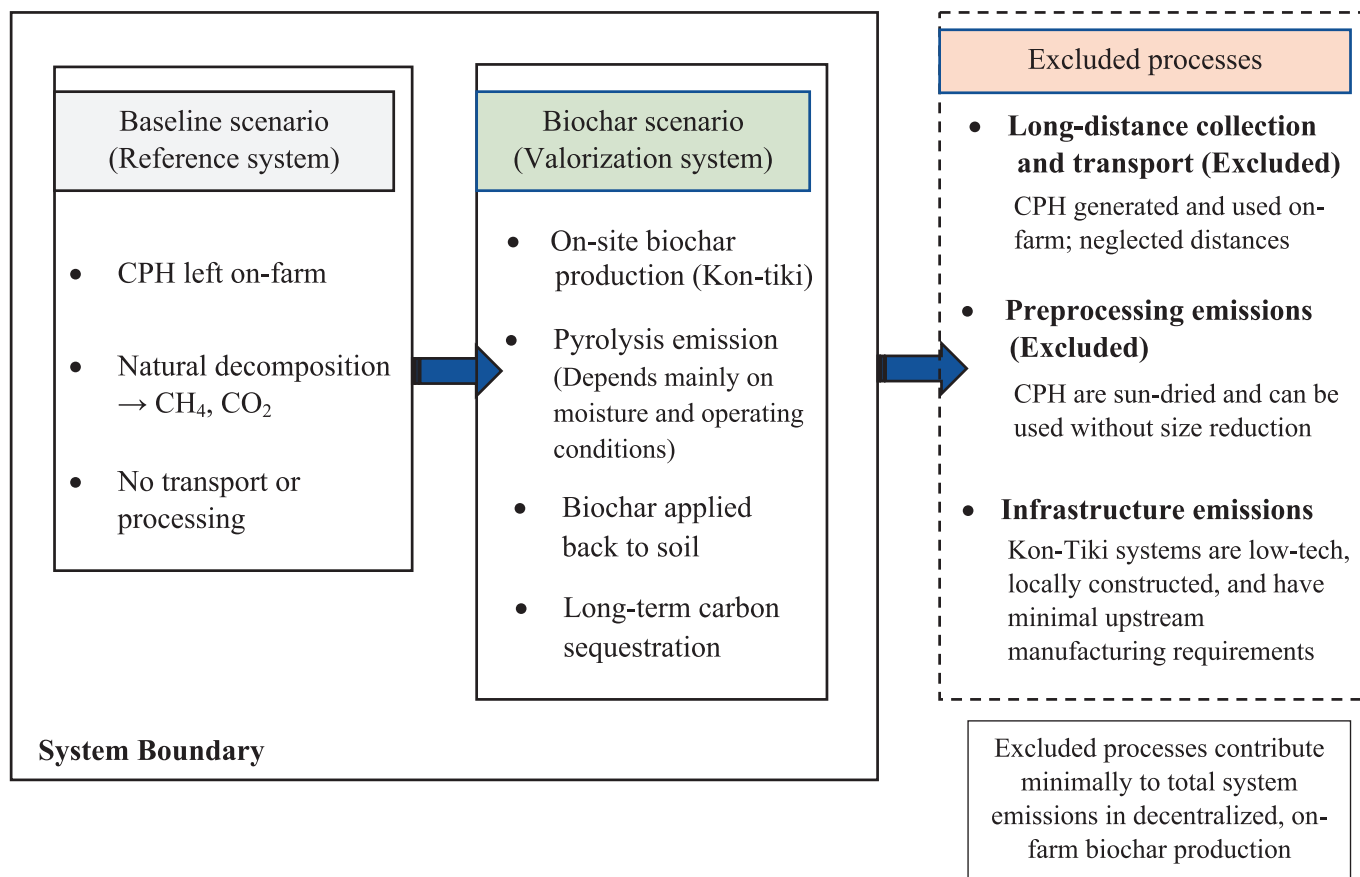


Fig. 3. System boundary diagram defining processes included and excluded in the calculation of emissions for the baseline and biochar scenarios.

Nigeria, CPH can be found in the south-western parts of the country (Ondo, Ogun, Ekiti and Oyo states). Due to soil degradation, old farms, climate change, and government reliance on crude oil, the country has experienced some fluctuations. Yet, it produced a substantial 70 million tonnes (Averaging 3 million tonnes) (Schroth et al., 2016; AFOLAYAN, 2020). Liberia, Guinea, and Sierra Leone exhibited lower CPH potential of 2 million tonnes, 3 million tonnes, 4 million tonnes respectively. Variation may be due to limited sector development, inconsistent agricultural practices or climate challenges (Moinina et al., 2023). Guinea shows modest improvement with stable per-hectare yields since 2014 but still limited in overall potential. On average these countries produced 101 thousand tonnes, 156 thousand tonnes, 200 thousand tonnes, respectively. Togo, on the other hand, produced 8 million tonnes with an average of 423 thousand tonnes. It has the highest CPH per hectare while CPH potential is decreasing due to reduced farming intensity (Céron-Siméon et al., 2022). Despite the enormous potential of CPH, the lack of waste recovery in all countries reveals a missed opportunity for resource optimization and circular economy, which ultimately translates into environmental degradation. The seven countries generated on average 4 million tonnes of CPH per year which is 47% greater than that of rice husk over the same period (FAO, 2025).

