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**Valorization of Okara (Soy pulp) and yam peels for bioenergy: effect  
of anaerobic co-digestion on biogas generation efficiency**

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## **Dedication**

I dedicate this thesis work to my parents Gabin Luc AVIANSOU and Geneviève TOUPE, my brothers and sisters for their support throughout my academic cursus. I also dedicate this thesis to Isso Solam Dieu Donné OUTCHI for his continual help and support no matter the time.

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## Abstract

In West Africa, reliance on firewood for cooking contributes to deforestation and household air pollution, while agro-industrial residues such as Okara and yam peels are often discarded, creating environmental challenges. Valorizing these wastes through anaerobic digestion (AD) offers a suitable alternative, though mono-digestion of Okara is often unstable and can lead to low biogas yield. Therefore, the objective of the present study is to evaluate the biogas potential of co-digesting Okara with local lignocellulosic wastes such as yam peels.

Batch experiments were conducted under mesophilic conditions with three mixing ratios (Okara:yam peels 1:3, 1:1, and 3:1) at substrate-to-inoculum (S/I) ratios of 0.5 and 0.6. The environmental implications of the best performing ratio were then compared to landfilling using the ReCiPe 2016 Midpoint (H) method in OpenLCA software, while biogas combustion impacts were contrasted with firewood use. Credits from firewood substitution and digestate fertilizer displacement were also considered in the net assessment.

Results confirmed the suitability of both substrates for AD due to their high volatile solids and organic matter content. Mono-digestion yielded 610.58 mL/g VS for Okara and 468.82 mL/g VS for yam peels. The co-digestion tests produced between 609.10 to 661.00 mL/g VS, with the highest yield performed at the 3:1 mix ratio. The findings highlight synergistic effects between nitrogen-rich Okara and carbon-rich yam peels. The environmental assessment revealed that landfilling 1 kg of Okara and yam peels generated high burdens, particularly climate change (0.55 kg/CO<sub>2</sub>-Eq) and terrestrial acidification, while AD significantly reduced impacts. Replacing firewood with biogas further reduced emissions harmful to human health and terrestrial ecosystems. Overall, AD reduces impacts and became impact-avoiding when accounting for avoided burdens. Economically, the system proved viable, with a benefit-cost ratio of 1.64 and a payback period of 3.20 years.

These findings support anaerobic co-digestion as a sustainable valorization route for local bio-wastes in West Africa, offering simultaneously energy recovery, environmental improvements, and economic benefits.

**Keywords:** Biogas; Co-digestion; Okara; Yam peels; Environmental Assessment.

## Résumé

En Afrique de l'Ouest, l'utilisation du bois de chauffage pour la cuisson contribue fortement à la déforestation et à la pollution de l'air domestique, tandis que des résidus agro-industriels tels que l'Okara et les épluchures d'igname sont souvent jetés, générant ainsi des problèmes environnementaux. La valorisation de ces déchets par digestion anaérobie (DA) constitue une alternative pertinente, même si la mono-digestion de l'Okara demeure instable et peut conduire à de faibles rendements en biogaz. La présente étude vise donc à évaluer le potentiel de production de biogaz par co-digestion de l'Okara avec des déchets lignocellulosiques locaux tels que les épluchures d'igname.

Des essais ont été réalisés en conditions mésophiles, avec trois proportions de mélange (Okara:épluchures d'igname 1:3, 1:1 et 3:1) et deux rapports substrat/inoculum (S/I) de 0,5 et 0,6. Les impacts environnementaux du mélange le plus performant ont ensuite été comparés à ceux de la mise en décharge, en utilisant la méthode ReCiPe 2016 Midpoint (H) dans le logiciel OpenLCA. Les impacts de la combustion du biogaz ont par ailleurs été comparés à ceux du bois de chauffage, et l'évaluation nette a intégré les crédits liés à la substitution du bois de chauffage et des engrais grâce au digestat.

Les résultats ont confirmé la pertinence des deux substrats pour la DA en raison de leur forte teneur en matières volatiles et en matières organiques. La mono-digestion a permis d'obtenir 610,58 mL/g VS pour l'Okara et 468,82 mL/g VS pour les épluchures d'igname, tandis que les tests de co-digestion ont donné des rendements compris entre 609,10 et 661,00 mL/g VS, le plus élevé étant atteint avec un mélange de 3:1. Ces performances mettent en évidence les effets synergiques de la combinaison d'un substrat riche en azote (Okara) avec un substrat riche en carbone (épluchures d'igname).

L'analyse environnementale a montré que la mise en décharge de 1 kg de résidus entraînait de fortes charges, notamment en matière de changement climatique (0,55 kg/CO<sub>2</sub>-Eq) et d'acidification des sols, tandis que la DA permettait de réduire significativement ces impacts. Le remplacement du bois de chauffage par le biogaz limitait en outre les émissions nocives pour la santé humaine et les écosystèmes terrestres. Globalement, la DA ne se contente pas de réduire les impacts. Elle permet d'éviter certains effets négatifs lorsqu'on prend en compte les charges évitées. Sur le plan économique, le système s'est avéré viable, avec un rapport bénéfice/coût de 1,64 et une période de retour sur investissement de 3,20 ans.

Ces résultats confirment que la co-digestion anaérobie constitue une voie de valorisation durable des déchets organiques locaux en Afrique de l'Ouest, en combinant production d'énergie, bénéfices environnementaux et retombées économiques.

**Mots-clés:** Biogaz; Co-digestion; Okara; Épluchures d'igname; Évaluation environnementale.

## Acronyms and abbreviations

<b>Abbreviation</b>	<b>Definition</b>
<b>AC</b>	Ash content
<b>ACoD</b>	Anaerobic co-digestion
<b>AD</b>	Anaerobic Digestion
<b>BCR</b>	Benefit Cost Ratio
<b>BMP</b>	Biomethane Potential
<b>CAPEX</b>	Capital Expenditure
<b>CC</b>	Climate Change
<b>CH<sub>4</sub></b>	Methane
<b>C/N</b>	Carbon-to-Nitrogen ratio
<b>CO<sub>2</sub></b>	Carbon dioxide
<b>CO</b>	Carbon monoxide
<b>DM</b>	Dry Matter
<b>FET</b>	Freshwater ecotoxicity
<b>HRT</b>	Hydraulic Retention Time
<b>H<sub>2</sub>S</b>	Hydrogen Sulfide
<b>HTC</b>	Carcinogenic Human toxicity
<b>HTnC</b>	Non-Carcinogenic Human Toxicity
<b>K</b>	Potassium
<b>LCOB</b>	Levelized Cost of Biogas
<b>MC</b>	Moisture content
<b>MET</b>	Marine Ecotoxicity
<b>N</b>	Nitrogen
<b>NH<sub>3</sub></b>	Ammonia

<b>NPV</b>	Net Present Value
<b>OLR</b>	Organic Loading Rate
<b>OPEX</b>	Operational Expenditure
<b>P</b>	Phosphorus
<b>pH</b>	potential of Hydrogen
<b>PM</b>	Particulate Matter formation
<b>POF HH</b>	Photochemical Oxidant Formation Human Health
<b>POF TE</b>	Photochemical Oxidant Formation Terrestrial Ecosystems
<b>PP</b>	Payback Period
<b>S/I</b>	Substrate-to-Inoculum ratio
<b>TA</b>	Terrestrial acidification
<b>TET</b>	Terrestrial Ecotoxicity
<b>TS</b>	Total Solids
<b>VFAs</b>	Volatile Fatty Acids
<b>VS</b>	Volatile Solids

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# Introduction

## 1. Background

In many developing countries, especially in West Africa, traditional cooking practices based on biomass fuels, such as firewood, charcoal, and agricultural residues, significantly contribute to greenhouse gas emissions, deforestation, and other environmental degradation. These practices not only expose users, particularly women, to hazardous smoke that can cause respiratory illnesses, but also worsen the ongoing climate change issue (World Health Organization, 2024). Cooking with biomass in rural areas often leads to the release of carbon dioxide and toxic pollutants into the air, further aggravating global warming. Additionally, the inefficient burning of wood and charcoal leads to incomplete combustion and the emission of particulate matter hazardous to human health (Idowu et al., 2023).

Addressing these challenges requires the adoption of sustainable and alternative energy solutions, particularly in rural areas reliant on traditional biomass fuels. Biogas emerges as a promising alternative, providing a renewable and clean energy source derived from organic waste through anaerobic digestion. Biogas production not only mitigates greenhouse gas emissions but also promotes sustainable methods of managing organic waste, lessening dependence on traditional fuels, and supplies clean energy for cooking (Neri et al., 2023). Anaerobic digestion also yields a nutrient-rich digestate, that can be used as an organic fertilizer, thereby supporting sustainable agriculture and improving soil quality. Biogas thus offers dual benefits by addressing both energy poverty and environmental degradation in rural communities.

Meanwhile, soybean farming is gaining importance in West Africa as an essential agricultural activity. With its high protein and oil content, this adaptable legume has become a significant global agricultural commodity, serving as a source of diverse products such as soy milk, soy oil, soy cheese, and soy flour. In countries like Benin and Togo, soybean is increasingly valued for its adaptability to local climates and its role in enhancing soil fertility through biological nitrogen fixation. Recently, these countries have emerged as leaders in soybean production in West Africa (Africa View Facts, 2024), acknowledging its potential as a key crop for food security, economic growth, and agro-industrial development.

Togo has witnessed a significant increase in soybean production, rising from 25,000 tons in 2015 to over 260,000 tons in 2023 (Togo First, 2024). The country is now the largest provider of organic soybeans to the European Union, a result of favorable agro-ecological conditions and targeted government initiatives, including export credit facilities and industrial partnerships. Notably, the launch of Togo Soja, the country's largest soybean processing facility located at the Adétikopé Industrial Platform, highlights the government's aspiration to transition

from raw exports to value-added processing for oil and soy-based derivatives (Milling MEA, 2023).

At the same time, Benin has strategically positioned soybean as a crop for local food systems and small-scale processing, with production rising from 349,000 tons in 2019 to more than 600,000 tons for the production season 2024/2025 (Foreign Agricultural Service, 2025). The government's policy shift, including a ban on raw soybean exports in 2024, aims to enhance domestic value chains, particularly for soy cheese, and animal feed (Feed Business MEA, 2024). Investments in infrastructure such as Benin Organics in the Glo-Djigbé Industrial Zone, along with government backing for cooperatives and women's groups, reflect a broader dedication to transforming soybean into a means for rural employment, food sovereignty, and industrial development. These differing yet complementary strategies underscore the growing importance of soybean in national agricultural plans and its potential for circular economy initiatives in the sub-region.

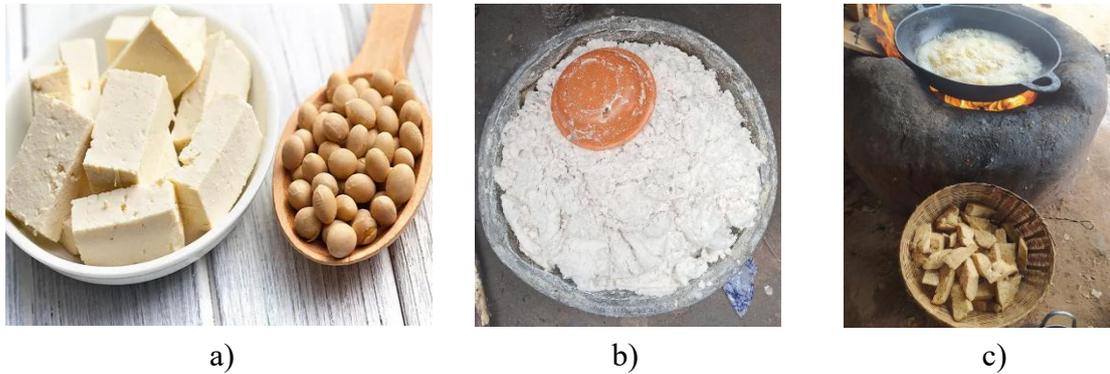
Soy cheese, also known as tofu, serves as a vital food source, offering a more affordable and healthier alternative to animal-based proteins. Its production involves basic steps: soaking dried soybeans, grinding them with water into a slurry, cooking the mixture, and then filtering it to separate the soy milk from the fibrous residue known as Okara. The soy milk is then coagulated using salts such as calcium sulfate or magnesium chloride, and the resulting curds are pressed into tofu blocks. These blocks are then fried or cooked based on preferences. In Benin and Togo, tofu production is primarily managed by rural women who use traditional cooking methods, exposing themselves to harmful smoke emissions (see Figure 1).

While tofu provides significant nutritional value, its production also generates considerable amounts of organic waste, particularly Okara and wastewater (Hartini et al., 2024). On average, processing 1 kg of soybeans results in approximately 1.1 to 1.2 kg of wet Okara, which is rich in protein and fiber but often discarded or underutilized. Additionally, 1.5 to 10 liters of wastewater per kilogram of soybeans are produced, influenced by the process's scale and efficiency (Colletti et al., 2020). This wastewater, rich in organic materials and nutrients, is habitually discharged untreated into the environment, threatening water quality. Consequently, the environmental impact of artisanal tofu production can be significant, notably in areas lacking effective waste treatment infrastructure.

Despite these obstacles, tofu by-products offer potential for waste-to-energy initiatives. Okara, abundant in organic content, can be utilized as feedstock in anaerobic digestion. Integrating this process into tofu production can mitigate waste-related pollution and generate biogas for clean cooking and digestate for sustainable agriculture, aligning with broader objectives of a circular economy and the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action).

## 2. Problem Statement

In both Benin and Togo, the production of soy cheese (tofu) generates substantial quantities of by-products, particularly Okara and wastewater, which are largely neglected and frequently discharged without appropriate treatment. This poor waste management contributes to local pollution, unpleasant odors, and methane emissions. Additionally, the ongoing use of firewood for cooking tofu accelerates deforestation and poses respiratory health risks for women.



**Figure 1:** a) Tofu produced from Soybeans (*Oriental Market, 2021*); b) Tofu solid residues/Okara; c) Frying of Tofu using firewood for selling (*Wikipédia, 2020*)

Although anaerobic digestion offers a promising method to transform these wastes into clean energy through biogas and useful digestate for farming, there is a gap in the assessment of Okara's potential in West Africa, specifically in Benin and Togo. Studies outside Africa show that mono-digestion of Okara on its own is often hindered by its low carbon-to-nitrogen ratio (C/N), quick acidification (low pH), and ammonia inhibition risks (Song et al., 2021). In that regard, anaerobic co-digestion of Okara and other local agricultural residues, such as yam peels, may help in improving methane yield and process stability.

Several studies have investigated the anaerobic digestion of Okara or yam peels as individual substrates for biogas production. For instance, Ali et al. (2024) evaluated biohythane production from tofu processing residues and Zhu et al. (2014) examined the co-digestion of soybean processing waste with lignocellulosic biomass to enhance methane yield. Additionally, Heiske et al. (2015) explored the biomethane potential of yam peels as a single substrate. However, the anaerobic co-digestion of Okara and yam peels specifically for enhanced methane production remains underexplored, particularly in the context of artisanal tofu production systems in West Africa. There is therefore a critical need to evaluate the biogas potential and sustainability outcomes of co-digesting Okara with yam peels with the aim of reducing dependence on firewood, and promoting clean energy access and economic empowerment for rural women.

## 3. Research Questions

This research is guided by the following questions:

- What are the physical and chemical characteristics of Okara and yam peels that impact anaerobic digestion?
- What is the potential for biogas production from the mono-digestion of Okara, and yam peels?
- How does co-digesting Okara with yam peels enhance methane production?
- What environmental and economic effects arise from biogas production through the co-digestion of Okara and yam peels?

#### **4. Research Hypothesis**

The hypotheses driving this research are as follows:

- Anaerobic co-digestion of Okara with yam peels improves methane yield compared to the mono-digestion of Okara, due to a better-balanced carbon-to-nitrogen (C/N) ratio and enhanced process stability.
- Co-digestion mitigates acidification and ammonia inhibition, which are common limitations in the digestion of Okara alone.
- Utilizing Okara and yam peels for co-digestion offers environmental benefits and is economically viable.

#### **5. Objectives of the Study**

To enhance the well-being of rural tofu producers by tackling larger environmental and health issues, this study aims to explore the potential of Okara as a feedstock for biogas production through its anaerobic co-digestion with yam peels. More specifically, it seeks to:

- Identify the physical and chemical properties of Okara and yam peels relevant to anaerobic digestion.
- Assess the biogas production potential of Okara and yam peels mono-digestions.
- Study the impact of co-digesting Okara with yam peels on methane output, using different mixing and substrate-to-Inoculum ratios (S/I).
- Conduct an environmental and economic evaluation of biogas production from the co-digestion of Okara and yam Peels.

#### **6. Structure of the thesis**

This thesis was divided into five main sections. The Introduction highlighted the environmental and energy issues linked to traditional cooking methods in West Africa, and introduced the potential of generating biogas from Okara as a sustainable alternative. The first chapter (State of Knowledge) talked about the basics of anaerobic digestion, the utilization of agricultural byproducts like Okara and yam peels, and the benefits of co-digestion for increasing methane

production and stabilizing the process. The second chapter (Materials and Methods) provided details about the study location, the collection and analysis of substrates, the BMP test procedures, and the criteria used for assessing environmental and economic viability. The third chapter (Results and Discussion) shared the experimental findings, compared the performance of single and combined digestion, and analyzed the environmental and economic consequences of the co-digestion for rural waste management and energy provision. Lastly, the final section (Conclusion, Summary and Recommendations) covered the main discoveries and offered guidance for future research and practical applications.

# Chapter 1: State of knowledge

This chapter provides a comprehensive review of the scientific and technical background underlying the present study.

## I.1 Anaerobic Digestion as a Renewable Energy Technology

### I.1.1 Principles of Anaerobic Digestion

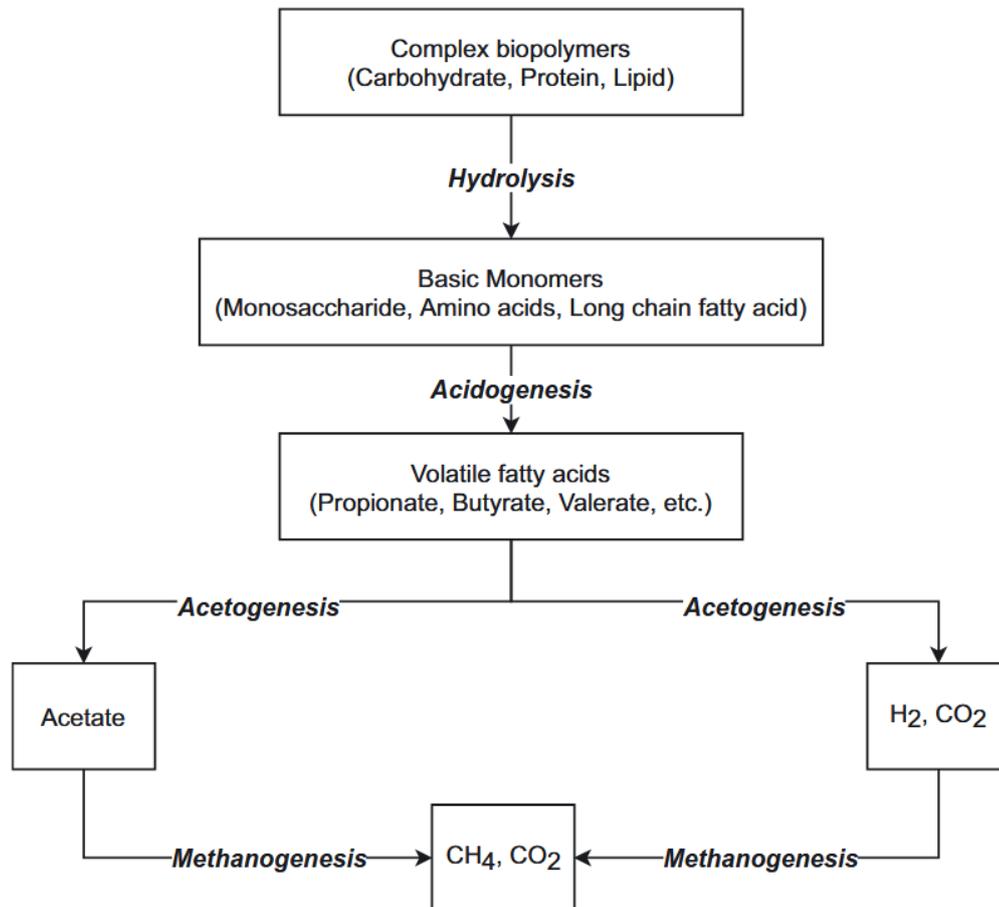
For many years now, the focus of governments and institutions is increasingly towards renewable and sustainable energy sources, as the world is affected by climate change with its consequences. Therefore, research and development (R&D) has helped to implement renewable energy technologies of which the biodigester for anaerobic digestion (AD) Even though the phenomena of gas production from organic matter have been observed since the 17<sup>th</sup> century, anaerobic digestion has evolved in recent decades from a simple waste treatment technology to a vital component of the circular economy, integrating energy production, waste recycling, and nutrient recovery.