#### Cocoa pod husk management practices in West Africa

The survey data illustrate current CPH management patterns and associated influencing factors (Fig. 5). It revealed that field abandonment is the most common treatment method, representing 81% of cases. This has been highlighted by several authors such as (Patel and Panwar, 2023) who pointed out that there is still an issue regarding the management of crop residues. Lack of knowledge, labor and time constraints as well as limited access to training programs are considered the main

obstacles in rural areas. Nonetheless, only 13% of farmers produced potash and 6% used CPH for composting, demonstrating the lack of adoption of more sustainable residue management strategies. It further unveils those farmers with extensive experience (>10 years) are more inclined to adopt sustainable practices such as composting, although some still abandon residues on the field. On the other hand, farmers with less experience (<5 years) or moderate experience (5–10 years) predominantly leave CPH unmanaged. Education also has a significant influence on decisions related to residue management. Farmers with secondary or tertiary education are more likely to use sustainable practices, whereas those with no formal education or only primary-level education predominantly abandon CPH. Although this study was conducted in Togo and may not fully reflect the broader West Africa context, field observations of selected farms in Côte d'Ivoire, the world's largest cocoa producer, confirmed the amplitude of field abandonment practices. Such findings highlight an immediate need for targeted interventions such as capacity-building initiatives, awareness-raising campaigns to address the main barriers to the implementation of sustainable CPH management practices.

Despite these important findings, the survey is subject to certain limitations. Farmers may have misunderstood some questions, or their answers might have been shaped by what they thought was the right answer. Translation and interviewer guidance helped, but these issues cannot be ruled out. The small number of participants (16 in total) also means that each individual response represents approximately 6% of the dataset. This makes the findings sensitive to even a single unclear or inconsistent response, especially in yes or no questions. Recognizing these limits, the results were treated with caution, while still providing important insights into how farmers manage cocoa residues.

**Table 1**  
Nomenclature.

Symbols	Descriptions	Values	Uncertainty range	Units
$AE_{CPH}$	Avoided emission from abandoned cocoa pod husk	–	–	tCO <sub>2</sub> -eq
$C_{biochar}$	Carbon content in the biochar	62.33 <sup>a</sup>	40–67	%
$C_{stable}$	Stable carbon content of the biochar	80 <sup>b</sup>	70–85	%
$CF_{CH_4}$	Methane correction factor (for unmanaged shallow)	0.40 <sup>c</sup>	–	–
$DOC$	Degradable organic carbon (for garden or agricultural residues)	0.20 <sup>c</sup>	0.18–0.22	–
$E_{CPH}$	Emission from abandoned cocoa pod husk	–	–	tCO <sub>2</sub> -eq
$EF_{CO_2-eq,ref}$	Reference emission factor determined based on extrapolation from experimental studies	103 <sup>d</sup>	–	gCO <sub>2</sub> -eq/kg biochar
$EX_{CO_2-eq}$	Emission from biochar production through Kon Tiki kilns	–	–	t
$F_{Biochar}$	Fraction of biochar in the pyrolysis products	25 <sup>f</sup>	20–35	%
$F_{CH_4}$	Fraction of methane in anaerobic process	55 <sup>d</sup>	–	%
$F_{DOC}$	Fraction of degradable organic carbon	0.50 <sup>c</sup>	–	–
$GHGRP$	Greenhouse gas reduction potential	–	–	tCO <sub>2</sub> -eq
$GWP_{CH_4}$	Global warming potential factor for methane	25	–	–
$m_{Biochar}$	Mass of biochar	–	–	t
$m_{CO_2-eq,Seq}$	CO <sub>2</sub> sequestration capacity of biochar application to soil	–	–	t
$m_{CPH}$	Mass of cocoa pod husk	–	–	t
$M_{ref}$	Reference moisture content of dried Biomass	10	–	%
$M_X$	Feedstock moisture content	15	≤20	%
$R_{CH_4/C}$	Molecular weight ratio of methane and carbon	1.33	–	–
$R_{CO_2/C}$	Molecular weight ratio of carbon dioxide and carbon	3.67	–	–
$\beta$	Sensitivity factor of emissions to moisture calculated through experimental studies	0.13	–	–

<sup>a</sup> (Tsai et al., 2018).<sup>b</sup> (Lontsi et al., 2024).<sup>c</sup> (IPCC, 2006).<sup>d</sup> (Antwi et al., 2019a).<sup>e</sup> (Cornelissen et al., 2016).<sup>f</sup> (Quansah, 2021).