Sustainable solution for organic waste management then, the anaerobic digestion is a biological process in which microorganisms break down organic matter in the absence of oxygen. The decomposition happens in a sealed environment called biodigester and leads to the production of a gas named biogas, as well as a nutrient-rich residue known as digestate (Sevillano et al., 2021). The biogas produced is a mixture of gas, mainly composed of carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>), with traces of other components like hydrogen sulfide (H<sub>2</sub>S), hydrogen (H<sub>2</sub>), water vapor (H<sub>2</sub>O), all this in variable proportion according to the nature of organic waste degraded.

Anaerobic digesters can be classified by their operation mode, solids content, and temperature regime. In terms of operation, batch digesters are loaded once and sealed for the entire digestion period, whereas continuous stirred-tank reactors (CSTRs) receive a steady feed of substrate and remove digestate continuously, allowing stable biogas production. Digesters may also be “wet” (total solids <15%) or “dry” (>15% solids), affecting mixing and feeding strategies (Uddin & Wright, 2023).

Reactor designs vary from small-scale household units to industrial installations. Common small-scale types include the fixed-dome and floating-drum digesters (simple, robust structures widely used in rural areas of Asia and Africa) and tubular digesters made of flexible plastic membranes (Tolessa, 2024). At larger scales, technologies such as up-flow anaerobic sludge blanket (UASB) reactors, anaerobic filters, and anaerobic lagoons are employed for high-strength industrial and municipal wastes (Banerjee et al., 2022).

Talking about the process itself, anaerobic digestion is divided into four complex biochemical successive stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, as shown in Figure 2.



**Figure 2:** Anaerobic digestion stages (Uddin & Wright, 2023)

❖ Hydrolysis

As biogasifier's feedstocks, organic wastes contain complex molecules which are difficult to be used by microorganisms present in the reactor. Therefore, wastes are sometimes pretreated before loading into the biogasifier where they are broken down to simple molecules in the first stage (Meegoda et al., 2018).

In fact, hydrolytic/acidogenic bacteria can produce extracellular enzymes such as cellobiase, proteases, and lipase responsible of the conversion of carbohydrates, lipids, and proteins respectively into sugars, long chain fatty acids (LCFAs), and amino acids. Even if the rate of decomposition depends significantly on the type of feedstock, hydrolysis stage has, on its own, an optimum temperature between 30 to 50°C with an optimum pH of 6 to 8 (Van et al., 2019).

### ❖ Acidogenesis

Here, the simpler soluble monomers previously obtained are absorbed by acidogenic microorganisms to produce acetic acid, CO<sub>2</sub>, H<sub>2</sub>O, H<sub>2</sub>, as well as volatile fatty acids (VFAs) and alcohol (Emebu et al., 2022). Acidogenesis is carried out by two types of bacteria: facultative anaerobic acidogens that can survive with or without oxygen, and obligate anaerobic acidogens that thrive only in oxygen-free environments (Laiq Ur Rehman et al., 2019).

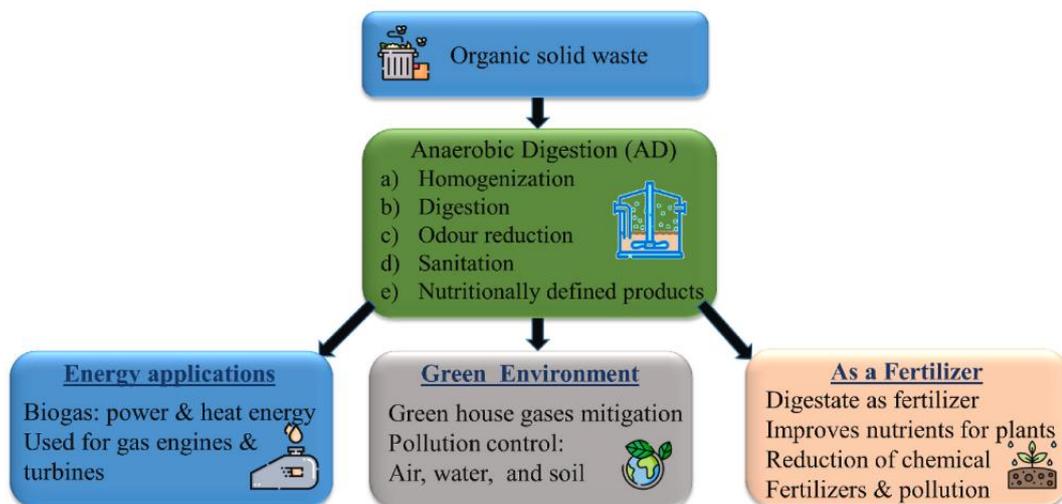
### ❖ Acetogenesis

Acetogenesis is a closely linked subprocess that occurs alongside acidogenesis. It consists of the anaerobic oxidation of VFAs and other intermediates into methanogenic substrates like acetate, hydrogen and carbon dioxide (Van et al., 2019). Acetate production is driven by two groups of acetogenic bacteria: one that converts carbohydrates into acetate, and another that oxidizes organic acids and alcohols into acetate, hydrogen, and CO<sub>2</sub> (Laiq Ur Rehman et al., 2019). The efficiency of biogas production largely depends on this stage.

### ❖ Methanogenesis

This final stage is where methanogenic bacteria under strict anaerobic conditions use H<sub>2</sub>, CO<sub>2</sub> and acetate along with intermediate products to produce methane and other gases. Here is how it happens: a first group of methanogenic bacteria splits acetate into methane and carbon dioxide and a second group uses hydrogen as electron donor and carbon dioxide as acceptor to produce methane (Uddin & Wright, 2023). This stage ends when biogas production stops.

About the applications of products obtained from AD, biogas can be used for cooking, electricity generation, and heating, thereby providing an alternative to traditional biomass fuels such as firewood and charcoal. Furthermore, the digestate can be utilized as a biofertilizer, enhancing soil fertility and supporting sustainable agricultural practices. Environmental benefits are also recorded in Figure 3.



**Figure 3:** Applications of anaerobic digestion products (Prasanna Kumar et al., 2024)

### **I.1.2 Factors Affecting Anaerobic Digestion Efficiency**

The performance of AD is highly sensitive to several operational and environmental factors that directly impact microbial activity and process stability. Among the most critical parameters are pH, temperature, carbon-to-nitrogen (C/N) ratio, volatile fatty acids (VFAs), and organic loading rate (OLR). Here is an overview of their individual effects and the importance of maintaining optimal conditions throughout the digestion process.

#### **❖ pH**

Hydrogen-ion (pH) concentration significantly influences the survival and growth of anaerobic digestion bacteria. Of course, each group of micro-organisms has a different optimum pH range but a neutral pH is the most favorable for the AD process. However, the process can tolerate a range of 6.5 up to 8.0 (Tolessa, 2024). The process is severely inhibited with microorganisms' washout or death if the pH is outside this boundary.

#### **❖ Temperature**

Three different temperature ranges exist for AD processes: psychrophilic AD (10–20°C), mesophilic AD (30–40°C), and thermophilic AD (50–60°C). Depending on the choice of temperature made, it is important to keep a constant temperature during the process, as a slight fluctuation can change the rate of biological activities/decomposition and negatively affect the rate of biogas production (Banerjee et al., 2021).

#### **❖ Carbon-to-Nitrogen ratio**

A great parameter which affects the AD process is the feedstock composition in carbon and nitrogen. It should be noted that carbon serves as a source of energy for the bacteria, while nitrogen promotes their growth and development. Thus, an optimum carbon-to-nitrogen (C/N) ratio is required to assure the stability of the process: between 20:1 and 30:1 (Laiq Ur Rehman et al., 2019; Tolessa, 2024; Banerjee et al., 2021). It can be interpreted like microorganisms utilize carbon 30 times faster than nitrogen.

What happens when the C/N ratio is high is that nitrogen is quickly utilized by the microorganisms, stopping the remaining carbon from reacting and then causing a low biogas yield. On the other hand, a low ratio results in nitrogen surplus which is synthesized into ammonia, increasing the pH over 8.5 as it is a strong base. This causes bacteria inhibition and eventually lower gas generation rates.

#### **❖ Volatile Fatty Acids**

Volatile Fatty Acids (VFAs) play a central role in the anaerobic digestion process as key intermediates between the acidogenic and methanogenic phases. However, when VFAs accumulate beyond the metabolic capacity of methanogens (often due to process imbalances), they can cause acidification of the reactor environment. This leads to a decline in pH, which severely inhibits methanogenic activity and can result in process failure if not corrected.

Maintaining a stable concentration of VFAs is thus critical to ensure efficient methane production and overall reactor stability (Prasanna Kumar et al., 2024).

#### ❖ Organic loading rate

The Organic Loading Rate (OLR) refers to the quantity of organic matter (or volatile solids VS) fed to a digester per day per unit volume in continuous digesters. It is also a key operational parameter that directly affects microbial activity and biogas yield. An optimal OLR allows for a balanced degradation process, where acidogens, acetogens, and methanogens operate in harmony (Meegoda et al., 2018).

However, a sudden increase or consistently high OLR can overwhelm the microbial community, leading to excessive VFAs accumulation, a drop in pH, and potential system failure. Conversely, a low OLR may lead to inefficient use of the digester volume and reduced gas production. Prasanna Kumar et al. (2024) in their work presented a range of organic loading rates (OLRs) applied in the recent AD process.

After examining the core principles of AD process and the key parameters influencing its efficiency, it becomes essential to consider the types of feedstocks that can be sustainably utilized within this process. Agro-industrial residues, generated in large volumes from agricultural and food processing activities, offer an abundant and low-cost resource for biogas production. The following section explores the relevance of these organic wastes in the context of renewable energy generation through anaerobic digestion, with a focus on their characteristics and the challenges involved in their use.

## **I.2 Biogas Production from Agro-Industrial Waste**

### **I.2.1 Agricultural Residues as Feedstock for Biogas Production**

A wide range of biomass exists for the production of biogas from the AD process. Part of these possible biomass are agricultural wastes, a type of organic residues generated from farming activities which can be broadly divided into animal waste and lignocellulosic biomass (Nwokolo et al., 2020). These two categories differ significantly in their composition, biodegradability, potential for methane production through AD and varies across different regions and locations.

On one hand, animal waste, such as manure from cattle, pigs, poultry, or goats, varies in composition depending on the animal species, diet, housing system, and age. Rich in nitrogen, phosphorus, and organic matter, animal manure serves as a nutrient-dense substrate with good buffering capacity in AD systems. Goat and pig manure, in particular, have been reported to yield high methane outputs, making them attractive for small- and large-scale biogas applications. Additionally, the digestate from manure digestion is commonly used as a biofertilizer, closing the nutrient loop and supporting sustainable agriculture.

On the other hand, lignocellulosic biomass which includes crop residues and forest residues can be separated into primary and secondary residues: primary residues for biomass produced in the field during harvesting like soybean straw, maize stalks, and secondary residues for biomass co-produced during processing as coconut shell, cassava and yam peels (Rowan et al., 2022). These abundant and renewable lignocellulosic materials are composed mainly of cellulose, hemicellulose, and lignin, three key structural polymers in plant cell walls.

While the disposal of agricultural waste on farmlands serves the purpose of supplying nutrients to the farmland, when deposited in large quantities, they result in environmental degradation, emission of greenhouse gases and other toxic gases. So, anaerobic digestion holds promise for broad applications in both urban and rural settings, by providing not only a sustainable energy source but also mitigating environmental issues associated with the conventional disposal methods of such residues (Alengebawy et al., 2024).

### **I.2.2 Challenges of Using Agro-Industrial Waste in Anaerobic Digestion**

Despite their benefits, the use of agricultural wastes in AD faces several operational and logistical challenges. For farm manures, they contain concentrations of ammonia which are greater than that necessary for microbial growth and may be inhibitory to anaerobic digestion if not managed through dilution or co-substrates (Sevillano et al., 2021). The variability in their composition may also impact the stability and predictability of the digestion process.

Similarly, lignocellulosic biomass can be subject to collection logistics requirement, and seasonal availability leading to inconsistent biogas production rates. The efficiency of biogas production from this residue is influenced by several factors including the chemical composition of the feedstock and the physical characteristics such as particle size, but another significant issue is the high lignin content in many lignocellulosic substances, making the substrate difficult to be decomposed and utilized by microorganisms (Pan et al., 2021). To overcome these limitations, pre-treatment techniques are often applied to break down the lignin structure and increase substrate accessibility. Methods such as chemical treatment, mechanical grinding, or thermal and biological processes have shown to improve methane yields from lignocellulosic materials (Poddar et al., 2022).

Overall, agricultural and agro-industrial wastes represent a valuable resource for biogas production. When their composition is well understood and their limitations addressed through strategic process design, they offer a sustainable pathway to decentralized renewable energy and nutrient recycling.

## **I.3 Okara (Tofu Solid Residue) as a Feedstock for Anaerobic Digestion**

### **I.3.1 Origin and Characteristics of Okara**

Okara is the solid by-product from tofu and soy beverage production. The Okara name comes from Japan, but there are several other names for this by-product such as biji (Korean), douzha

(Chinese), soybean curd residue (SCR), soy pulp or bean curd dreg. In its raw nature, Okara is white, similar to wet sawdust. Its composition can differ depending on the origin of the soybeans, the method of soymilk or Tofu processing, and the amount of water extracted from the ground soybeans.

On dry basis, Okara contains mainly carbohydrates (50–60%), proteins (20–30%), and lipids (10–20%) (Karim et al., 2025). In term of fiber content (still on dry matter), Okara is rich in dietary fiber with insoluble fibers such as cellulose, hemicellulose, lignin and pectin largely dominant in 40–60%, while soluble fibers are limited to 4–5%. Okara is also composed of a variety of minerals, with a reasonable amount of potassium, calcium and iron. Its Carbon to Nitrogen (C/N) ratio ranges between 11 and 20.62 (Choe et al., 2021; Song et al., 2021).

However, Okara is highly susceptible to rapid degradation when exposed to natural environmental conditions, primarily due to its physical and biochemical characteristics. With a moisture content of approximately 75–80%, Okara provides an ideal medium for microbial growth, especially for spoilage organisms such as bacteria, molds, and yeasts (Karim et al., 2025). Its rich content in proteins, carbohydrates, and lipids further accelerates microbial activity and organic breakdown. Additionally, its pulp-like texture enhances oxygen penetration and moisture retention, which promotes both aerobic and anaerobic microbial metabolism. These factors combined lead to rapid fermentation, foul odor development often within 24–48 hours, causing this by-product difficult to handle and use. Natural drying is not even a suitable approach as Okara begins to rot before the drying is complete. Therefore, appropriate conservation methods of Okara can be storage at low temperatures, drying in oven drying or vacuum freeze-drying (Colletti et al., 2020) or transformation into energy or feed products.

### **1.3.2 Biodegradability and Methane Potential of Okara**

Okara is considered as a promising feedstock for anaerobic digestion (AD). Its substantial organic content could contribute to its biodegradability and potential for biogas production (Zhang et al., 2019). Zhou et al. (2011) registered high methane yields of 478-495 ml CH<sub>4</sub>/g VS at S/I ratio ranging from 0.6-0.9 for Okara batch anaerobic digestion in mesophilic conditions (36°C) with a Total Solid (TS) loading of 10%. Song et al. (2021) who also conducted mono-digestion of Tofu Residues at S/I ratio equal to 2:1, 1:2 and 1:2 found the highest methane yield of 360.77 mL/g VS at S/I=1:2. Zhang et al. (2019) observed that thermophilic anaerobic digestion (55°C) yielded higher methane production (about 20% more) than mesophilic conditions (35°C). The highest organic loading rate (OLR) applied was 4.96 g VS/L, which was optimal up to a maximum of 3.3 g VS/L for both systems before performance declined.

Okara fiber content can nevertheless be difficult to degrade by the anaerobic microorganism (Choe et al., 2021). Then pre-treatment can be helpful in increasing fiber solubility and improving methane yield. It can be by physical method (thermal or mechanical), chemical

method (alkali or acid), biological method (enzymatic hydrolysis), or the combination of these methods. Another concern is the low carbon-to-nitrogen (C/N) ratio of Okara which is not suitable for AD, contributing to ammonia accumulation through protein deamination. Additionally, the amino acid breakdown in protein-rich substrates like Okara generates volatile fatty acids (VFAs) and ammonia, further acidifying the system if not properly managed. For example, ammonia nitrogen concentrations remained within non-inhibitory levels during Zhou et al. (2011) and Song et al. (2021) studies, but when the S/I ratio was 2:1, acidification inhibition caused low gas production throughout the experimental periods. Despite all this, Okara remains a valuable substrate when properly conditioned or co-digested with carbon-rich materials.

## **I.4 Yam Peels as a Feedstock for Anaerobic Digestion**

### **I.4.1 Origin and Characteristics of Yam Peels**

Yams belong to the botanical genus, *Dioscorea* and family, *Dioscoreaceae*. Native to tropical regions, yam is a tuber crop mostly grown in Africa, Asia, South and Central America. There are more than 600 species of yams out of which six are socially and economically important in terms of food, cash and medicine (Obioma et al., 2023). In West Africa, the zone of yam production is called the “yam belt” and the most important species found are white yam (*Dioscorea rotundata*) and Guinea yam (*Dioscorea cayenensis*) (Neina, 2021).

Yams are consumed differently in forms of boiled yam, pounded yam, fried yam, roasted yam, etc., and yam peels are the wastes generated when yam is peeled whether for domestic food preparation or industrial transformation into products such as yam flour or chips. The peels constitute about 10% of the yam and are either used to feed livestock on family-run farms or discarded as waste (Obioma et al., 2023).

According to (Ologunde & Oladipo, 2022), the proximate composition of yam peels includes approximately 5.98% crude protein, 14.36% crude fiber, 39.06% carbohydrates, 1.14% lipids, 28.71% moisture, and 4.37% ash. Mineral analysis reveals substantial levels of essential elements such as potassium (137.0 mg/100g), sodium (99.5 mg/100g), iron (68.5 mg/100g), and calcium (45.5 mg/100g) (Lawal et al., 2014). About the C/N ratio, Makinde & Odokuma (2015) got a value of 45:1, whereas Heiske et al. (2015) had a higher value of 55.

### **I.4.2 Biodegradability and Methane Potential of Yam Peels**

Studies suggest that agricultural wastes like yam peels can be effectively converted into biogas, contributing to renewable energy initiatives and waste management solutions. As illustration, Ologunde & Oladipo (2022) successfully produced biogas from yam peels and observed the degradation process initiated within the first 1–15 days of setup. Furthermore, the authors found that the levels of CO and Smoke in the biogas from yam peels were significantly lower than

those from poultry waste and plantain peels. This outcome underlined a relatively cleaner combustion profile for yam peel-derived biogas.

Makinde & Odokuma (2015) indicates that yam peels have a high potential for biogas production due to their high content of highly hydrolyzed polysaccharides, including starch and biodegradable organic matter. This high biodegradable organic content contributes to the higher biogas yield observed from yam peels compared to other substrates like plantain peels. Additionally, the physicochemical analysis shows that yam peels have a higher volatile matter content, which further enhances their biodegradability for biogas production. The presence of these easily digestible organic compounds facilitates microbial activity and, consequently, higher biogas yields during anaerobic digestion.

About the biochemical methane potential (BMP) of yam peels, Heiske et al. (2015) registered  $271 \pm 17$  mL CH<sub>4</sub>/g VS and Kan et al. (2023) who evaluated the mono and co-digestion of yam peels with cattle dung, found that yam peel alone yielded 373 mL/g VS of biogas, while co-digestion with cattle dung significantly improved the yield to 556 mL/g VS. The same study further highlighted that yam peels exhibit high organic content (TS = 25.66%, VS = 94.57%) and a C/N ratio of 24.54, all favorable parameters for biogas production. However, an acidic pH (~5.78) is mentioned for yam peels, which can lead the mono-digestion process to volatile fatty acid (VFA) accumulation and pH instability, potentially inhibiting methanogenesis.

## **I.5 Co-Digestion as a Strategy to Enhance Biogas Yield**

### **I.5.1 Principles and Advantages of Co-Digestion**

Anaerobic co-digestion (AcoD) process is the simultaneous digestion of a mixture of two or more substrates for biogas production. Apart from that, the process is still the same as for the anaerobic mono-digestion where only one type of feedstock is fed into the biodigester. The purpose of AcoD is usually to optimize the C/N ratio, balance nutrients (macro and micronutrients) and dilute inhibitors/toxic compounds, thus enhancing methane production and system resilience. Moreover, co-digestion can reduce the risk of acidification by distributing the organic load more evenly and facilitating buffer capacity in the digester. It is clearly advantageous compared to digestion of a single substrate, with ecological, technological, and economic benefits.

Ecologically, AcoD contributes to improved waste management and reduced greenhouse gas emissions by allowing the simultaneous treatment of various organic waste streams. Technologically, co-digestion enhances process stability and methane yield through nutrient balancing and microbial synergy. Kan et al. (2023) demonstrated that co-digesting yam peels with cattle dung improved biogas production by nearly 49%, due to better pH control and volatile fatty acid (VFA) management. Shahbaz et al. (2018) also found higher daily biogas

production from mixtures of Municipal Solid Wastes (MSW) and food waste (FW), compared to control mono-substrate MSW throughout the digestion time.

Economically, AcoD improves the energy output per unit of digester volume, making systems more profitable. Safe and superior quality co-digestate is also produced for agricultural use. But for optimal results, some rules should be followed like ensuring complementary parameters of the co-substrates (not same type of feedstock) to degrade, ensuring proper mixing ratio of the co-substrates (Ferdeş et al., 2023).

### **1.5.2 Synergistic Effects of Co-Digesting Protein-Rich and Fiber-Rich Substrates**

Anaerobic co-digestion (AcoD) is a well-established strategy to address the limitations of mono-digesting substrates with imbalanced nutritional profiles. The core principle of AcoD lies in leveraging the complementary characteristics of different feedstocks to create a more favorable environment for microbial consortia. This synergy enhances both process stability and methane yield. A classic example is the co-digestion of protein-rich substrates such as Okara with fiber-rich lignocellulosic materials like yam peels, where each feedstock compensates for the weakness of the other.

One of the key benefits of this synergy is the balancing of the C/N ratio. Okara is rich in nitrogen, while yam peels provide a high carbon content. When combined, these substrates could yield a feedstock with a C/N ratio closer to the optimal range for anaerobic digestion. Such a balance ensures a more stable nutrient supply, supporting robust microbial growth and metabolic activity (Ferdeş et al., 2023).

Another important aspect is the buffering capacity and pH stability. The lignocellulosic fibers from yam peels could help to counteract the rapid acidification that often results from the degradation of protein-rich substrates like Okara. By diluting the protein fraction, the release of ammonia during digestion is also moderated, thereby reducing the risk of microbial inhibition (Eliasson et al., 2023). This creates a more stable environment for the microbial community, which is crucial for sustained biogas production.

Finally, these combined effects could contribute to enhanced methane yield. The balanced nutritional environment and improved process stability result in higher volumetric methane production compared to mono-digestion of each substrate separately (Ma et al., 2019). In this interaction, the readily available nitrogen from Okara could support the microbial breakdown of the more recalcitrant yam peels, while the carbon from the peels could supply the necessary building blocks for methane formation. Together, these mechanisms illustrate the multifaceted synergistic benefits of co-digesting Okara and yam peels.

## **I.6 Process Optimization for Co-Digestion of Okara and Yam Peels**

### **I.6.1 Key Parameters for Optimization**

Maximizing the synergistic potential of co-digesting Okara and yam peels requires careful control of several operational parameters. These parameters collectively determine microbial activity, reaction kinetics, and overall process efficiency. Among them, the mixing ratio is arguably the most critical. The proportion of Okara to yam peels directly influences the C/N ratio, the organic loading rate (OLR), and the concentration of potential inhibitor compounds in the feedstock. Identifying the optimal blend is therefore essential to exploit substrate synergy while avoiding conditions that could destabilize the system.

The S/I ratio is another important factor. This ratio reflects the balance between the available food (substrate) and the active microbial biomass (inoculum). If the S/I ratio is too low, the reactor volume may be underutilized, whereas an excessive high ratio risks rapid accumulation of VFAs, potentially leading to process failure. This risk is particularly relevant for highly biodegradable substrates like Okara.

Maintaining stable pH and temperature conditions is also fundamental to process optimization. The buffering capacity of the co-digestion mixture (with the inoculum) should be sufficient to keep the pH within a range that supports methanogenic activity. Similarly, temperature governs microbial metabolic rates and can be set under either mesophilic or thermophilic regimes. HRT must also be carefully managed. Since yam peels contain lignocellulosic fractions that degrade slowly, retention times need to be long enough to ensure complete digestion and to avoid the washout of slower-growing methanogenic archaea. Finally, OLR adjustments should be gradual to allow the microbial community to adapt, thereby reducing the risk of overload and acidification.

### **I.6.2 Strategies to Overcome Process Challenges**

The distinct characteristics of Okara and yam peels introduce specific challenges that must be addressed through targeted process strategies. A primary control measure is the organization of the mixing ratio. Carefully managing the proportion of Okara in the feed can prevent the rapid accumulation of inhibitory compounds beyond what the microbial community can process.

In addition, substrate pre-treatment is particularly relevant for yam peels. Their high lignin content forms a protective barrier around cellulose and hemicellulose, hindering enzymatic accessibility. By applying appropriate pre-treatment methods, this rigid structure can be disrupted, increasing surface area and improving carbohydrate accessibility. Such interventions enhance hydrolysis rate and ultimately increase methane yield (Li et al., 2024). Together, these strategies highlight the importance of tailored process management to unlock the full potential of Okara and yam peels co-digestion.

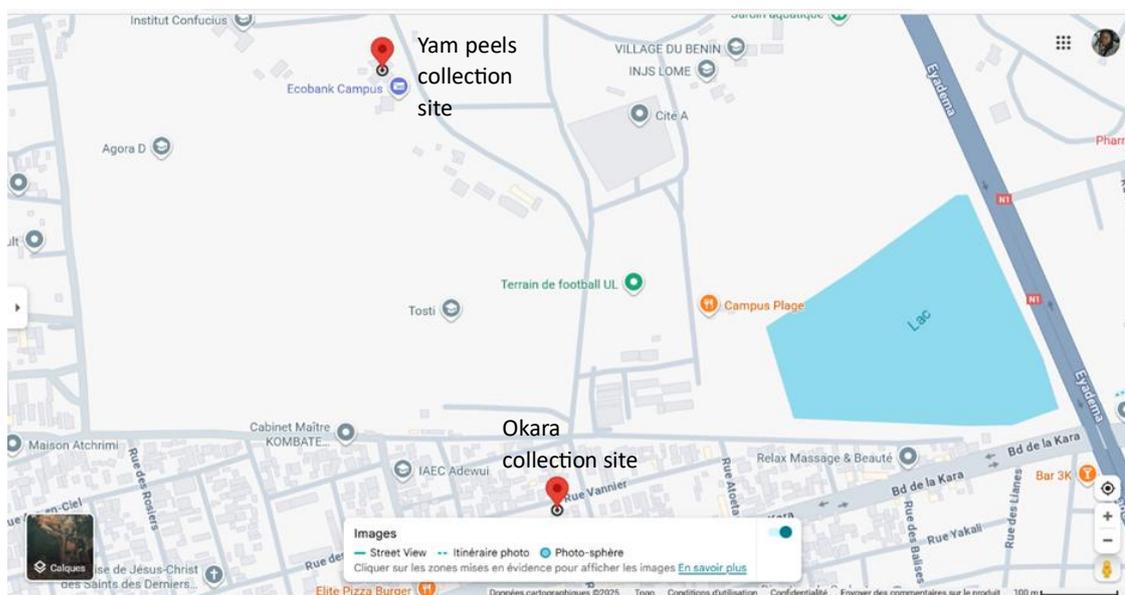
## Chapter 2: Materials and methods

This chapter describes the materials, experimental procedures, and analytical methods employed in this study.

### II.1. Methodology of data collection and materials

#### II.1.1. Materials and sample collection area

Wet Okara (Tofu solid residues) were collected from a soy cheese producer at the south side of the University of Lomé in Togo. It was transported in two nylon bags well attached to ‘Albert Salon’, a students’ residence on the campus. Yam peels were rather sourced at ‘Espace Restauration & Loisirs – Campus Sud’, a place on the campus (near Ecobank Campus) where students can buy food. The wastes were collected from people selling fufu or fried yams, and transported too in nylon bags to ‘Albert Salon’. The red points on Figure 4 give an indication of the wastes’ collection sites.



**Figure 4:** Places of wastes collection – in and outside the University of Lomé

#### II.1.2. Sample pre-treatment and preparation

The samples collected were divided into two batches, after manual sorting of the yam peels to remove the impurities. The first batch was taken directly to the laboratory for proximate analysis, while the second batch, intended for anaerobic digestion, followed first a pre-treatment step at the students’ residence. There, using a clean tissue, quantities of Okara were taken and pressed to remove as much of its water content as possible. The less humidified Okara was then collected in a clean container and brought to the laboratory for drying. The yam peels were rather immersed in a bucket filled with tap water to remove any sand. They were after spread out on a bag in the sun so that the moisture on the surface could be absorbed before being transported to the laboratory.

Once in the laboratory, quantities of Okara and Yam peels were separately spread out on aluminum paper and put in the dryer at 105°C for 4 hours and 24 hours respectively. A cooled step follows and the operation was repeated until all the available quantities were dried. Once drying was complete, the dried yam peels were ground using the laboratory grinder to obtain small particle sizes. Additional grinding was then carried out using a dry blender to reduce the dried Okara and yam peels to powder. These powders were collected and stored respectively in air-tight plastic containers for transportation from Lomé to Rostock in Germany for the research analysis and experiments. Below in Figure 5 are some pictures of the steps.



Wet Okara



Yam peels



Oven-dried Okara



Oven-dried Yam peels



Yam peels and Okara reduced into powder

**Figure 5:** Pre-treatment steps of Okara and yam peels for AD

## II.2. Research approach and design

The research approach for this study is divided into three parts: the first part is related to the physico-chemical characterization of the different samples; the second part covers the methods used for the mono and co-digestion tests for biogas production and the third part presents the environmental and economic analysis approach in this study.

### II.2.1. Samples characterization

#### II.2.1.1. Proximate analysis

The proximate analysis of Okara and yam peels was performed to determine key parameters relevant to anaerobic digestion. The proximate composition of the substrate (mainly Total Solids (TS), Moisture Content (MC), Volatile Solids (VS or oTS), and Ash Content (AC)) was determined using a LECO TGA 701 Thermogravimetric Analyzer. This instrument allows automated, time-resolved analysis of mass loss under controlled temperature programs, thereby enabling precise quantification of water, organic matter, and mineral content in biomass samples.

- pH

The Hydrogen-ion (pH) concentration of the Okara and yam peels was also determined. According to the standards DIN EN 15933 and DIN EN 16197, the pH is measured by preparing a slurry of the fresh sample in distilled water and using a calibrated pH meter. In practice, 60g of sample was filled into a wide-mouth tube and 300 mL of pure water was added. The tube was shaken after for 1 hour in an overhead shaker. When the time was over, the slurry was left to rest for 1 hour. After the required time, the pH of the aqueous suspension obtained at room temperature (around 25°C) was measured using an electronic pH meter.

#### II.2.1.2. Ultimate analysis

- C, H, N, O, S composition in samples

With regard to mineral elements, Carbon (C), Hydrogen (H), Nitrogen (N) were determined using DIN EN ISO 21663 (2021-03). Oxygen was then determined using DIN 51733 (2016-04) while Gross and Net calorific values were obtained using DIN EN ISO 21654 (2021-12). DIN EN 15408 (2011-05) was used to determine Sulfur (S) while other elements like Potassium (K), Phosphorus (P), Calcium (Ca), Sodium (Na), Zinc (Zn) were done using DIN 22022-2 (2001-02).

- C/N ratio determination

The carbon-to-nitrogen (C/N) ratio of the Okara and yam peels was determined as an indicator of their biodegradability and suitability for anaerobic digestion. The C/N ratio was calculated as a simple ratio of carbon and nitrogen content of the sample, as below:

$$C/N \text{ ratio} = \frac{\text{Total Carbon Content (\%TS)}}{\text{Total Nitrogen Content (\%TS)}} \quad (\text{Equation 1})$$

### II.2.1.3. Fiber analysis

The fiber composition of Okara and yam peels was determined using the sequential detergent fiber analysis method to quantify neutral detergent fiber (NDF), acid detergent fiber (ADF), and acid detergent lignin (ADL). These analyses provided estimates of the main structural carbohydrate components: hemicellulose, cellulose, and lignin. The procedures were carried out using a Fibretherm FT 12 automated system and followed protocols based on the VDLUFA Book of Methods adopted by the DBFZ (Liebetrau & Pfeiffer, 2020).

From the sequential measurements, cellulose and hemicellulose contents were derived by difference using:

$$\mathbf{Hemicellulose\ (\%) = NDF - ADF} \quad \text{(Equation 2)}$$

$$\mathbf{Cellulose\ (\%) = ADF - ADL} \quad \text{(Equation 3)}$$

$$\mathbf{Lignin\ (\%) = ADL} \quad \text{(Equation 4)}$$

All values were reported on a dry matter basis. Each measurement was performed in duplicate to ensure analytical precision.

### II.2.2. Biogas production tests

Mono-digestion and Co-digestion tests were carried out to estimate the Biochemical Methane Potential (BMP) of Okara and yam peels, and the biogas potential from the co-digestion of the two substrates. Three kinds of reactors were used for the tests: samples (mixture between substrate and inoculum), blanks (only inoculum) and positive controls (mixture between cellulose and inoculum). 4.8 gVS was chosen as initial loading based on the work of Zhou et al. (2011) who got the highest methane yield at that concentration. Two Substrate-to-Inoculum ratios ( $S/I$ ) were also chosen: 0.5 and 0.6. The reactors' volume ( $V$ ) was 500 ml with 400 ml as working volume ( $R_{wv}$ ) and each test was performed in duplicate for consistency. The reactors were incubated at mesophilic temperature (37°C) for 30 days. The various steps can be seen in Figure 6 below.

#### ➤ Inoculum

The inoculum used for the tests was taken from Hofladen Hof Postma biogas plant in Lambrechtshagen. It is a continuous mesophilic biogas plant with stirring in Rostock, fed with agricultural wastes (cow manure and straw). The inoculum was collected to the lab one week before the BMP tests and incubated in ambient temperature.

To determine the mass of inoculum required for the reactors, the following formula were used, knowing the TS and VS of the substrate:

$$\mathbf{Q_{Substrate}\ (gVS) = SC \times R_{wv}} \quad \text{(Equation 5)}$$

$$\mathbf{Q_{Inoculum}\ (gVS) = \frac{Q_{Substrate}\ (gVS)}{S/I}} \quad \text{(Equation 6)}$$

$$Q_{Inoculum} (g) = \frac{Q_{Inoculum} (gVS)}{VS_D} \quad (\text{Equation 7})$$

With  $Q_{Substrate} (gVS)$  the mass of Substrate based on Volatile Solids,  $Q_{Inoculum} (gVS)$  the mass of Inoculum based on Volatile Solids,  $Q_{Inoculum} (g)$  the fresh mass of Digestate,  $SC = 12g VS/L$  the Substrate Concentration,  $R_{WV}$  the Reactor's working volume,  $S/I$  the Substrate-to-Inoculum ratio, and  $VS_D$  the Volatile Solids of Digestate.

➤ Cellulose

For the positive control reactors, a precise mass of 3 g of cellulose was measured.



Okara & yam peels



Inoculum



Cellulose



Filling of vessels with inoculum and/or substrates (Okara and/or yam peels, cellulose)



Vessels stirring



Vessels in ANKOM Gas Production System

**Figure 6:** Steps for biogas batch tests

### II.2.2.1. Mono-digestion of Okara and yam peels

Here is the calculation to determine the mass of Okara and Yam Peels to be put in the indicated reactors for the mono-digestion tests:

$$Q_{OKR} (g) = \frac{Q_{Substrate} (gVS)}{VS_{OKR}} \quad (\text{Equation 8})$$

$$Q_{YP} (g) = \frac{Q_{Substrate} (gVS)}{VS_{YP}} \quad (\text{Equation 9})$$

With  $Q_{OKR} (g)$  the mass of Okara,  $VS_{OKR}$  the Volatile Solids of Okara,  $Q_{YP} (g)$  the mass of Yam Peels, and  $VS_{YP}$  the Volatile Solids of Yam Peels.

### II.2.2.2. Co-digestion of Okara and yam peels

Three mixing ratios were chosen to test the co-digestion of Okara and yam peels:

- 25% Okara and 75% Yam Peels: ratio 1:3
- 50% Okara and 50% Yam Peels: ratio 1:1
- 75% Okara and 25% Yam Peels: ratio 3:1

All ratios were based on Volatile Solids (VS) to ensure balanced comparisons.

For the calculation of the fresh mass of the samples, the mass of each substrate is multiplied according to its percentage in the mix. As example, for 75% Okara and 25% Yam Peels, the following calculations were done:

$$Q_{OKR75\%} (g) = Q_{OKR} (g) * 75\% \quad (\text{Equation 10})$$

$$Q_{YP25\%} (g) = Q_{YP} (g) * 25\% \quad (\text{Equation 11})$$

### II.2.2.3. Biogas production monitoring using the ANKOM Gas Production System (GPS)

The AD batch tests were performed using the ANKOM Gas Production System (GPS). This system enables high-resolution, automated monitoring of gas production under standardized anaerobic conditions. Each test was conducted in 500 mL digestion vessels equipped with integrated pressure sensors and automated pressure release valves. The system ensures real-time pressure data acquisition at fixed intervals and transmits it wirelessly to a connected computer via Bluetooth.