### Emissions from conventional treatment of cocoa pod husk in West Africa

The disposal of CPH over the past two decades has emitted potent CH<sub>4</sub>. Côte d'Ivoire showed on average the greatest CH<sub>4</sub> emissions (389 thousand tonnes) from 13 million tonnes of CPH. This is approximately 10 million tonnes of CO<sub>2</sub>-eq (Fig. 6a). From unprocessed 6 million tonnes of CPH in Ghana, 187 thousand tonnes of CH<sub>4</sub> comparable to 5 million tonnes CO<sub>2</sub>-eq was emitted. The agricultural sector in Ghana is a driving force for economic growth, including cocoa and other cash crops (Antwi et al., 2019b). However, the environmental impact is significant. Moreover, Nigeria has emitted significant quantities of CH<sub>4</sub>. From 3 million tonnes of CPH, an average 82 thousand tonnes of CH<sub>4</sub> corresponding to 2 million tonnes of CO<sub>2</sub>-eq was emitted. Thus, handling cocoa residue management in Nigeria in a more sustainable way is key to mitigating emissions from this sector. CH<sub>4</sub> emissions from unrecovered CPH potential are relatively lower in the remaining countries, Guinea,

Liberia, Sierra Leone, and Togo. For instance, Guinea with 125 thousand tonnes of CPH, emitted 4 thousand tonnes of CH<sub>4</sub>, resulting to 92 thousand tonnes of CO<sub>2</sub>-eq. Liberia has CH<sub>4</sub> emissions rate of 2 thousand tonnes (59.43 thousand tonnes of CO<sub>2</sub>-eq) from 81 thousand tonnes of CPH. Sierra Leone emitted 4.70 thousand tonnes of CH<sub>4</sub> (118 thousand tonnes of CO<sub>2</sub>-eq) from 160 thousand tonnes of CPH. Furthermore, Togo's CH<sub>4</sub> emissions from 338 thousand tonnes of CPH was 10 thousand tonnes (248 thousand tonnes of CO<sub>2</sub>-eq). The recovery and utilization of cocoa residues can lead to improvements in these countries, as cocoa farms expansion could further lead to rising emissions in the future (Ouattara et al., 2021b).

Cocoa farms in West Africa are primarily owned by smallholder farmers, with an average harvested area of 1 to 3 ha (Aneani et al., 2012; Sonwa et al., 2019; Mashamaite et al., 2024). Hence, it is also important to analyze CH<sub>4</sub> emissions from a hectare of farm (Fig. 6b). In Côte d'Ivoire for example, the average hectare of cocoa farm generates 4.44 tonnes of CPH, which emits up to 0.13 tonnes of CH<sub>4</sub> representing 3.26 tonnes of CO<sub>2</sub>-eq. On the other hand, Ghana's average CH<sub>4</sub> emissions rate is 0.11 tonnes per hectares, equal to 2.75 tonnes of CO<sub>2</sub>-eq from 3.75 tonnes of CPH. Guinea's CH<sub>4</sub> emissions are comparable to Côte d'Ivoire's, with an average of 0.12 tonnes per hectares, equivalent to 3.09 tonnes of CO<sub>2</sub>-eq, due to its production of 4.21 tonnes of CPH per hectare. In comparison, Liberia has the lowest emissions, with an average CH<sub>4</sub> emissions rate of 0.04 tonnes per hectares (0.96 tonnes of CO<sub>2</sub>-eq) from 1.31 tonnes of CPH. Furthermore, Nigerian cocoa farms produce 2.47 tonnes of CPH per hectare, with an average CH<sub>4</sub> emissions of 0.08 tonnes, resulting in 1.81 tonnes of CO<sub>2</sub>-eq. Besides, from 3.03 tonnes of CPH, Sierra Leone has an average CH<sub>4</sub> emissions of 0.09 tonnes per hectare, which converts to an average of 2.23 tonnes of CO<sub>2</sub>-eq. Out of all the countries, from 6.73 tonnes of CPH, Togo emits the highest levels of CH<sub>4</sub> emissions, averaging 0.20 tonnes per hectare (4.94 tonnes of CO<sub>2</sub>-eq). This demonstrates that the emissions from small farms cannot be neglected. CPH from a farm should also be reported given that its environmental impact contributes to the local GHG emissions profile. CH<sub>4</sub> emissions in these contexts need to be reduced to achieve regional climate goals (Critchley et al., 2023). Emission reduction approach that focuses on small-scale farmers could have a significant impact. Therefore, promoting the use of CPH-biochar for soil amendment and carbon sequestration could be more sustainable (Lal, 2015).

It is important to note that accounting for emissions from fertilizer use and fuel consumption, is crucial for a comprehensive assessment of the carbon footprint of cocoa farming. However, due to the lack of crop-specific data in the seven West African countries, this study is limited to emissions directly associated with CPH decomposition.

### Sustainable valorization strategy

#### Biochar potential

In West Africa, a circular economy approach in CPH management can reduce waste and help sustain agriculture. The implementation of CPH-biochar can have a positive environmental impact. Kon tiki kiln for instance, as stated above is a low-cost, portable, and self-energy supply technology, that can be exploited in the local context. As explained by Lehmann and Joseph (2024), the biochar production using this system can emit little amount of GHG. But in general, it is a biogenic carbon (carbon that was sequestered by plants through photosynthesis). When the system is designed in a controlled manner the emissions are minimized. Biochar as a soil amendment can enhance soil structure, water retention, nutrient retention, and reduce leaching (Kundu and Kumar, 2024), besides promoting the growth of other soil microbial organisms, thus creating a more productive and resilient agricultural system. The integration of biochar production from abandoned CPH illustrated in the bio-circular farming approach (Fig. 7a), creates local socio-economic and environmental benefits such as creating seasonal income opportunities, gender and community benefits. The survey data showed that more than 90% of farmers are willing to use biochar as a soil amendment