For each test condition, a certain mass of inoculum was placed in each vessel, and the corresponding substrate was added. Blank controls (inoculum only) and standard substrate tests (cellulose) were included and prepared in duplicate to ensure statistical reliability. The vessels were then sealed, and their headspace purged with nitrogen to ensure anaerobic conditions. Subsequently, the digestion vessels were placed in a thermostatic water bath at 37°C. After a 10-minute stabilization period, automated pressure recording commenced. The system was configured to record the internal pressure every 30 minutes, with a maximum overpressure threshold of 5 kPa (50 mbar), beyond which the pressure release valve was triggered for 250

milliseconds to maintain safe operational conditions. Each vessel was stirred daily using a magnetic stirrer to ensure homogenization.

The gas production was calculated using the ideal gas law, considering the individual headspace volume ( $V_0$ ) of each reactor, determined gravimetrically before testing.

$$dV = dp \cdot \frac{V_0 \cdot v_0}{R \cdot T} \quad (\text{Equation 12})$$

$$V_{Br}(t) = P \cdot \frac{V_0 \cdot v_0}{R \cdot T} \quad (\text{Equation 13})$$

$V_{Br}(t)$  is the volume of biogas produced at time  $t$  in the reactor ( $\text{m}^3$ ),  $v_0$  is the molar volume ( $22.4 \text{ m}^3/\text{kmol}$ ),  $P$  is the pressure at that time  $t$  in the reactor (Pascal),  $R$  is the constant of Planck ( $8314.46 \text{ J/kmol} \cdot \text{K}$ ), and  $T$  is the temperature (K). Therefore, the specific biogas yield  $V_{Spez}(t)$  was determined by subtracting the cumulative gas volume of the blank control from that of the test sample and normalizing it to the mass of substrate VS introduced. The following formula was applied:

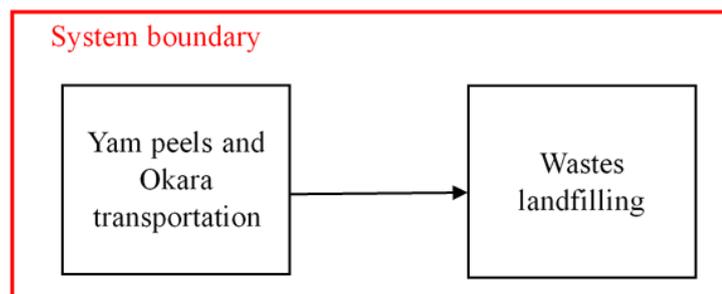
$$V_{Spez}(t) = \frac{V_{Br}(t) - V_{Spez(I)}(t) \cdot m_I}{m_S(VS)} \quad (\text{Equation 14})$$

$V_{Spez(I)}(t)$  is the specific gas production from the inoculum alone at time  $t$ ,  $m_I$  is the inoculum mass (g), and  $m_S(VS)$  is the substrate's volatile solids mass (g VS).

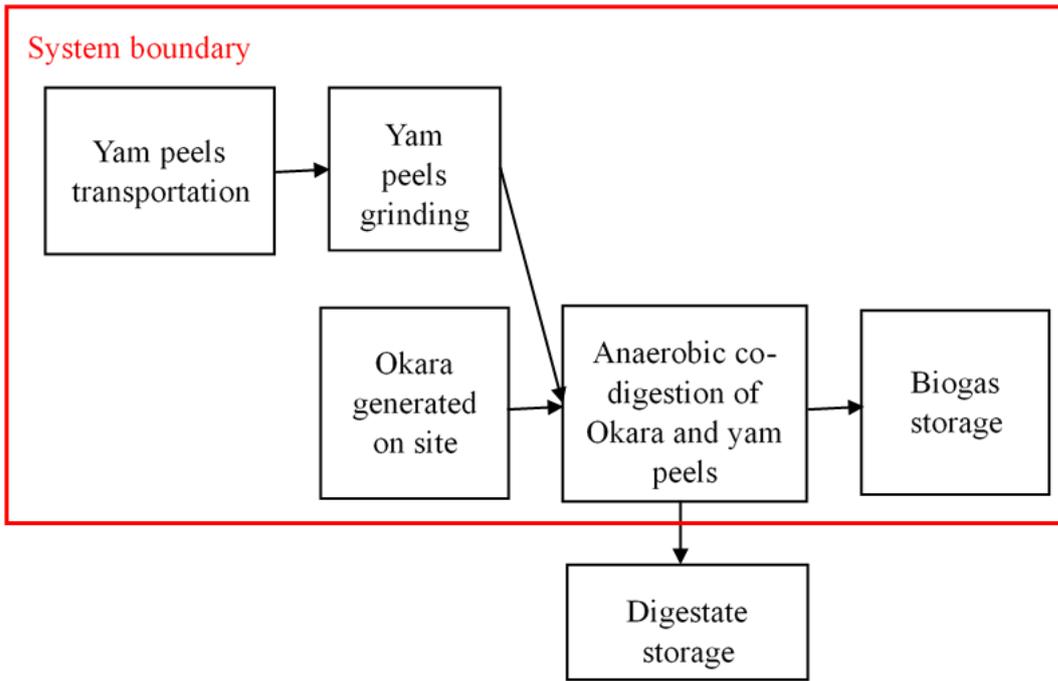
### II.2.3. Environmental assessment of the co-digestion of Okara and yam peels

#### II.2.3.1. Scenarios

For the environmental study, OpenLCA software (version 2.4.1) was used, and the functional unit was 1 kg of fresh Okara+Yam peels (considering the mixing ratio with the highest biogas yield from the co-digestion tests). Landfill and anaerobic digestion as methods of organic waste management were first compared. For landfill as shown in Figure 7, the impacts taken into account included the transport of waste to the site and direct emissions linked to the decomposition process under anaerobic conditions. For anaerobic digestion, the scope included transport, pre-treatment operations (yam peels grinding) and biogas production in the biodigester (see Figure 8). This initial comparison made it possible to determine the relative environmental performance of each waste management method studied.

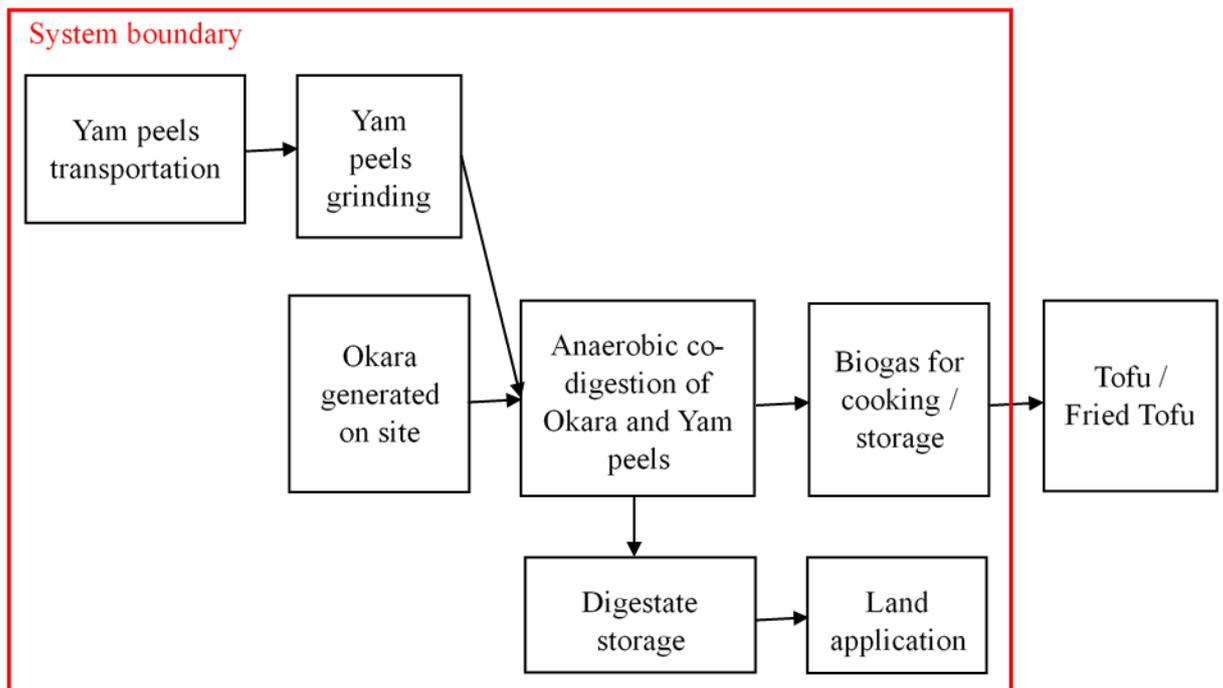


**Figure 7:** Landfilling scenario of Okara and yam peels wastes



**Figure 8:** Waste valorization method through anaerobic digestion

In a second step, a specific analysis was conducted on the available energy combustion options. Here, the combustion phase was considered in order to directly compare the use of biogas and firewood as domestic fuels. This step aimed to isolate the impacts related to final energy conversion. Finally, a comprehensive assessment of the anaerobic digestion scenario in Figure 9 was carried out, covering the entire process chain.



**Figure 9:** Biogas production scenario from the co-digestion of Okara and yam peels

The results of this scenario were compared to the case in which avoided emissions are accounted for, particularly those related to the substitution of firewood by biogas and chemical fertilizers by digestate. This systemic approach highlights the net impact of energy recovery from residues, integrating both the direct environmental costs and the benefits associated with substitutions.

The transport distances taken into account between collection points and waste management sites were 25 km for the landfill scenario and 10 km for anaerobic digestion.

### II.2.3.2. Life cycle Inventory (LCI)

This phase involved detailed data collection on the various inputs, outputs, and processes contained in each scenario. Principal data were gathered from the proximate and ultimate results, as well as the biogas tests. They were supplemented with the literature and background data derived from the Ecoinvent database (version 3.11). This allowed a more accurate reflection of local waste properties compared to Ecoinvent's generalized biowaste assumptions.

#### II.2.3.2.1. Landfill scenario

##### ❖ Methane emissions

0.00357 m<sup>2</sup> was considered as the area occupied by the waste in the landfill (Rohrer et al., 2025). During anaerobic decomposition, part of the carbon in the wastes is converted to methane (CH<sub>4</sub>), and some is released as CO<sub>2</sub>. This CO<sub>2</sub>, considered as biogenic, is not counted as a climate change contributor because it is part of the short-term carbon cycle. Therefore, only methane emissions were manually calculated using Tier 1 from IPCC (2006) with the formula:

$$CH_4 \text{ emissions} = MSW * DOC * DOC_f * MCF * F * \frac{16}{12} * (1 - R) * (1 - OX) \quad (\text{Equation 15})$$

$$DOC = \frac{\text{Default DOC for food wastes (15\%)*TS of Okara and yam peels}}{\text{Default TS of food wastes (40\%)}} \quad (\text{Equation 16})$$

where *MSW* is the total mass of wet waste disposed on landfill (in kg), *DOC* is the degradable organic carbon in the waste, *DOC<sub>f</sub>* is the fraction of DOC that degrades to landfill gas, *MCF* is the methane correction factor reflecting landfill management (managed, unmanaged, uncategorized), *F* is the fraction of methane in landfill gas, 16/12 is the molecular weight ratio of CH<sub>4</sub> to C, *R* is the recovered methane, and *OX* is the oxidation factor reflecting the amount of CH<sub>4</sub> that is oxidized in the soil or other material. After calculation, the amount was set according to the functional unit.

##### ❖ Ammonia emissions

According to Rohrer et al. (2025) for Okara, 25% of total Nitrogen (N) is lost as ammonia (NH<sub>3</sub>) and all other Nitrogen related emissions in the original Ecoinvent database were multiplied by 4.56. The same parameters were used for our evaluation, and 10% was assumed for yam peels using:

$$NH_3 \text{ emissions} = m_N * loss_{\%} * \frac{17}{14} \quad (\text{Equation 17})$$

with  $m_N$  the mass of N presents in the considered dry mass of waste,  $loss_{\%}$  being the percentage of total N lost as  $NH_3$  and  $17/14$  the molecular weight ratio of  $NH_3$  to N.

### II.2.3.2.2. Anaerobic digestion scenario

#### ❖ Volume of biogas produced

Biogas is the first output of the AD process. To calculate the specific biogas yielded from the functional unit, the following calculation was done:

$$V_{biogas} = V_{sp}(biogas) * VS_{fresh} * TS_{fresh} \quad (\text{Equation 18})$$

with  $V_{biogas}$  the biogas yield for 1 kg of wet substrate (Okara+yam peels) in L/kg VS,  $V_{sp}(biogas)$  the biogas potential of the co-digestion in L/kg VS,  $VS_{fresh}$  the Volatile Solid content of the fresh substrates, and  $TS_{fresh}$  the Total Solid content of the fresh substrates.

#### ❖ Methane emissions from AD

Methane emissions exist in the AD process, due to unintentional leakages during the process or other unexpected events. 5% of the total methane generated is a default value (IPCC, 2006). In the current work, 8% was chosen to account for the emissions during the AD process and the storage of the biogas. The volume of methane was calculated assuming a content of 60% in the biogas.

$$V_{CH_4 \text{ emissions}} = 8\% * (V_{biogas} * 60\%) \quad (\text{Equation 19})$$

$$m_{CH_4 \text{ emissions}} = \rho_{methane} * V_{CH_4 \text{ emissions}} \quad (\text{Equation 20})$$

with  $V_{CH_4 \text{ emissions}}$  the volume of methane emitted,  $m_{CH_4 \text{ emissions}}$  the mass of methane emitted, and  $\rho_{methane} = 0.657 \text{ kg/m}^3$  the density of methane.

#### ❖ Mass of digestate generated

Second output of the anaerobic digestion process, the mass of solid digestate generated from the functional unit was calculated considering 50% VS reduction (Rohrer et al., 2025; Zhou et al., 2011). The following formula were used:

$$Q_{VS} = Q_w * TS_w * VS_w \quad (\text{Equation 21})$$

$$Q_{AC} = Q_w * TS_w * AC_w \quad (\text{Equation 22})$$

$$mass_{Digestate} = (0.5 * Q_{VS}) + Q_{AC} \quad (\text{Equation 23})$$

with  $Q_w$  the mass of wet substrate in kg,  $Q_{VS}$  the mass of VS in the wet substrate,  $Q_{AC}$  the mass of AC in the wet substrate, and  $mass_{Digestate}$  the mass of digestate from the AD of the wet substrate.

❖ Emissions from biogas combustion

A thermal efficiency of a biogas stove of 57% was considered (Bruun et al., 2014). Also, emissions from the burning of biogas for heat production was estimated, using data of gas emissions in standard household stoves in developing countries from the same author. 1 MJ delivered energy emitted 81.5 g CO<sub>2</sub>, 57 mg CH<sub>4</sub>, 0.11 g CO and 5.4 mg N<sub>2</sub>O. CO<sub>2</sub> emissions are considered biogenic.

❖ Emissions from firewood combustion

Firewood replacement is the first avoided burden considered in the AD process. Knowing the effective volume of methane used for the combustion process, and then the energy output, a corresponding was done to estimate the mass of wood replaced. A thermal efficiency of 17.40% was considered for a traditional cooking system (Dzokom et al., 2025) and waste wood was used in the software (LHV=13.99 MJ/kg). This allowed the estimation of gas emission per MJ delivered energy from wood, still using data from Bruun et al. (2014): 532 g CO<sub>2</sub>, 600 mg CH<sub>4</sub>, 14 g CO and 4.3 mg N<sub>2</sub>O.

❖ Emissions from inorganic fertilizers

Inorganic fertilizer replacement is the second avoided burden of the AD process. For the values to input in the LCA Software, the following calculations were done, considering 50% of N losses, 2% of P losses, and 30% of K losses (Rohrer et al., 2025). It allows to estimate the corresponding amount of inorganic fertilizer to replace by the digestate:

$$\text{mass of N (fertiliser)} = \%_{0N} * \text{mass}_{\text{Digestate}} * (1 - \text{loss}\%) \quad (\text{Equation 24})$$

$$\text{mass of P (fertiliser)} = \%_{0P} * \text{mass}_{\text{Digestate}} * (1 - \text{loss}\%) * \frac{M(P_2O_5)}{M(P)} \quad (\text{Equation 25})$$

$$\text{mass of K (fertiliser)} = \%_{0K} * \text{mass}_{\text{Digestate}} * (1 - \text{loss}\%) * \frac{M(K_2O)}{M(K)} \quad (\text{Equation 26})$$

*mass of N, P or K (fertiliser)* are the mass of nitrogen phosphorus and potassium in the solid digestate;  $\%_{0N}$ ,  $\%_{0P}$  and  $\%_{0K}$  represent respectively the composition in N, P and K of the substrate (Okara+yam peels);  $M(P_2O_5)$ ,  $M(P)$ ,  $M(K_2O)$ , and  $M(K)$  correspond to the molecular mass of Phosphorus pentoxide ( $P_2O_5$ ), Phosphorus ( $P$ ), Potassium oxide ( $K_2O$ ), and Potassium ( $K$ ).

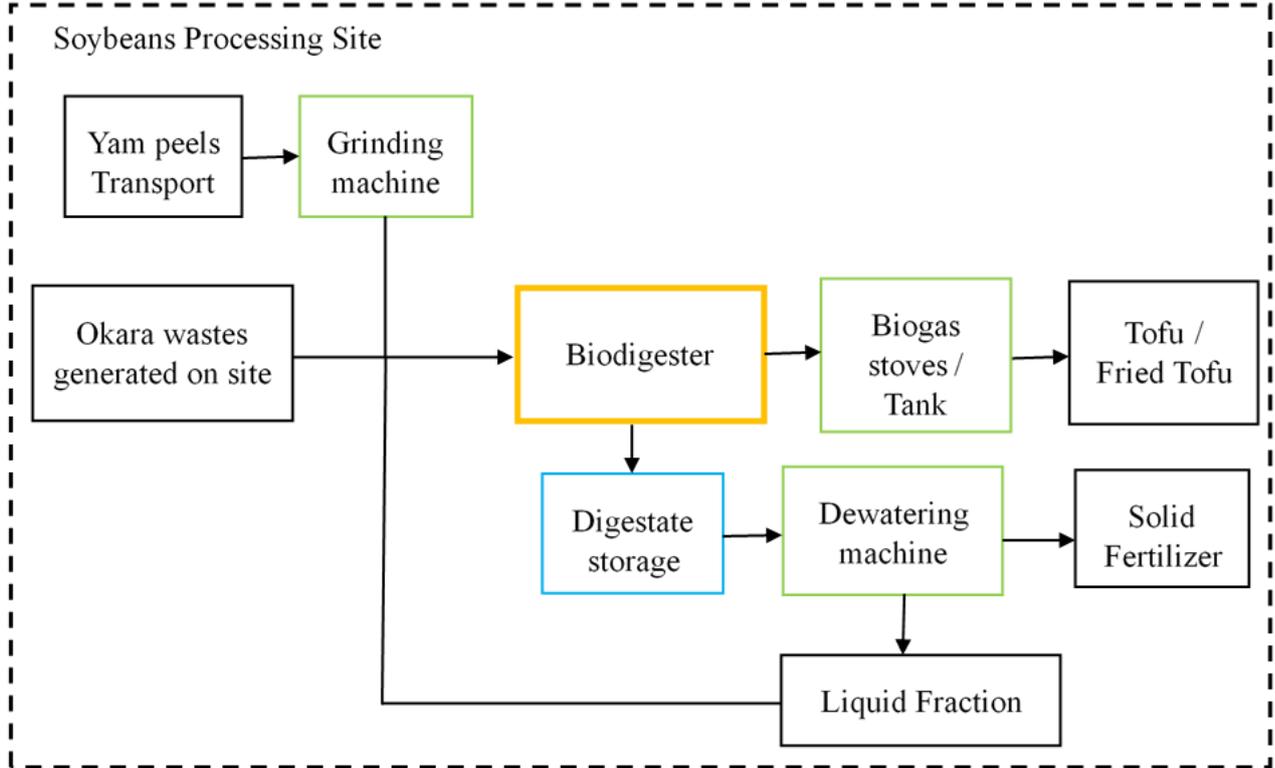
### II.2.3.3. Life Cycle Impact Assessment (LCIA)

Among the available methods in the database, ReCiPe 2016 midpoint H was used as Life Cycle Impact Assessment (LCIA) for the running of the processes. It allows the calculation of the impacts of each scenario in terms of acidification, climate change, ecotoxicity, photochemical oxidant formation, particulate matter formation, human toxicity, etc.

## II.2.4. Economic analysis of biogas production from co-digestion of Okara and yam peels

### II.2.4.1. Biodigester sizing using waste available

For the economic assessment, a cooperative of 15 women producing Tofu and generating 150 kg of Okara daily (6 over 7 days) was used as a case study. Figure 10 shows the flow chart of operations done in the Soybeans processing site for Tofu production.



**Figure 10:** Flow chart for the economic assessment of the case study

The sizing of a fixed dome biodigester undergoes many calculations. Only the total volume of the biodigester was calculated. Here also, the co-digestion with high biogas yield was considered for the sizing. At first, the methodology provided by Naidu et al. (2024) was followed to estimate the active digester volume  $V_r$  (in L).

$$Q = m_{fresh\ waste} + m_{water} \quad (\text{Equation 27})$$

$$V = \frac{m_{fresh\ waste}}{\rho_{fresh\ waste}} + \frac{m_{water}}{\rho_{water}} \quad (\text{Equation 28})$$

$$V_r = HRT * V \quad (\text{Equation 29})$$

$Q$  is the daily available feedstock (kg/day),  $m_{fresh\ waste}$  is the mass of fresh Okara and yam peels available daily (kg),  $m_{water}$  is the quantity of water added to the fresh substrate in order to have a homogenous slurry to feed the biodigester (kg),  $V$  is the volume of the daily available feedstock (L),  $V_r$  is basically the bioreactor's volume where the feedstock stays and undergoes decomposition, and  $HRT$  is the hydraulic retention time (in days).

Finally, the overall biodigester's volume was determined considering the volume of the gas generated as 25% of the volume of the bioreactor:

$$V_g = 25\% * V_r \quad (\text{Equation 30})$$

$$V_T = V_r + V_g \quad (\text{Equation 31})$$

$V_g$  is the volume of the gas (biogas) holder and  $V_T$  is the overall volume.

#### II.2.4.2. Biogas production

An estimation of the biogas yield from the sized biodigester was done using the equations below (Naidu et al., 2024):

$$S = \frac{VS_{feedstock}}{V} \quad (\text{Equation 32})$$

$$OLR = \frac{Q*S}{V_r} \quad (\text{Equation 33})$$

$$Q_{Biogas} = OLR * BP * V_r \quad (\text{Equation 34})$$

$S$  is the substrate inflow concentration (kg VS/m<sup>3</sup>),  $VS_{feedstock}$  is the mass of the Volatile Solids in the feedstock (kg VS),  $OLR$  is the organic loading rate of the biodigester (kg VS/m<sup>3</sup>),  $Q_{Biogas}$  is the daily biogas production (m<sup>3</sup>/day), and  $BP$  is the biogas potential of the feedstock (m<sup>3</sup>/kg VS).

#### II.2.4.3. Digestate production

Digestate production is generally calculated on the basis of a 15% loss in mass during anaerobic digestion, compared with the tonnages entering the site. The calculation was then:

$$Q_{Digestate} = (1 - 15\%) * Q \quad (\text{Equation 35})$$

#### II.2.4.4. Energy output and firewood substitution

The daily energy output of the produced biogas was calculated considering a content of 60% methane, and 1 m<sup>3</sup> of methane equals 9.97 kWh (Rohrer et al., 2025):

$$E_{Biogas} = Q_{Biogas} * 9.97 * 60\% * 3.6 \text{ MJ} \quad (\text{Equation 36})$$

$Q_{Biogas}$  is in m<sup>3</sup>. Taking into account the thermal efficiency of biogas stoves and knowing the energy content of firewood, the daily amount of replaced fuel ( $Q_{Firewood}$ ) was obtained using:

$$Q_{Firewood} = \frac{E_{Biogas} * \eta_{biogas}}{LHV(Wood) * \eta_{wood}} \quad (\text{Equation 37})$$

$\eta_1=0.57$  is the thermal efficiency of stove running on biogas,  $LHV(Wood)=14$  MJ/kg is the lower heating value of wood and  $\eta_2=17.40\%$  is the thermal efficiency of traditional cooking system.

#### II.2.4.5. Economic assessment

Economic parameters such as the Net Present Value (NPV), the Benefit Cost Ratio (BCR), the Payback Period (PP), and the Levelized Cost of Biogas (LCOB) were determined. The capital investment for the construction of the biodigester was \$443.70/m<sup>3</sup> (1\$=563.44 CFA), estimated considering \$300/m<sup>3</sup> as benchmark cost from Mohammed et al. (2017). Cost of building and facilities were determined at 25% of the capital investment of the biodigester (Ogundari, 2023). The price of the grinder for yam peels pre-treatment and the dewatering machine for the digestate processing were found on Alibaba.com. OPEX costs consisted of yam peels collection and transport costs, operation and maintenance cost estimated at 9% of the Fixed Capital Investment (Dossow et al., 2024), Labor costs, and contingency (10% of total costs).

The benefit costs of the AD system in terms of money saving in the case of firewood replacement, and selling of the digestate were also determined. 33.3% is the quantity of solid fraction in the digestate (Ogundari, 2023) but only 10% was considered here for valorization as solid fertilizer for selling. The prices used for the various calculations were \$0.27/kg of solid fertilizer (Mohammed et al., 2017) and \$0.18/kg of firewood.

##### ❖ Net Present Value (NPV)

The NPV was calculated using:

$$NPV = \sum_{t=0}^n \frac{R_n}{(1+\Omega)^n} - \sum_{t=0}^n \frac{C_n}{(1+\Omega)^n} \quad (\text{Equation 38})$$

$n$  is the lifetime of the biodigester (years),  $\Omega$  is the discount rate (%),  $R_n$  and  $C_n$  are respectively the Revenue and Operating costs made per year (Gabisa & Gheewala, 2019). An  $NPV > 0$  translates that the project is economically viable, then can be undertaken.

##### ❖ Benefit Cost Ratio (BCR)

Other important parameter when analyzing the cost benefits of a project, the BCR was computed using:

$$BCR = \frac{\sum_{t=1}^n \frac{B_n}{(1+\Omega)^n}}{\sum_{t=1}^n \frac{C_n}{(1+\Omega)^n}} \quad (\text{Equation 39})$$

$B_n$  is the benefit gained per year. A  $BCR > 1$  shows the profitability of the project for each 1\$ invested at a discounted rate  $\Omega$  (Gabisa & Gheewala, 2019).

##### ❖ Payback Period (PP)

The payback period of the proposed study case project was calculated by:

$$PP \text{ (years)} = \frac{\text{Initial investment}}{\text{Annual operation cash flow}} \quad (\text{Equation 40})$$

This parameter indicates the time it will take to recover the total initial investment.

❖ Levelized Cost of Biogas (LCOB)

The LCOB was assessed by using:

$$LCOB (\$/m^3) = \frac{(CAPEX*CRF)+OPEX}{Annual\ yield\ (m^3)} \quad (\text{Equation 41})$$

$$CRF = \frac{\Omega(1+\Omega)^n}{(1+\Omega)^n-1} \quad (\text{Equation 42})$$

*CAPEX* is the Capital Expenditure, *OPEX* is the Operational Expenditure and *CRF* is the capital recovery factor which help in calculating the annualized CAPEX.

For a better comparison with firewood use for cooking, the cost per useful kWh was determined using the equations:

$$Cost_{Biogas}(per\ useful\ kWh) = \frac{LCOB}{E_{Biogas}*\eta_{biogas}} \quad (\text{Equation 43})$$

$$Cost_{Firewood}(per\ useful\ kWh) = \frac{P_{wood}}{E_{wood}*\eta_{wood}} \quad (\text{Equation 44})$$

$E_{Biogas}=0.6*9.97$  kWh per m<sup>3</sup> of biogas, and  $E_{wood}=3.89$  kWh per kg of firewood. They represent respectively the energy content in biogas and firewood.

## Chapter 3: Results and discussion

This chapter presents and discusses the key findings of the study, including the physicochemical characterization of the substrates, biogas production performance under mono- and co-digestion, as well as the environmental and economic assessments of the anaerobic digestion system.

### III.1. Results

#### III.1.1. Characterization of Okara and yam peels

##### III.1.1.1. Proximate and Fiber analysis

Analysis of the freshly collected samples of Okara and Yam peels revealed a MC of 80.70% and 71.55% respectively (see Table 1). This indicates that fresh Okara contains more water compared to yam peels waste.

As reported in Table 2, the proximate analysis of the dried and ground samples of Okara and yam peels shows that the 2 samples have approximately the same VS content, with Okara recording the highest value (92.75%). Concerning the AC, yam peels were found having the highest content (5.29%) compared to Okara. The pH results also revealed that the two substrates are acidic with Okara having the lowest pH (4.98) and yam peels having a pH of 5.93.

**Table 1:** Proximate analysis of the freshly collected samples (on wet basis)

Samples	TS (%)	MC (%)	VS (%)	AC (%)	pH
Okara	19.30	80.70	96.69	3.31	4.98
Yam peels	28.45	71.55	94.57	4.43	5.93

**Table 2:** Proximate analysis of the grounded and dried samples (on dry basis)

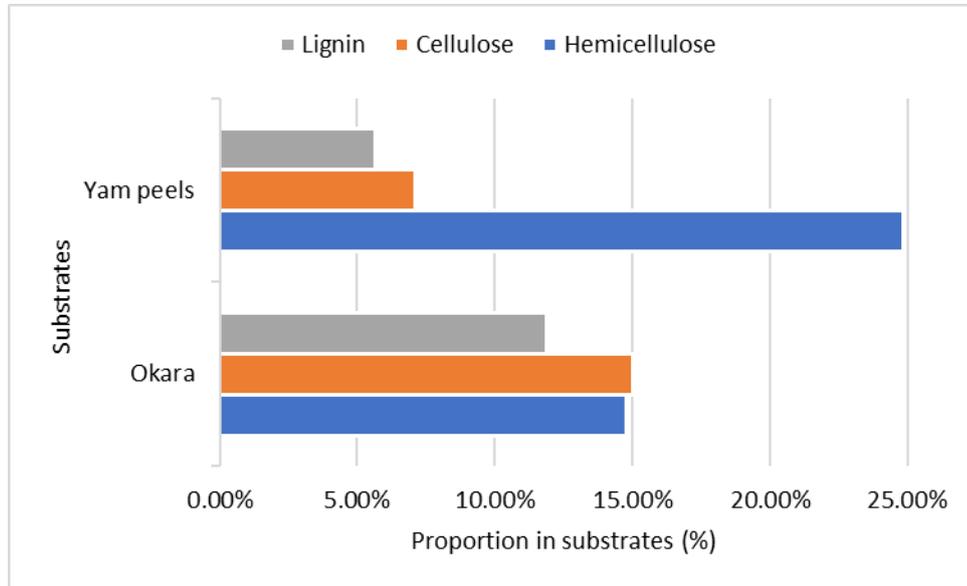
Samples	TS (%)	MC (%)	VS (%)	AC (%)
Okara	95.96	4.04	92.75	3.21
Yam peels	96.38	3.62	91.09	5.29

Considering the fiber analysis, yam peels have a relatively high proportion of hemicellulose (24.85%) with a low content of cellulose (7.12%) and lignin (5.66%), while Okara has approximately the same proportion of hemicellulose and cellulose (around 15%), accompanied with a higher proportion of lignin (11.91%) (see Figure 11).

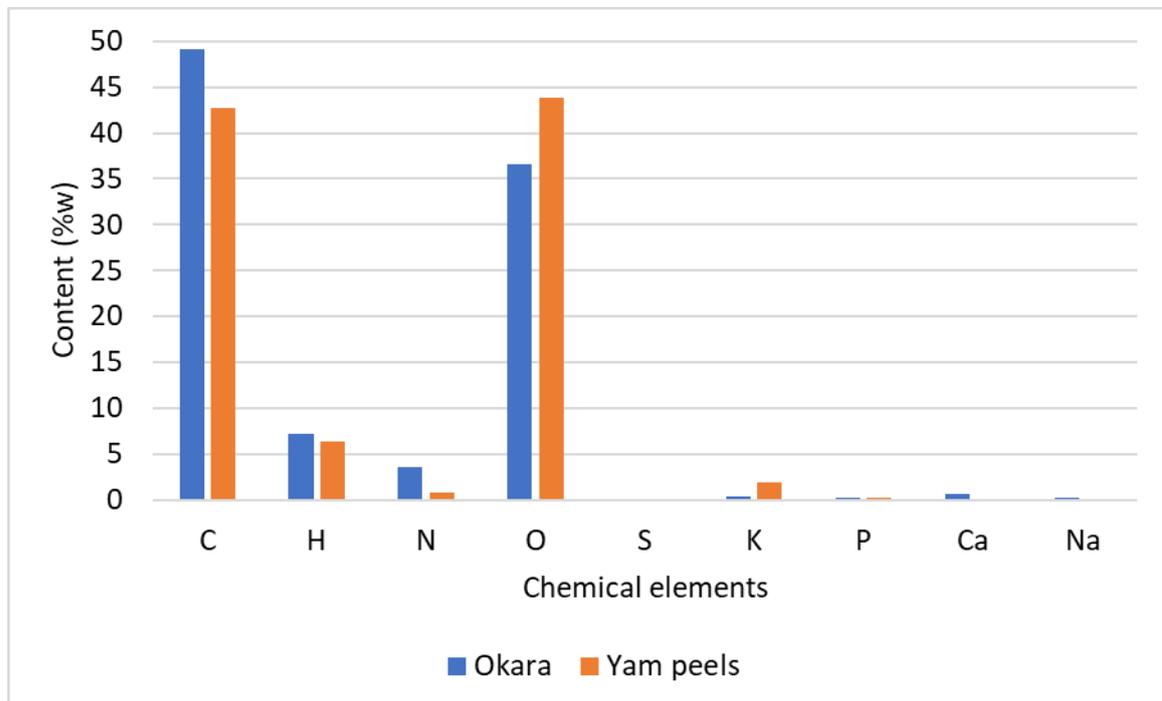
##### III.1.1.2. Ultimate analysis

The results of the elemental analysis are presented in Figure 12 (the detailed results can be found in Appendix A). Calculated on dry basis, the analysis revealed that Okara had a higher

carbon content (49.1%) compared to yam peels (42.7%). Okara also contained more hydrogen (7.16%) and nitrogen (3.60%), reflecting its protein-rich composition. In contrast, yam peels had significantly lower nitrogen (0.812%), resulting in a C/N ratio of 52.59, whereas Okara exhibited a much lower C/N ratio of 13.64. The oxygen content was higher in yam peels (43.8%) than in Okara (36.6%).



**Figure 11:** Fiber analysis of Okara and yam peels on dry basis

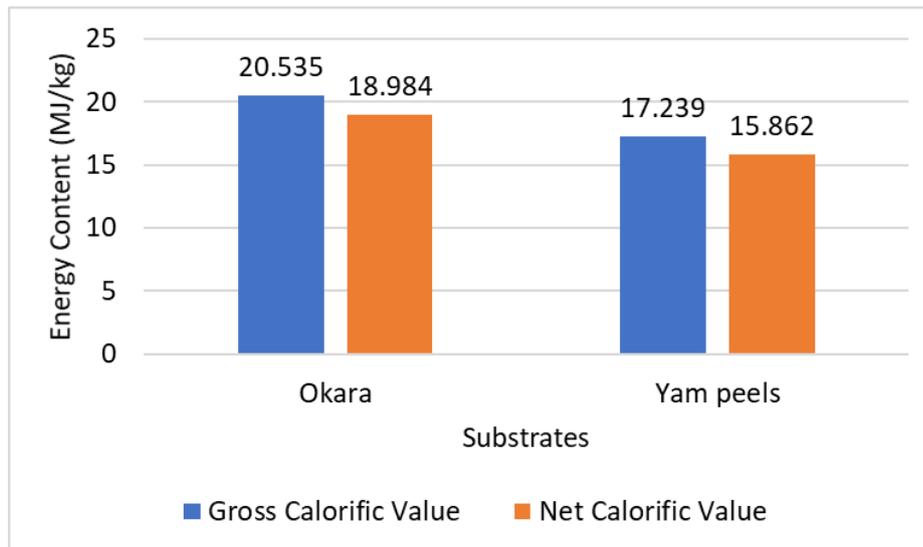


**Figure 12:** Elemental analysis of Okara and yam peel

In terms of mineral composition, yam peels were richer in macronutrients such as potassium (1.91%) and phosphorus (0.21%) while Okara had higher calcium (0.65%) and sodium (0.26%).

Sulphur was found to be very low with 0.11% in Okara and 0.06% in yam peels. Except Nickel which was 0.9% in Okara and 2.5% in yam peels, other micronutrients including Zinc (22.9 mg/kg in Okara, 18.8 mg/kg in yam peels), copper, manganese, and iron were recorded in traces in the two substrates. The presence of heavy metals like lead, chromium, and cobalt remained within acceptable ranges, with lead being under 0.31 mg/kg in both substrates.

Furthermore, Okara displayed a gross calorific value (GCV) of 20.535 MJ/kg and a net calorific value (NCV) of 18.984 MJ/kg, while yam peels recorded GCV and NCV values of 17.239 MJ/kg and 15.862 MJ/kg. This is presented in Figure 13.