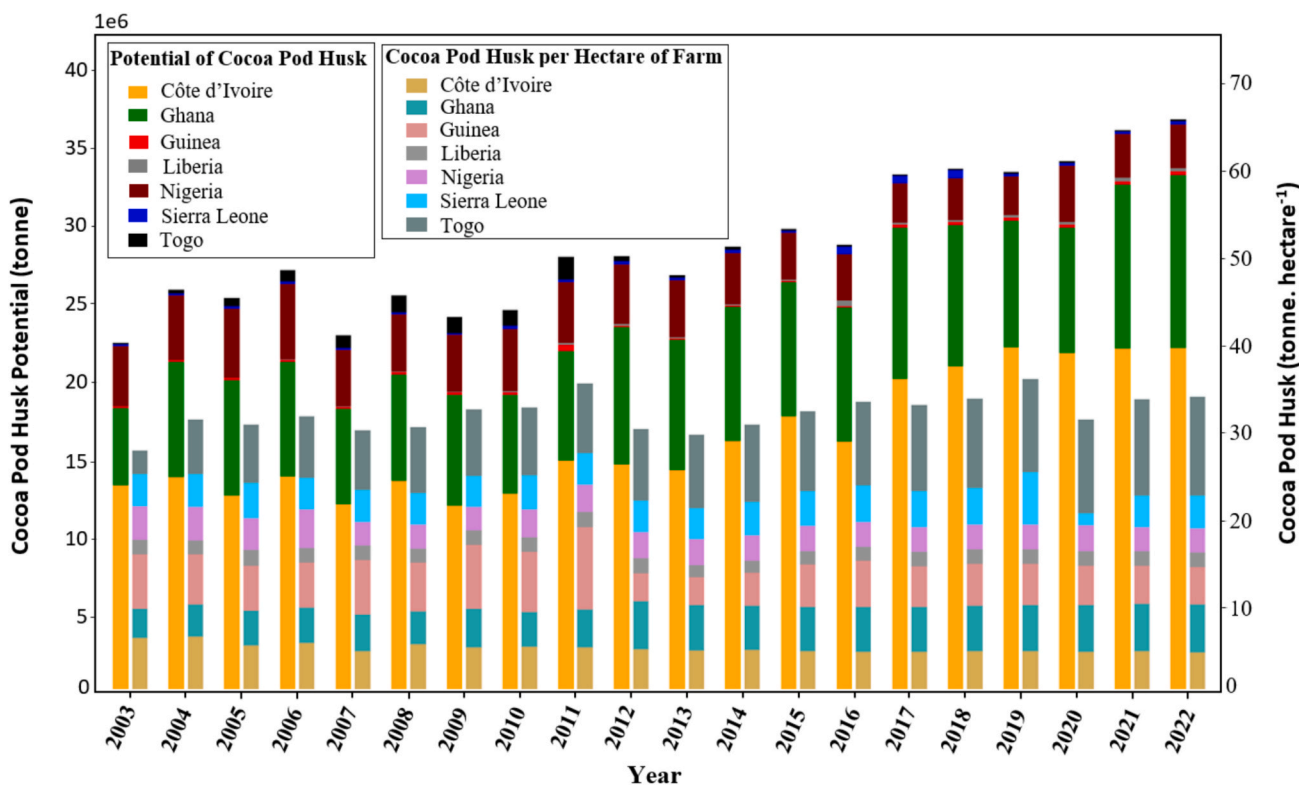


Fig. 4. Annual cocoa pod husk potential and yield per hectare of cocoa farms across West African countries (2003–2022).

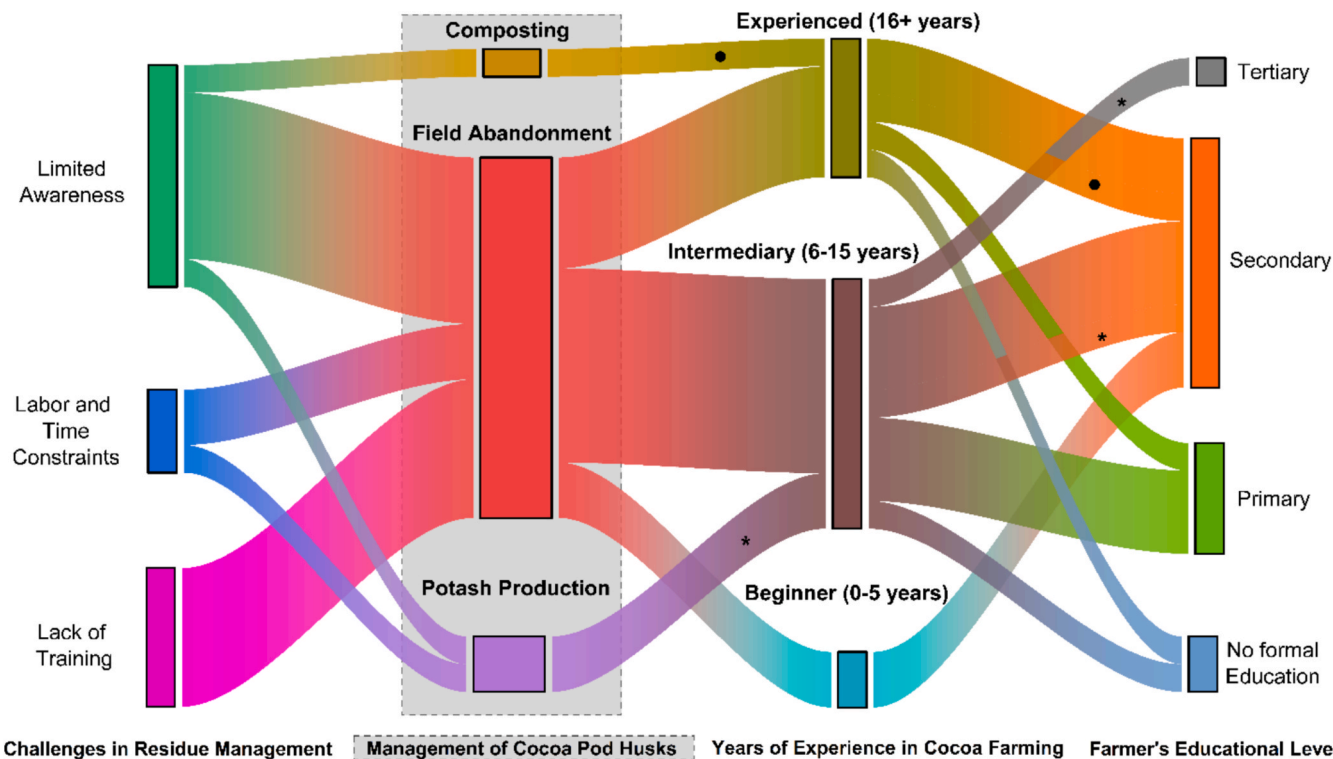


Fig. 5. Sankey diagram illustrating survey data on cocoa pod husk management practices and influencing factors (n = 16).

on their farms, underlining its ability to advance sustainable cocoa farming systems. However, biochar production may require additional labor and time to collect, dry, and pyrolyze pod husks, tasks that can compete with high-season cocoa harvests.

The estimated average biochar potential of the selected countries is shown in Fig. 7b. Côte d'Ivoire's CPH can potentially yield 497 thousand tonnes of biochar, with a potential rate per hectare of 0.17 tonnes. The potential for CPH-derived biochar in Ghana is about 240 thousand

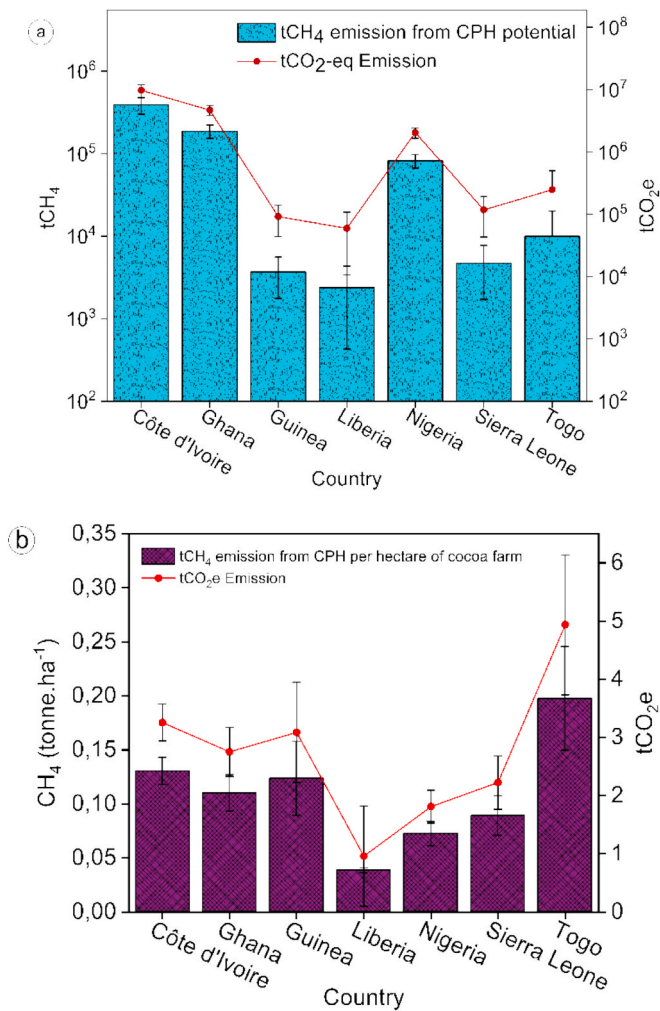


Fig. 6. a) average estimated emissions from unrecovered cocoa pod husk at country level in logarithmic scale; b) Average estimated emissions of cocoa pod husk per hectare of farm across seven West African countries (2003–2022).