**Figure 13:** Calorific values of Okara and Yam peels

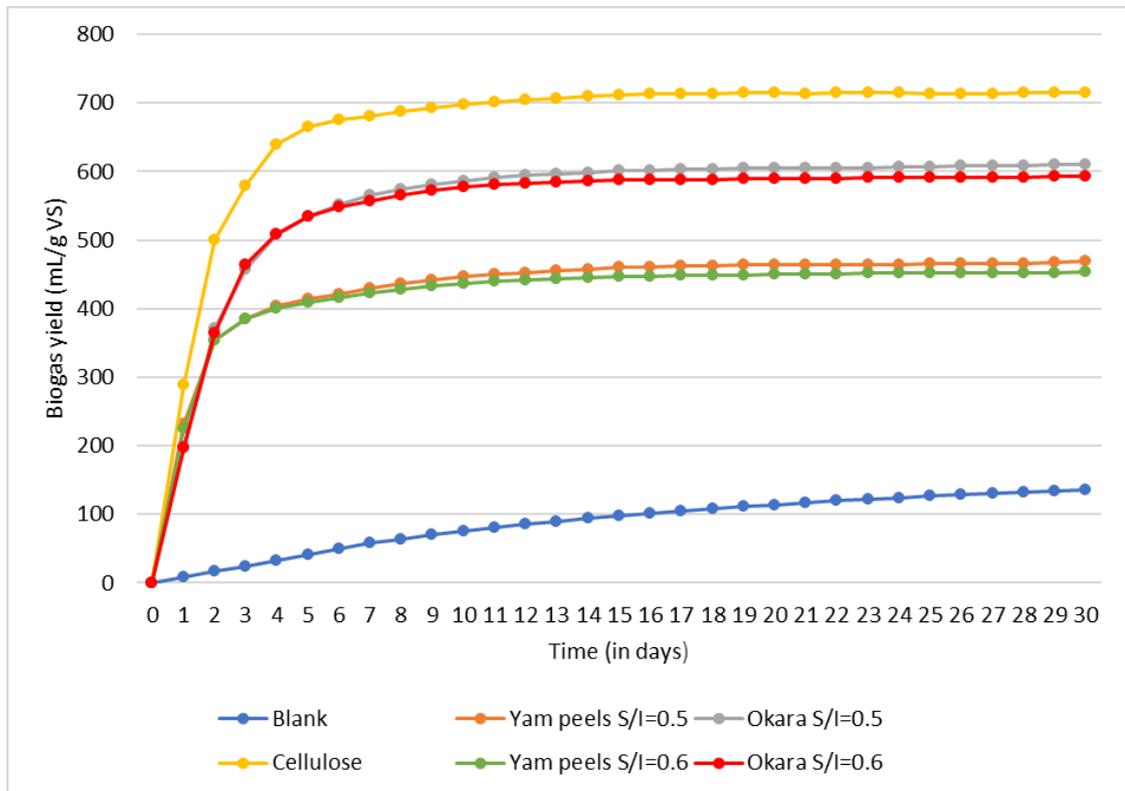
### III.1.2. Biogas potentials of Okara and yam peels through mono and co-digestion

#### III.1.2.1. Mono-digestion tests

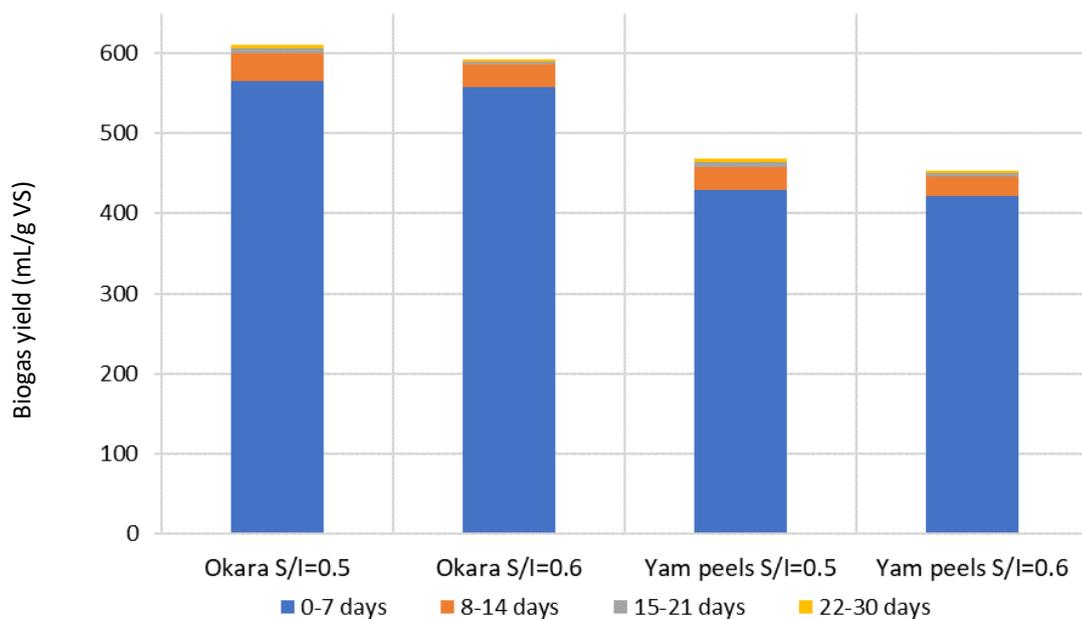
The results of the various mass calculations and the data of the mono-digestion tests recorded by the ANKOM system can be found respectively in Appendix B and C. These data were analyzed once the experimental period was completed. The cumulative biogas production is presented in Figure 14 and showed the highest yield for cellulose followed by Okara, yam peels and blank. A similar 3-phases profile was observed for the three first samples: biogas production rate was most rapid in the first 3 days, after which it slowed down for some days to finally become steady. The blank sample with no substrate had a very flat curve. It presented no visible peak and very little gas production, increasing only a little bit over time. In Okara and yam peels reactors, the increase from S/I=0.5 to S/I=0.6 showed a modest decrease in cumulative biogas yield.

Figure 15 presented the weekly cumulative biogas production from Okara and yam peels under both S/I ratios. It clearly showed for all cases that more than 90% of biogas was produced in the first 7 days, with almost the same yield per substrate type. The remaining weeks displayed an opposite trend: a very low biogas yield, slightly more at S/I=0.5 than 0.6, but extremely

negligible after week 2. However generally, Okara consistently outperformed yam peels, with S/I=0.5 showing the high production. Cumulative biogas yield registered were 468.82 mL/g VS, 610.58 mL/g VS, 453.28 mL/g VS and 592.73 mL/g VS respectively for yam peels and Okara at S/I=0.5 and S/I=0.6.

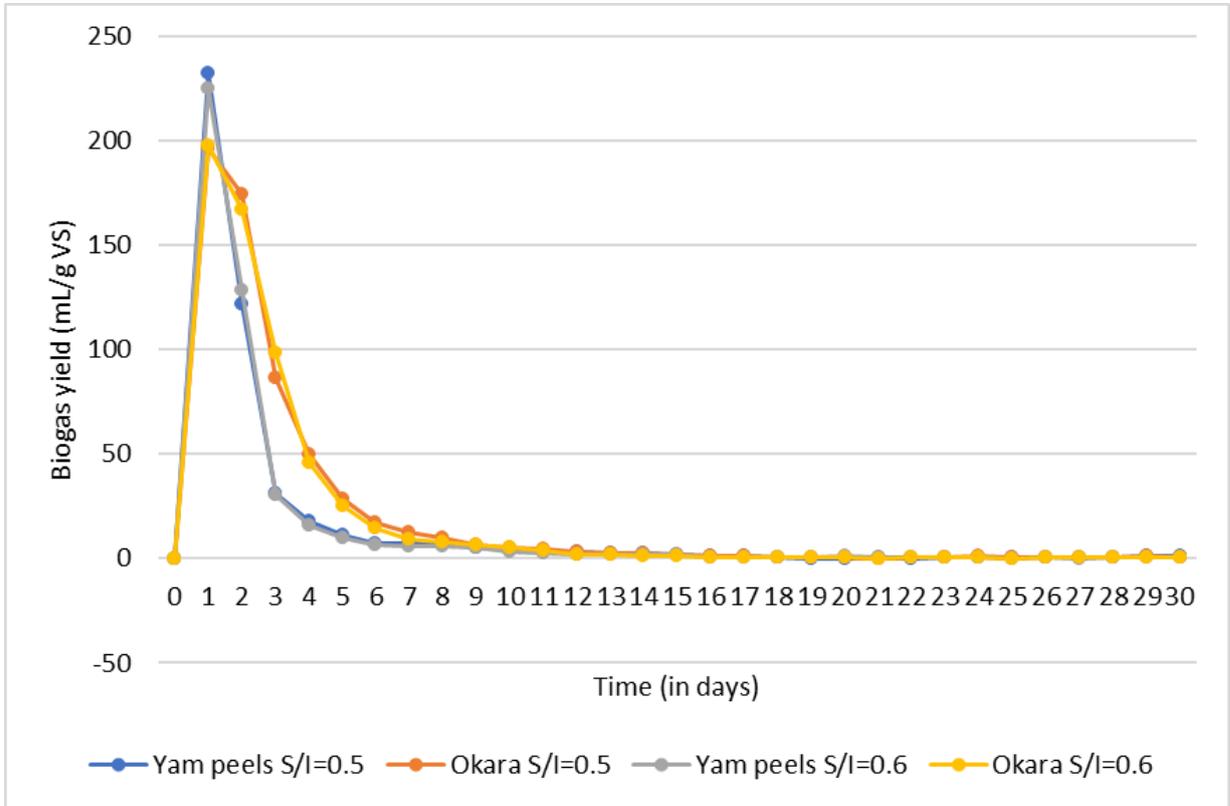


**Figure 14:** Cumulative biogas yield profiles under two S/I ratios (mono-digestion)



**Figure 15:** Weekly cumulative biogas production from Okara and yam peels mono-digestions under two S/I ratios

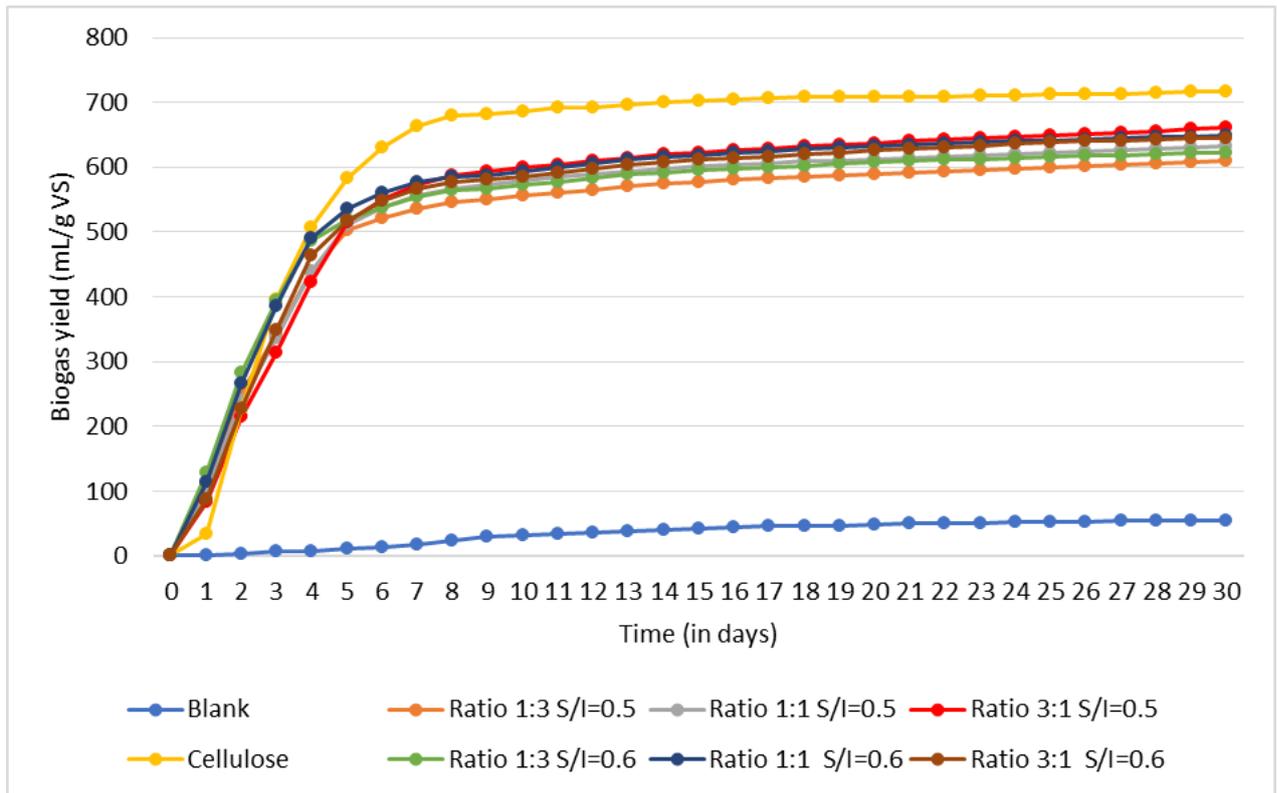
The amount of biogas produced each day during the AD experiments of Okara and yam peels was exposed in Figure 16. It showed that all samples produced the most gas around day 2, then the production dropped quickly and nearly stopped by day 12. Okara produced more gas than yam peels at both ratios, and the S/I ratio of 0.6 led sometimes to slightly better results than 0.5.



**Figure 16:** Daily biogas production from Okara and yam peels mono-digestions under two S/I ratios

### III.1.2.2. Co-digestion test

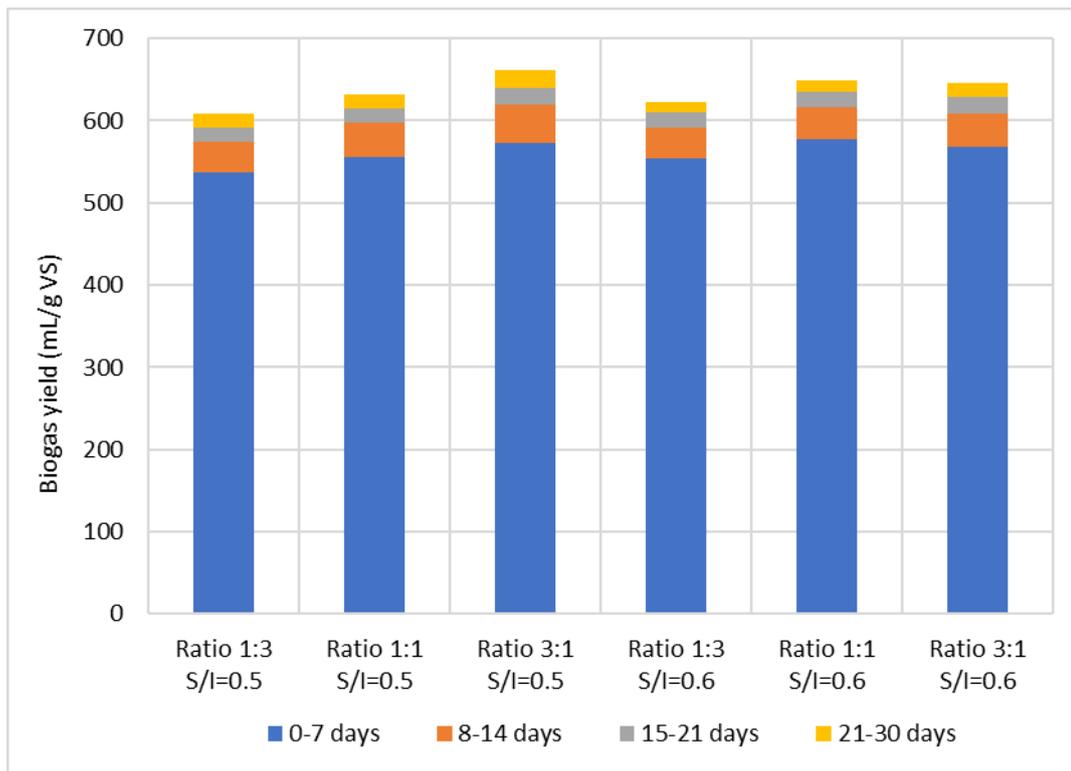
The mass inputted for the AD and the data of the co-digestion tests can also be found respectively in Appendix B and C. The cumulative biogas profiles of the co-digestion batch tests are presented in Figure 17. Similar to the mono-digestion tests, cellulose and blank reactors recorded respectively the highest and lowest biogas production. With a same generation profile in two phases, the various mixing ratios showed a very close cumulative biogas between 609.10 and 661.00 mL/g VS. During the first 5 days, there was a sharp and rapid increase in the yield, after which the production continued to rise gradually, getting more and more close to cellulose yield until the end of the experiments. In general, the biogas production increased with the proportion of Okara in the mixing ratio, and with the S/I ratio, at the only difference of 3:1 ratio where 0.5 had the highest yield.



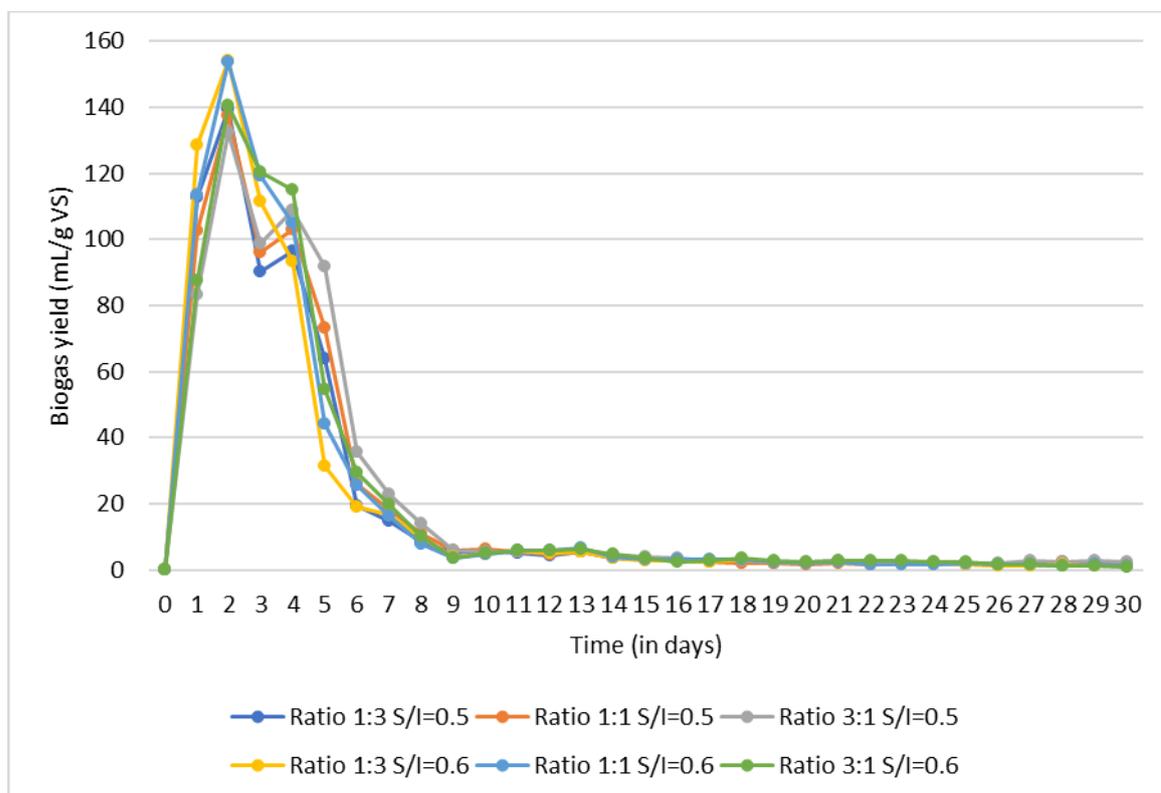
**Figure 17:** Cumulative biogas yield profiles of Okara and yam peels co-digestion at S/I=0.5 and 0.6

The weekly cumulative biogas of the various mixing ratios exposed in Figure 18 confirmed the highest biogas production during the first week (more than 500 mL/g VS). The following weeks produced very low biogas in all the reactors, but much more compared to the mono-digestion tests. Especially in the third and fourth weeks, biogas generation rate was still remarkable, ranging between 16.28 to 20.63, and 13.55 to 21.05 mL/g Vs respectively for each week. At the end of the experiments, the biogas cumulative yields were 609.10, 632.34, and 661.00 mL/g VS respectively for 1:3 1:1 3:1 mixing ratios at S/I=0.5, and 622.80, 648.72 and 645.10 mL/g VS for S/I=0.6.

The daily biogas production of the mixing ratios displayed in Figure 19 revealed a more dynamic production over the days of the experiments. All the co-digestion reactors reached their production peak at day 2 while the ones at 0.6 S/I ratio except 3:1 ratio, got the highest yield. In that period then, 3:1 had the lowest yield for both S/I ratios. A very steep decline period followed until day 9. This phase was characterized by the mix at 0.5 having high yield from day 5 to 6 due to a second peak, and from day 7 to 9, the yield was in the following order: 3:1 mixing ratios, 1:1 mixing ratios, and 1:3 mixing ratios. After that, gas production became almost flat and remained from day 15, close to zero for all mixing ratios, for the rest of the experiment.



**Figure 18:** Weekly cumulative biogas production from Okara and yam peels co-digestions under two S/I ratios



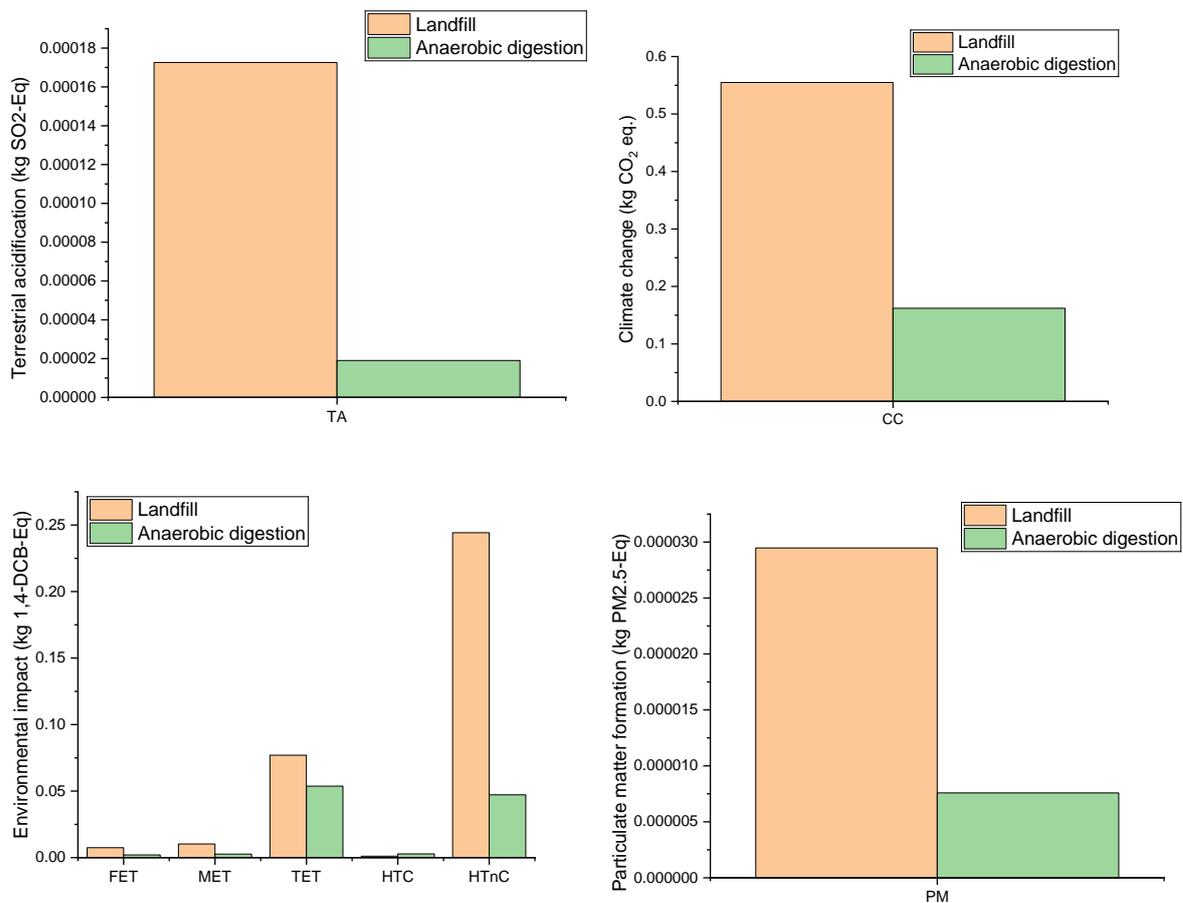
**Figure 19:** Daily biogas production from Okara and yam peels co-digestions under two S/I ratios

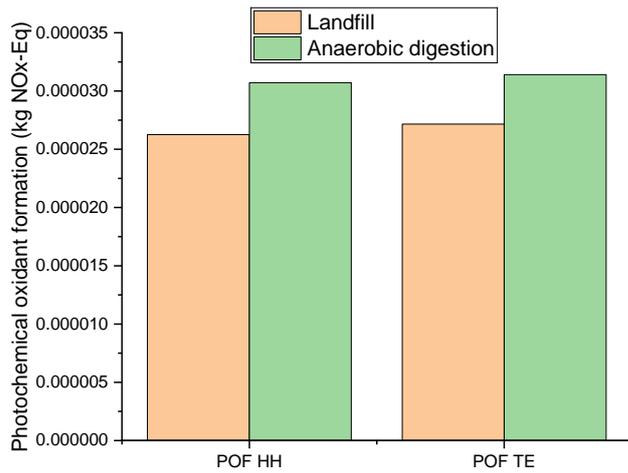
### III.1.3. Environmental impacts of anaerobic digestion process

#### III.1.3.1. Impacts of landfilling compared to biogas production via anaerobic digestion

1kg of Okara+Yam peels (75% Okara 25% Yam peels) was used as a functional unit, and the total waste available was 150kg of Okara and 50kg of yam peels. The original database from Ecoinvent was for biowaste with 40% dry matter. Emissions (excluding methane and N related compounds) were adjusted to the TS composition of the functional unit Okara+Yam peels (TS=21.59%). The manually inputted data in the software are available in Appendix D, and the data of the various environmental assessments are in Appendix E.

The results displayed in Figure 20 reveal that biogas production through anaerobic digestion (AD) significantly outperforms landfilling across several key impact categories. Most notably, biogas production scenario demonstrated a reduction in climate change impact, with CO<sub>2</sub>-equivalent emissions dropping from  $5.55 \times 10^{-1}$  kg CO<sub>2</sub>-Eq for landfilling to  $1.62 \times 10^{-1}$  kg CO<sub>2</sub>-Eq. Similarly, it showed a markedly lower impact on terrestrial acidification, freshwater ecotoxicity ( $7.48 \times 10^{-3}$  vs.  $2.02 \times 10^{-3}$  kg 1,4-DCB-Eq), marine ecotoxicity ( $1.03 \times 10^{-2}$  vs.  $2.68 \times 10^{-3}$  kg 1,4-DCB-Eq) and terrestrial ecotoxicity ( $7.70 \times 10^{-2}$  vs.  $5.37 \times 10^{-2}$  kg 1,4-DCB-Eq). Conversely, biogas production pathway exhibited a higher impact in other categories, highlighting critical environmental trade-offs.





**NOTE:**  
 TA=Terrestrial Acidification; CC=Climate Change; FET=Freshwater Ecotoxicity; MET= Marine Ecotoxicity; TET=Terrestrial Ecotoxicity; HTC=Carcinogenic Human Toxicity; HTnC=non-Carcinogenic Human Toxicity; PM=Particulate Matter formation; POF HH=Photochemical Oxidant Formation: Human Health; POF TE=Photochemical Oxidant Formation: Terrestrial Ecosystems

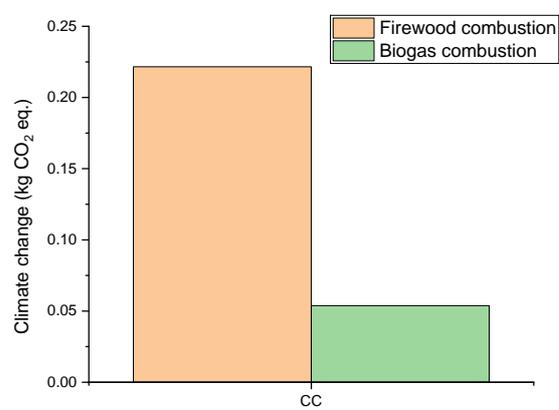
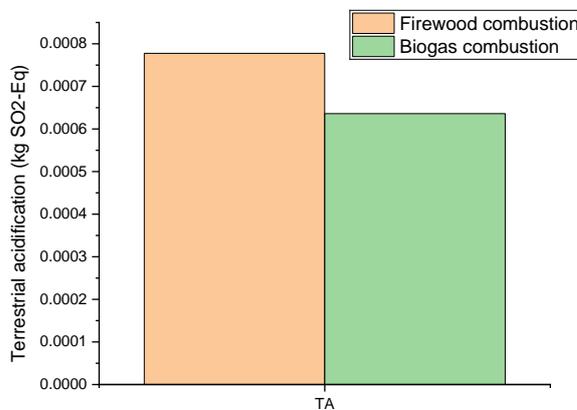
**Figure 20:** Environmental impacts of landfilling, and biogas production via anaerobic digestion.

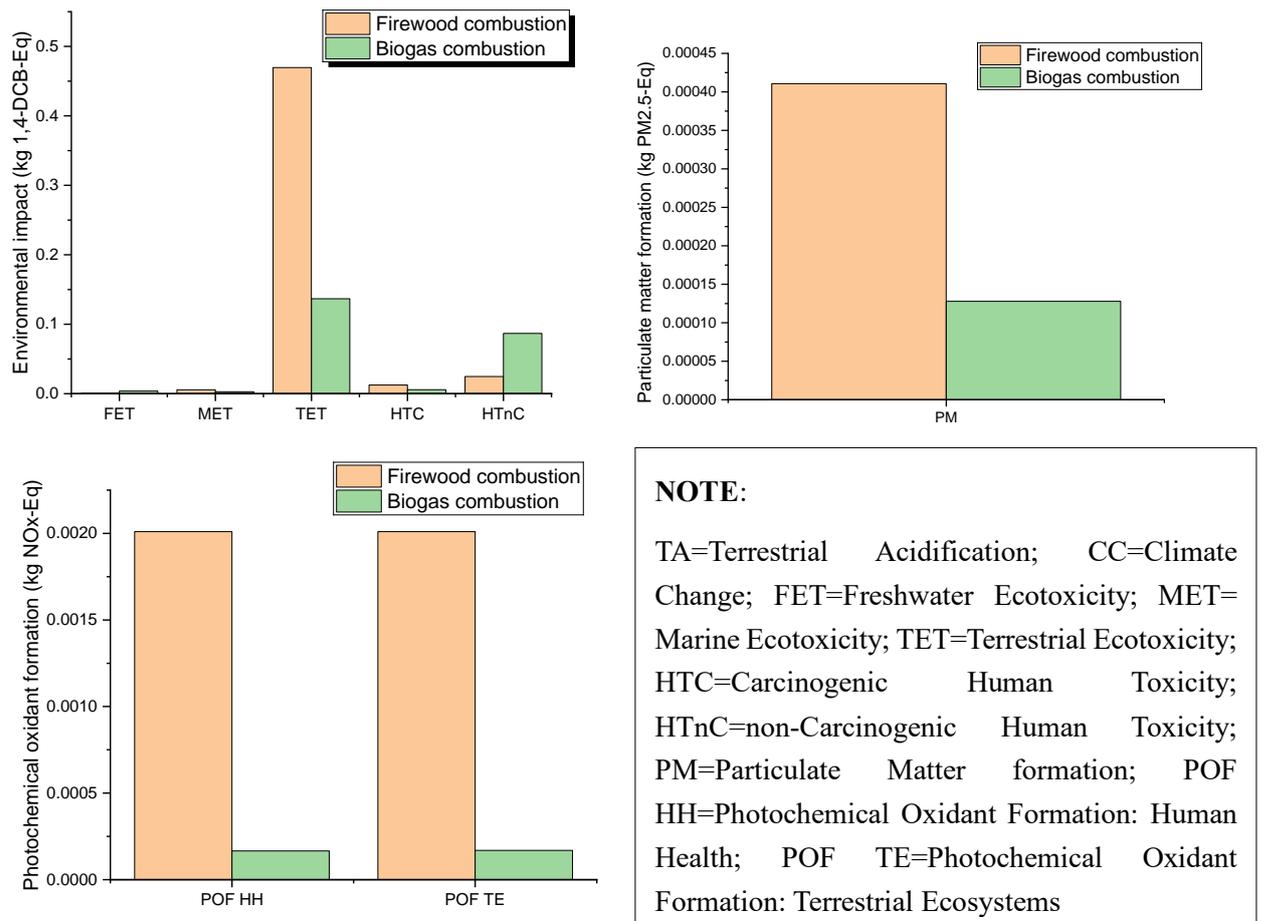
The most significant increase was observed for carcinogenic human toxicity ( $2.84 \times 10^{-3}$  vs.  $1.06 \times 10^{-3}$  kg 1,4-DCB-Eq), and both photochemical oxidant formations.

Furthermore, the pathway has a negligible impact on categories such as non-carcinogenic human toxicity, and particulate matter formation, where landfilling process contribute measurable impacts.

**III.1.3.2. Impacts of biogas as cooking alternative compared to firewood combustion**

About the impacts of each combustion method, results in Figure 21 showed that firewood as a cooking method severely affects human health and ecosystem quality. The most significant impacts were in terrestrial ecotoxicity with  $4.70 \times 10^{-1}$  vs.  $1.37 \times 10^{-1}$  kg 1,4-DCB-Eq. Major impacts were also observed in carcinogenic human toxicity ( $1.24 \times 10^{-2}$  vs.  $5.82 \times 10^{-3}$  kg 1,4-DCB-Eq), particulate matter formation ( $4.11 \times 10^{-4}$  vs.  $1.28 \times 10^{-4}$  kg PM2.5-Eq), photochemical oxidant formation, both for human health ( $2.01 \times 10^{-3}$  vs.  $1.66 \times 10^{-4}$  kg NOx-Eq) and terrestrial ecosystems ( $2.01 \times 10^{-3}$  vs.  $1.70 \times 10^{-4}$  kg NOx-Eq).





**Figure 21:** Impacts of biogas and firewood combustion approach for cooking

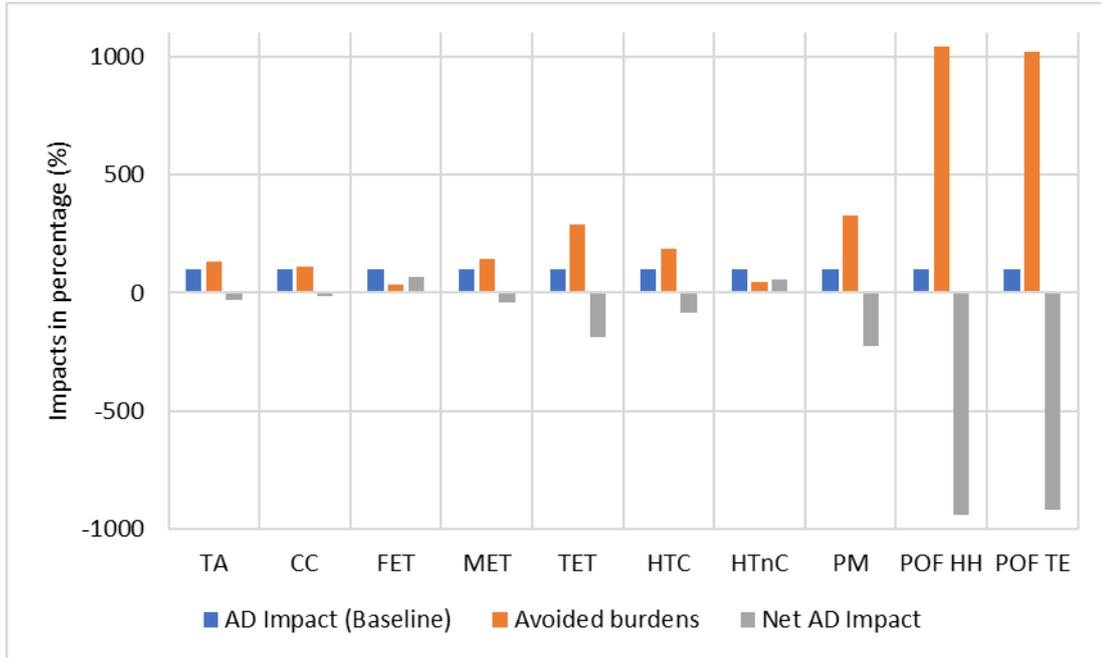
Major impacts were also observed in carcinogenic human toxicity ( $1.24 \times 10^{-2}$  vs.  $5.82 \times 10^{-3}$  kg 1,4-DCB-Eq), particulate matter formation ( $4.11 \times 10^{-4}$  vs.  $1.28 \times 10^{-4}$  kg PM<sub>2.5</sub>-Eq), photochemical oxidant formation, both for human health ( $2.01 \times 10^{-3}$  vs.  $1.66 \times 10^{-4}$  kg NO<sub>x</sub>-Eq) and terrestrial ecosystems ( $2.01 \times 10^{-3}$  vs.  $1.70 \times 10^{-4}$  kg NO<sub>x</sub>-Eq). Furthermore, replacing firewood with biogas leads to a positive outcome for climate change ( $5.38 \times 10^{-2}$  vs.  $2.22 \times 10^{-1}$  CO<sub>2</sub>-Eq for firewood combustion). Benefits were also observed for terrestrial acidification and marine ecotoxicity.

However, the analysis also highlights trade-offs where biogas combustion results in increased environmental burdens compared to firewood. These include impacts on non-carcinogenic human toxicity, and freshwater eco-toxicity.

### III.1.3.3. Overall environmental impact of anaerobic digestion pathway

The total impact of anaerobic digestion (AD) pathway was now determined considering feedstock transportation and its grinding, as well as biogas production and its combustion for cooking. The avoided burdens were also estimated taking into account impacts from firewood combustion and inorganic fertilizer replacement.

Results (in percentage) of the total impact of AD, the avoided burdens, and the net impact of AD with avoided burdens were presented in Figure 22. In most of all the categories showcased on the chart, the environmental impacts related to the avoided burdens is higher than the impacts of the AD process (baseline). As a consequence, the net impacts of AD are lower than the baseline or even negative, with considerable drop for photochemical oxidant formation.



**Figure 22:** Percentage graph of anaerobic digestion (AD) impact and its net impact with avoided burdens

### III.1.4. Economic assessment of the case study

#### III.1.4.1. On-site biodigester sizing

Considering here the same total waste available as 150 kg of Okara and 50kg of yam peels, the sizing of the biodigester was done, considering a feeding waste to water ratio of 1:2, knowing  $\rho_{Okara} = 0.52 \text{ g/mL}$ ,  $\rho_{yam\ peels} = 0.68 \text{ g/mL}$ , and  $\rho_{water} = 1 \text{ g/mL}$ . The characteristics of the digester were presented in Table 3 below. The table shows that 30 m<sup>3</sup> of digester will be required for biogas production in the case study with a loading rate of 1.88 kg VS/m<sup>3</sup>/day, allowing a daily biogas production of 28.31 m<sup>3</sup> equivalent to 609.75 MJ as energy output.

**Table 3:** Characteristics of the biodigester to construct

Parameters	Values	Units
Daily available feedstock (Q)	200	kg
Volume of daily available feedstock (V)	761.991	L
Hydraulic Retention Time (HRT)	30	days

<b>Volume of bioreactor (<math>V_r</math>)</b>	22.86	$m^3$
<b>Total Volume of biodigester (<math>V_T</math>)</b>	28.57	$m^3$
<b>Organic Loading Rate (ORL)</b>	1.88	kg VS/ $m^3$ /day
<b>Substrate inflow concentration (S)</b>	52.30	VS/ $m^3$
<b>Daily Biogas production (<math>Q_{Biogas}</math>)</b>	28.31	$m^3$
<b>Daily Biogas Energy output (<math>E_{Biogas}</math>)</b>	609.75	MJ
<b>Daily quantity of digestate (<math>Q_{Digestate}</math>)</b>	510	kg

The corresponding amount of replaced firewood for the same energy output was found as follow:

$$Q_{Firewood} = 168.88 \text{ kg/day} = 53.54 \text{ tons/year}$$

#### III.1.4.2. Assessment of project feasibility

The results from the calculation of economic parameters such as NPV, BCR, PP, and LCOB were presented in Table 4. Also, net cost per useful kWh in cooking settings were found as 0.26\$ and 0.31\$ respectively for biogas and firewood.