tonnes and each hectare of cocoa plantation has a production capacity of approximately 0.14 tonnes. Biochar could be inoculated with organic fertilizers and applied to the soil, reducing reliance on expensive chemical fertilizers (Khan et al., 2024). Similarly, biochar could also be useful for the Nigerian cocoa industry where the average potential of biochar is estimated at 105 thousand tonnes, with a yield per hectare of 0.09 tonnes. Compared to these three countries above, Guinea, Liberia, Sierra Leone, and Togo have a lower potential for biochar. It is estimated at 5 thousand tonnes (0.16 tonnes per hectare), 3 thousand tonnes (0.05 tonnes per hectare), 6 thousand tonnes (0.11 tonnes per hectare), 13 thousand tonnes (0.25 tonnes per hectare), respectively. Encouraging local value addition and improving resource efficiency could be achieved by valuing cocoa residues, which could open up economic opportunities within the cocoa production chain. Kon Tiki kilns could be a cost-effective and adapted technology for biochar production in the local remote areas and can lead to emissions reduction (Pandit et al., 2017). Scaling CPH-biochar across the seven West African countries requires consideration of the socioeconomic and institutional realities that shape farmer decision-making. Although Kon-Tiki kilns are low-cost technologies, the initial construction cost may still represent a barrier for smallholders. At present, formal biochar markets are largely underdeveloped in West Africa, limiting the financial incentive for farmers.

According to van Long and van Dung (2023); Liu et al. (2025), biochar field application rates generally vary between 5 and 20 tonnes per hectare, depending on soil degradation levels. The estimated annual

biochar potential in the seven West African countries above can amend 43–174 million hectares of farm. Given that the combined cocoa-growing area of these countries is 7.22 million hectares (FAO, 2023), this potential could cover 0.60–2.4% of the land per year. Such coverage is meaningful when targeted to severely depleted soils and newly rehabilitated plantations.

#### Environmental impact assessment

The valorization of CPH for biochar production has a positive environmental impact compared to the abandonment of these residues on the field. The emissions that could be avoided in the seven countries examined are estimated at 17 million tonnes of CO<sub>2</sub>-eq. Even if only 50% of this potential were realized, it would represent a significant effect for the cocoa sector. For instance, the carbon sequestration far outweighs the emissions that could be generated by biochar production in Côte d'Ivoire (Fig. 8). Although the graph of the other six countries is not shown, the situation follows the same trends. Biochar is widely recognized for its long-term carbon stability due to its highly aromatic structure (Schmidt et al., 2022). Its permanence strongly depends on its composition. According to the meta-analyses of (Wang et al., 2016), it was revealed that mean residence time reached almost 1000 years, with an average of about 100 years. Hence, confirming the potential of biochar as a promising carbon storage solution (Woolf et al., 2010; Joseph et al., 2021; Schmidt et al., 2022). The estimated sequestration capacity of biochar application to soil ranges from 6 thousand tonnes of CO<sub>2</sub>-eq to 910 thousand tonnes of CO<sub>2</sub>-eq, with the highest amount in Côte d'Ivoire. Emissions associated with its production are relatively low and could reach 52 thousand tonnes of CO<sub>2</sub>-eq. This trend is consistent with the work of (Cornelissen et al., 2016), who point out that, under flame curtain kiln, emissions are relatively lower provided that feedstock moisture and process management are controlled. The annual GHGRP is estimated at 18.47 tonnes of CO<sub>2</sub>-eq and is particularly high in Côte d'Ivoire, Ghana and Nigeria, reaching 10.58 million tonnes of CO<sub>2</sub>-eq, 5.10 million tonnes of CO<sub>2</sub>-eq, 2.22 million tonnes of CO<sub>2</sub>-eq respectively. These results corroborate the projections of (Jeffery et al., 2011), who consider that the integration of biochar into agricultural systems can generate substantial climate benefits, particularly in contexts with high availability of biomass. The OAT sensitivity analysis shows that variation in DOC within the uncertainty range affects GHGRP by about ± 9% compared to the baseline estimate. The stable carbon fraction induces only smaller effect (±0.08), while moisture-related emissions from Kon-Tiki kilns have a negligible (±0.0025) influence on the GHGRP.

#### Study limitations

While this study offers a region-wide assessment, some limitations need to be considered. This includes the relatively small size of the survey sample, which limits multivariate analysis; the reliance on secondary data due to the lack of country-specific experimental data in the seven West African cocoa producing countries and lack of field CH<sub>4</sub> emissions measurements and validation of biochar application rates, carbon permanence and agronomic benefits. These limitations do not undermine the overall trends identified, but they highlight important areas for future research.

#### Recommendations

To facilitate a systemic transition from waste to value creation, the West African cocoa sector should adopt an integrated strategy combining policy, research, implementation and financing actions. Côte d'Ivoire's Café-Cacao Council and Ghana Cocoa Board (COCOBOD) and cocoa-growing countries should establish West African Biochar Standards (WABS) and incorporate CPH-biochar development into National Determined Contributions (NDCs). Additionally, a carbon credit mechanism should be created to monetize carbon sequestration benefits.

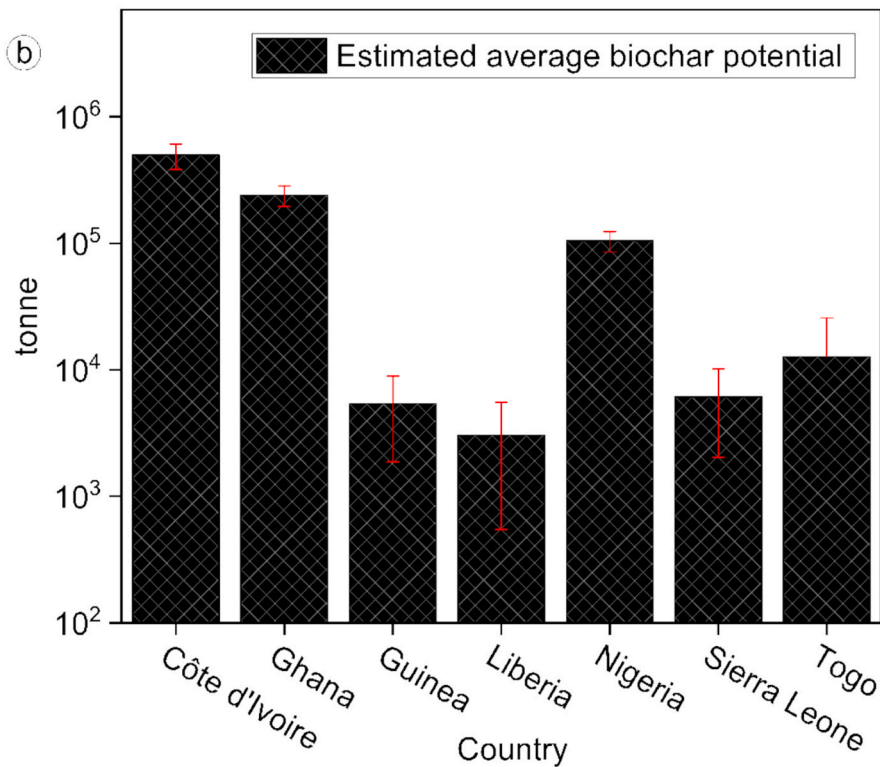
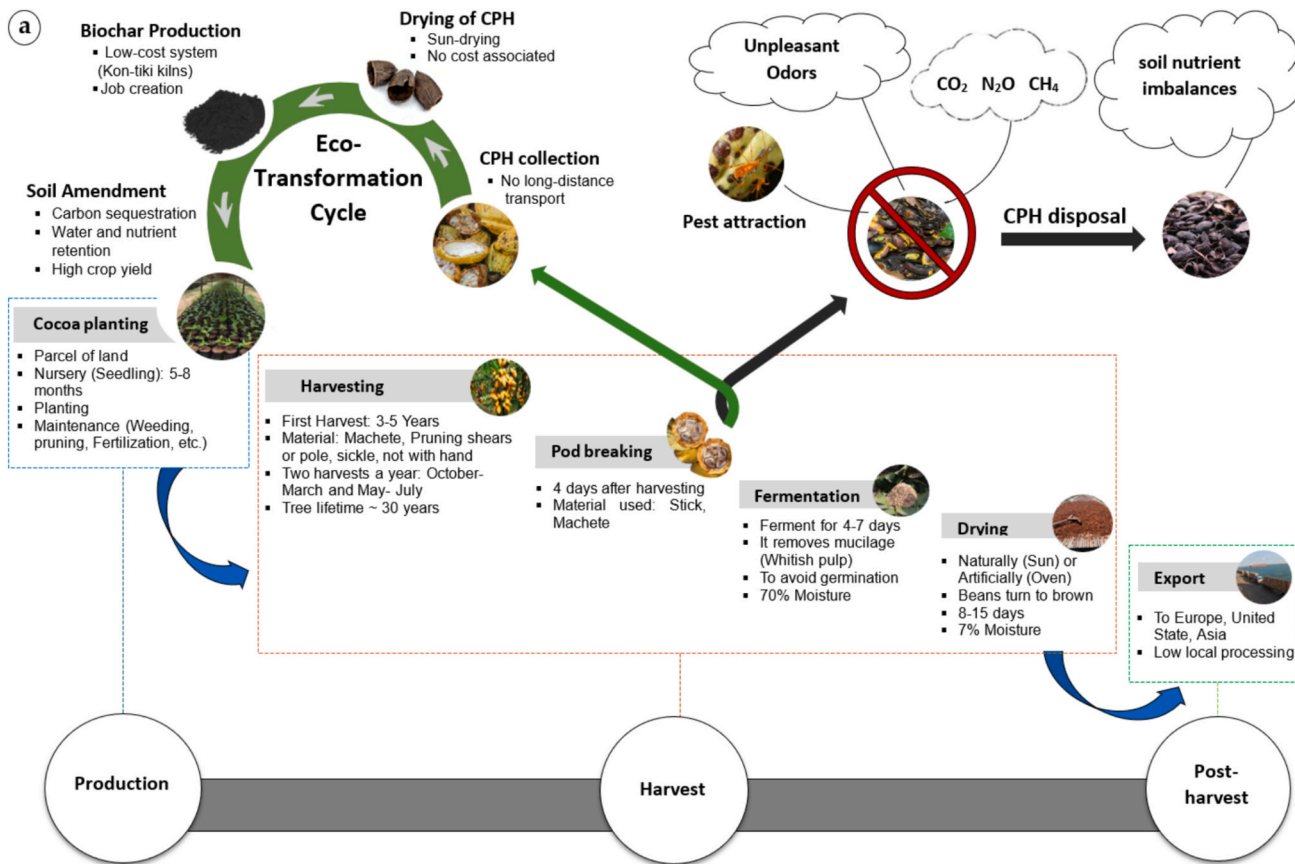
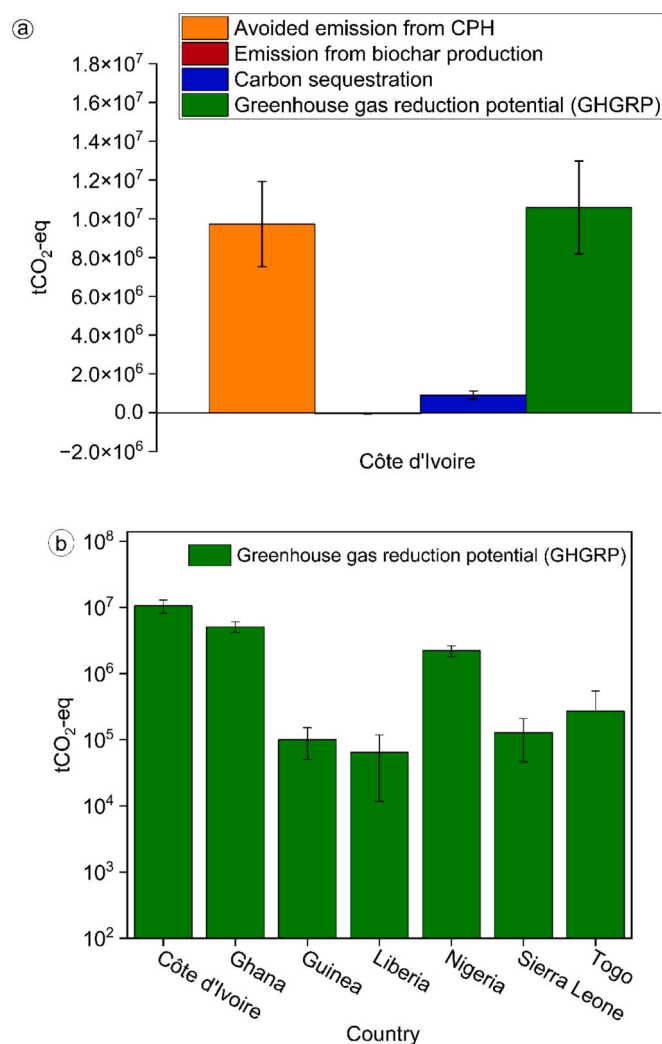


Fig. 7. a) Eco-friendly valorization of cocoa pod husk as an alternative to conventional disposal; b) Average biochar potential from cocoa pod husk in West Africa from 2003 to 2022 in a logarithmic scale.



**Fig. 8.** a) Estimated average emissions and greenhouse gas reduction potential in Côte d'Ivoire; b) Greenhouse gas reduction potential per country in logarithmic scale.

Targeted research is critical and should be prioritized by national research institutes such as the Cocoa Research Institute of Ghana (CRIG), the National Center for Agricultural Research (CNRA) in Côte d'Ivoire, the Cocoa Research Institute of Nigeria (CRIN), and the Sierra Leone Agricultural Research Institute (SLARI), etc. This research should include on-farm trials, techno-economic analyses focusing on labor and cost dynamics for smallholders, and comprehensive life cycle assessments (LCA) to develop region-specific emissions factors and validate climate benefits.

To secure funding, stakeholders should leverage eligibility for finance from the Green Climate Fund and explore biochar-backed loan with national banks. Pilot projects should be implemented in high cocoa-density regions of West Africa, particularly in the south-western part of Côte d'Ivoire (for example in Soubré) and in Ghana's Western and Ashanti regions, where cocoa production and the resulting pod husk residues are considerably concentrated and farmer cooperatives are well established. These initiatives can be developed in close partnership with agricultural cooperatives, NGOs, and private sector actors. While scaling up, region-specific challenges such as cultural resistance and knowledge gaps must be addressed through coordinated awareness campaigns and targeted training programs. These efforts will ensure widespread adoption and support systemic change across the cocoa sector.

## Conclusion

This study provided a comprehensive assessment of CPH generation across seven cocoa-producing countries in West Africa with an emphasis on the potential of its conversion into biochar as an alternative to the common on-farm abandonment practice. Over the past two decades, an estimated 578 million tonnes of CPH have been generated in these countries. Inadequate management of this residue results in annual GHG emissions of roughly 17 million tonnes of CO<sub>2</sub>-eq. The implementation of this approach on a large scale, could reduce up to 18.47 million tonnes of CO<sub>2</sub>-eq emissions each year.

## CRedit authorship contribution statement

**Kassé Jean Hugues Angbé:** Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Data curation, Conceptualization. **Dennis Krüger:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Funding acquisition. **Volker Lenz:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration. **Satyanarayana Narra:** Writing – review & editing, Writing – original draft, Supervision.

## Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: [Kasse Jean Hugues Angbe reports financial support was provided by German Biomass Research Center. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.]

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## Appendix A. Supplementary data

Table S1. Farmer-reported post-harvest management practices for cocoa pod husks (KoboTool survey). Supplementary data to this article can be found online at <https://doi.org/10.1016/j.wmb.2026.100282>.

## Data availability

Data will be made available on request.

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