**Table 4:** Cost benefit parameters of the case study

<b>Components</b>	<b>Value</b>	<b>Units</b>
<b>CAPEX</b>		
Land Acquisition	6211.84	\$
Biodigester Installation	13311.09	\$
Building and facilities	3327.77	\$
Grinder machine	709.92	\$
Digestate Solid-Liquid Separator Machine	1384.35	\$
Contingency	2494.50	\$
<i>Total</i>	<i>29 933.98</i>	<i>\$</i>
<b>OPEX</b>		
Yam peels collection and Transport	2250.46	\$
Operation and Maintenance	1685.98	\$
Digestate Processing	229.55	\$
Labor cost	1064.89	\$
Contingency	523.09	\$

<i>Total</i>	<i>5 231.81</i>	\$
<b>Benefits</b>		
Annual cost saving from Firewood use	9501.48	\$
Fertilizer production	4304.01	\$
<i>Total</i>	<i>13 805.47</i>	\$
<b>Economic parameters</b>		
Net Present Value (NPV)	56 738.17	\$
Benefit Cost Ratio (BCR)	1.64	-
Payback Period	3.20	years
Levelized Cost Of Biogas (LCOB)	0.89	\$/m <sup>3</sup>
Biodigester's Lifetime	20	years

## III.2. Discussion

### III.2.1. Substrates' physico-chemical characteristics and its impact on biogas production

#### III.2.1.1. Proximate analysis and its implication

The proximate analysis in Table 1 revealed that both fresh Okara and yam peels from tofu and agricultural processing respectively, exhibited high moisture content (MC). This property is beneficial for wet anaerobic digestion, where high water content supports microbial activity. Fresh Okara presented an MC of 80.70%, which is comparable to the 87.02% found by Ali et al. (2024). Variations can be attributed to differences in tofu production methods, particularly the amount of water used and the filtration process. For yam peels, our measured MC was 71.55%, while Makinde & Odokuma (2015) and Kan et al. (2023) reported 81.22% and 74.34%, respectively. These differences likely reflect the influence of yam species, agroecological zones, and environmental factors (Neina, 2021).

On a dry basis in Table 2, both Okara (92.75%) and yam peels (91.09%) had high volatile solids (VS) content, indicating a high concentration of biodegradable organic matter suitable for methane production. This aligns closely with the values of 91.5% and 94.58% reported respectively by Zhou et al. (2011) for Okara and Kan et al. (2023) for yam peels. Regarding ash content (AC), Okara and yam peels recorded 3.15% and 5.29% respectively (on dry basis), reflecting a moderate mineral load that can contribute essential nutrients like phosphorus, potassium, and magnesium for microbial metabolism during anaerobic digestion. These levels are below inhibitory thresholds, suggesting that neither substrate alone poses a risk of mineral-related process inhibition. Choe et al. (2021) recorded a close AC of 2.57% for Okara.

For the pH still in Table 1, Okara was found to be relatively acidic (pH 4.98). This may lead to rapid acidification or unstable digestion if digested alone, potentially inhibiting methanogenic activity and lowering methane yield. The current pH is relatively low compared to values from Choe et al. (2021) and Ali et al. (2024), possibly due to the origin of soybeans used in tofu production. In contrast, yam peels had a pH of 5.93, still mildly acidic but closer to the neutral range favorable for anaerobic microorganisms. Makinde & Odokuma (2015) however measured a lower value of 4.9, probably due to the difference in yam varieties. Nevertheless, in the present case, yam peels with its slightly higher pH could help partially neutralize the acidic nature of Okara in co-digestion, supporting better pH stability during fermentation. The digestate also with its alkaline/basic nature offers buffering potential to mitigate acidification during digestion.

### III.2.1.2. Impact of the chemical composition

The ultimate analysis of Okara and yam peels revealed appreciable concentrations of key elements. When looking at calculated C/N ratios in Table 5, they fell out of the range for optimal methane production as stated in I.1.2. More clearly, Okara's low ratio (13.64) indicated excess nitrogen which may lead when digested alone, to ammonia accumulation, inhibiting methanogenic activity. Choe et al. (2021) found a similar ratio of  $13.89 \pm 0.27$ , and Song et al. (2021) reported elemental compositions of 44.62 wt% C and 3.37 wt% N, yielding a C/N ratio of 13.24. On the contrary, yam peels' high C/N ratio (52.59) implied possible nitrogen deficiency, which can potentially limit microbial growth and lead to slower biogas production in mono-digestion. Makinde & Odokuma (2015) and Heiske et al. (2015) reported as well high values of 45 and 55, respectively. These extremes C/N ratios suggest that Okara and yam peels are highly complementary and well-suited for co-digestion, where the high nitrogen content of Okara can be balanced by the high carbon content of yam peels. Therefore, co-digesting these substrates could balance their nutrient content and move the system toward stoichiometric balance, reducing the risk of inhibition and stabilizing digestion.

**Table 5:** Comparison of C/N ratio

	<b>Okara</b>	<b>Yam peels</b>
	13.64	52.59
<b>C/N ratio</b>	13.24 (Song et al., 2021)	55 (Heiske et al., 2015)
	$13.89 \pm 0.27$ (Choe et al., 2021)	45 (Makinde & Odokuma, 2015)
	$20.67 \pm 0.04$ (Ali et al., 2024)	24.54 (Kan et al., 2023)

Additionally, anaerobic digestion requires a balanced supply of macro- and micronutrients to sustain microbial activity and ensure process stability. On one hand, macronutrients such as P, N, K, Na, Mg, and Ca are essential for cell synthesis and energy metabolism. They also impact

the quality of the digestate, for its use as fertilizer (Laiq Ur Rehman et al., 2019). In that setting, Okara and yam peels showed appreciable concentrations of crucial macro-nutrients with yam peels having higher quantities of Phosphorus and Potassium (0.21% and 1.91%) while Okara had Calcium, Sodium, and Magnesium in high proportions (0.65%, 0.26% and 0.15% respectively). On the other hand, micro-nutrients (Mn, Zn, Fe, Co, Ni, Cr, W, Se...) act as a crucial cofactor in enzymatic reactions (Neri et al., 2023). However, these trace elements must remain within safe ranges, as excessive concentrations may inhibit microbial populations (Laiq Ur Rehman et al., 2019). They appeared in very low quantities in the 2 substrates. The complementary nutrient profiles of Okara and yam peels thus can enhance microbial resilience, promote enzymatic functionality, and contribute to more stable and efficient biogas production. Moreover, the presence of Sulfur in both substrates is relatively low (0.11% in Okara and 0.06% in yam peels), reducing the risk of hydrogen sulfide (H<sub>2</sub>S) formation, which could otherwise inhibit digestion. Heavy metals like Pb and Co were also in trace amounts, minimizing potential toxicity risks, making the digestate environmentally safe for land application.

Part of the organic molecular structure but not standing as nutrients for microbial growth, Hydrogen and Oxygen contents in substrates influence the theoretical methane yield and help in assessing substrate biodegradability. This concept is grounded in the Buswell and Mueller equation which predicts methane yield based on the chemical composition (C, H, O, N) of the substrate. In the current analysis, Okara contained more hydrogen and less oxygen (7.16% H and 36.6% O), while yam peels had the contrary (6.32% H and 43.8% O). The relative abundance of these 2 elements suggested that Okara is more reduced and could potentially yield more methane per unit of VS degraded. This aligned with the higher gross calorific value of 20.535 MJ/kg and net calorific value of 18.984 MJ/kg found for Okara, confirming its energy-rich composition. Yam peels, by contrast, presented a lower gross calorific value of 17.239 MJ/kg and net value of 15.862 MJ/kg, consistent with its lower theoretical biomethane potential.

### **III.2.1.3. Fiber content impact**

The fiber composition of the substrates revealed significant differences in their structural carbohydrate profiles, which directly influence their biodegradability under anaerobic digestion. From the results in Figure 11 and Table 6, Okara contained an equal proportion of cellulose and hemicellulose, but with high lignin (11.91%). That may hinder biodegradation due to lignin's inhibitory role in limiting microbial access to cellulose and hemicellulose. In contrast, yam peels exhibited a much lower lignin content (5.66%), which generally favors microbial hydrolysis. Notably, yam peels also contain a higher hemicellulose fraction (24.85%), a more easily degradable polysaccharide compared to crystalline cellulose, suggesting better initial biodegradability. However, the relatively lower cellulose content (7.12%) in yam peels may limit their long-term methane yield. These contrasting fiber profiles suggest that Okara is

rich in energy-dense but structurally complex fibers, while yam peels offer more accessible, but less energy-dense fibrous material. These opposite characteristics support once again the rationale for co-digestion to improve overall digestion kinetics and gas production.

**Table 6:** Fiber content in Okara and yam peels (on dry basis)

Samples	NDF (%)	ADF (%)	ADL (%)	Hemicellulose	Cellulose	Lignin
Okara	41.71	26.92	11.91	14.79	15.01	11.91
Yam peels	37.63	12.78	5.66	24.85	7.12	5.66

### III.2.2. Anaerobic digestion of Okara and yam peels

#### III.2.2.1. Biogas potential from Okara and yam peels

Figure 14 presents the cumulative biogas yield over 30 days for the mono-digestion of Okara and yam peels at two substrate-to-inoculum (S/I) ratios: 0.5 and 0.6. As anticipated, cellulose, used as a positive control due to its high biodegradability, recorded the highest yield, reaching 715.53 mL/g VS. The blank control remained very low, confirming minimal biogas production from the inoculum alone.

Among the tested substrates, Okara consistently outperformed yam peels, with a maximum yield of 610.58 mL/g VS at S/I = 0.5 and a slightly lower yield of 592.73 mL/g VS at S/I = 0.6. These results align with its biochemical properties and are comparable to values reported by Zhou et al. (2011), who observed 775 mL/g VS at the same S/I ratio and organic load. The observed difference may be due to experimental variations such as substrate preparation, inoculum characteristics, or ambient conditions. For yam peels, the peak yield was 468.82 mL/g VS at S/I = 0.5, which is relatively high when compared to Kan et al. (2023), who reported 373 mL/g VS with a much higher organic load (16 g VS). Such variation could come from differences in yam varieties or digestion setups.

The observed biogas yields reflected the various results found above. Okara could have exhibited a higher biogas potential than yam peels due to its superior volatile solids content, higher calorific value, and readily biodegradable composition. Its nutrient profile comprising protein, lipid, and carbohydrate as stated in 1.3.1, provides a rich biochemical energy source for microbial degradation. On the other side, yam peels are a type of lignocellulosic waste, which are characterized by a high lignin content difficult to degrade, and a low extractive composition (Rowan et al., 2022). It gives then gas more slowly.

The comparison between S/I ratios further highlights that a lower ratio (0.5) slightly outperformed 0.6, regardless of the substrate. This trend is consistent with Song et al. (2021), who found that decreasing the S/I ratio led to higher methane yields for tofu residues, with an

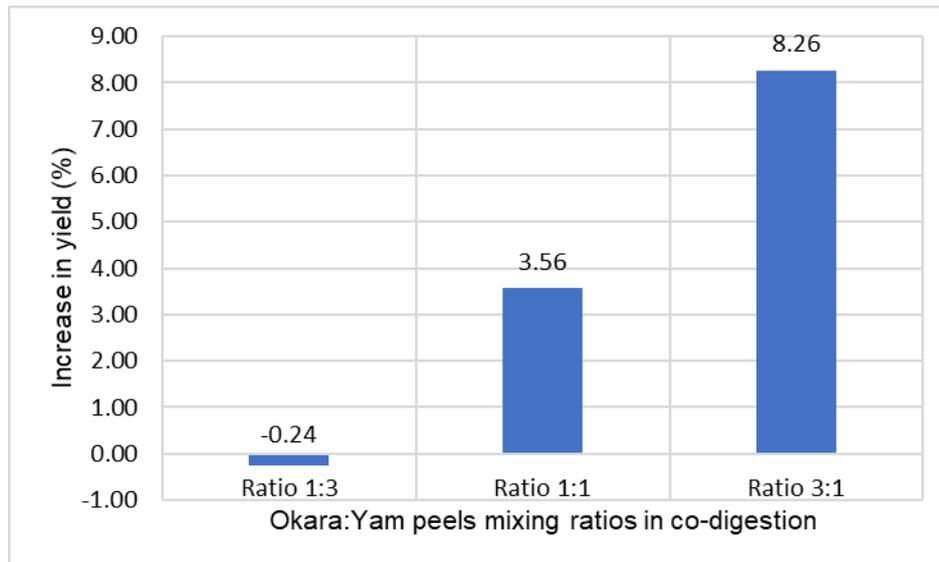
optimal yield of 360.77 mL/g VS at an S/I of 1:2. In the present study, the narrow difference between the two ratios may have limited the distinction in performance, though the trend remains observable.

As shown in Figure 15, most of the biogas was produced during the first 7 days, particularly for Okara. This rapid production may be attributed to the pre-treatment done to the substrates, and to their readily biodegradable organic matter. In contrast, yam peels showed slower microbial degradation confirming a certain limitation in its properties for efficient biogas production. This is illustrated in Figure 16 where gas production from both substrates peaked in the first two days and declined sharply afterward, especially for yam peels. This rapid start without lagging phase should be attributed to the pre-treated state of the substrates where especially the grinding had helped in breaking the structural bonds and making the degradable compounds accessible for digestion. As a result, upon contact with the inoculum in the AD setup, reactions were effective from the very beginning. The decrease in gas production after, suggests the rapid exhaustion of the easily degradable compounds, leaving only resistant components such as fiber which take time to degrade. Also, increasing the S/I ratio from 0.5 to 0.6 did not significantly improve gas yield, and in some cases slightly reduced it. This implies that sufficient microbial populations were already present at the lower S/I ratio, and excess inoculum may not necessarily enhance performance.

The complex fiber matrix in yam peels could have then been a limitation in its mono-digestion, while Okara may have had less structurally bounded fibers, due to its processing origin where heating and grinding were already involved. Nevertheless, from a broader perspective, the methane yields observed for the two substrates exceed values reported for other West African agro-residues. For example, banana peels have been reported to yield 334.82 mL/g VS (Gbiye et al., 2024) and cassava peels treated with sodium bicarbonate yielded around 327 mL/g VS (Sylvestre Ahou et al., 2021). Thus, Okara stands out as a viable substrate for biogas production. Its energy valorization is a promising path. Yam peels also showed potential, but their performance could be enhanced through co-digestion or other pretreatments.

### **III.2.2.2. Impact of co-digestion on biogas yield**

Co-digesting Okara and yam peels using three mixing ratios at S/I of 0.5 and 0.6, displayed a biogas cumulative yield between 609 and 661 mL/g VS as observed in Figure 17. It goes along with the co-digestion of food waste and rice husk performed by Haider et al., (2015) where 584 mL/g VS at C/N=20 was recorded. In all cases, the higher yield compared to Okara or yam peels' mono-digestion is the first sign of the benefit linked to the co-digestion process. As shown in Figure 23, yam peels as co-substrate to Okara illustrated a modest increase (a maximum of 8.26%). It did not unlock a big new energy pool, but it could have mainly alleviated the risk of potential ammonia stress at high loading, as Okara alone already digested well.



**Figure 23:** Impact of the co-digestion compared to Okara's mono-digestion

From Figure 17 in general, for both S/I ratios, biogas yield increased from 1:3 to 3:1 (Okara:Yam peels mixing ratio). This suggested that Okara contributed significantly to methane potential as shown by mono-digestion tests while yam peels could have helped to balance the carbon-to-nitrogen (C/N) ratio, improving microbial activity. Looking at the production curves, while the rapid biogas production phase in mono-digestion lasted only 2 days, co-digestion extended this period to 5 days. This implied that co-digestion improved substrate utilization and microbial efficiency, likely by balancing the C/N ratio, diluting inhibitory compounds, and enhancing the availability of degradable organic matter.

Overall, the difference between S/I ratios was minimal. This insinuated that using more inoculum (S/I = 0.5) or a bit less inoculum (S/I = 0.6) did not strongly affect the digestion process for most mixing ratios. The higher yields observed at S/I=0.6 for 1:3 and 1:1 mixing ratios may be attributed to the balanced nutrient environment created by the combination of Okara and yam peels, which facilitated microbial digestion even under higher substrate loading. In contrast, 3:1 mix with the highest yield at S/I=0.5 supposed that the higher inoculum amount was more favorable for the process. Mix with higher Okara content may then need more inoculum to avoid problems and achieve the best gas production. For example, Song et al., (2021) who co-digested garden wastes, food wastes and tofu residues remarked an antagonistic effect when tofu residue was superior to 40% in the mix.

High gas production in the first week as displayed in Figure 18 reflected once again the readily biodegradable nature of Okara and yam peels, thanks to the pre-treatment done. The higher yield in the remaining weeks compared to mono-digestion tests implied that co-digestion not only enhanced the initial degradation but also sustained microbial activity over time, likely because of better nutrient balance and synergistic effects between substrates (Mu et al., 2020). In contrast, mono-digestion may have led to nutrient limitations, reducing gas production in

later stages. This highlighted that co-digestion can maintain more stable fermentation dynamics than single-substrate digestion. Figure 19 clearly confirmed the effect of co-digestion in biogas production, showing more trends and a better production rate compared to mono-digestion. Song et al. (2021) experienced the same when they observed more daily methane production peaks (3-4) compared to mono-digestion tests (1-2 peaks).

In general, the co-digestion strategy, especially with Okara dominance, proved effective for enhancing biogas yield. In practice, this improved performance implies that more usable energy can be extracted from the same amount of waste. Even though Okara in the present study was easily digested on its own, it would be advisable to co-digest it in order to mitigate the potential risks of ammonia or volatile fatty acid accumulation, which are characteristic of protein-rich substrates.

### **III.2.3. Environmental benefits of anaerobic digestion and biogas as energy source for cooking**

#### **III.2.3.1. Environmental impact of anaerobic digestion for biogas production**

From the two scenarios presented in Figure 20 for 1kg of wastes, landfilling had the highest impact on climate change ( $5.55 \times 10^{-1}$  kg CO<sub>2</sub>-Eq). This can be explained by the fact that methane, the major gas emitted into the atmosphere on uncontrolled landfills, has 28 times greater global warming potential (GWP) than carbon dioxide. It is in fact the second most important greenhouse gas (GHG) contributor to climate change. This showed how bad unsanitary, and uncontrolled landfills are for the environment and planet. On the other side, instead of releasing this gas directly into the atmosphere, AD enables waste to be broken down in a closed system (biodigester), followed by controlled recovery of the methane produced (contained in biogas) so that it can be put to good use in the production of heat and electricity (Pasciucco et al., 2023).

Landfilling also showed the highest values concerning freshwater and marine ecotoxicity, and marine eutrophication. These landfilling impacts results can be attributed to the formation and migration of leachate, a toxic liquid generated when rainwater infiltrates waste layers. As a result, both organic and inorganic pollutants, including heavy metals, contaminates soil and groundwater or nearby surface water bodies, thereby posing serious risks to aquatic ecosystems (Siddiqua et al., 2022). The findings so far align with trends from Rohrer et al. (2025) who used Environment Footprint (EF) as LCIA method. Their scenario for uncontrolled landfill showed dominant impact for climate change ( $3.05 \times 10^{-1}$  kg CO<sub>2</sub>-Eq), followed by acidification and marine eutrophication. The difference in values can be due to the LCIA method type or the inputted data. Nevertheless, it confirmed the significant burden of landfilling Okara without valorization.

Apart from that, landfilling caused more terrestrial acidification than biogas production via AD. This impact resulting from the deposition of nutrients like nitrogen oxides (NO<sub>x</sub>), ammonia (NH<sub>3</sub>) and sulfur dioxide (SO<sub>2</sub>) on soils causing acidification, is justified by the higher air emissions of these pollutants during landfilling. To finish, landfilling presented higher non-carcinogenic human toxicity, and particulate matter formation, all related to the above-mentioned emissions.

On the other hand, biogas production scenario showed higher values for photochemical oxidant formations (POF). Both scenarios included transportation, related to nitrogen oxides (NO<sub>x</sub>) and non-methane volatile organic compounds (NMVOCs) emissions, with landfilling even requiring longer distances (25 km vs. 10 km for AD). However, the higher POF score of AD may be associated to additional diesel-intensive steps such as biomass grinding which emits significant amounts of NO<sub>x</sub>. In fact, the nitrogen in Okara and yam peels does not generate NO<sub>x</sub> during digestion, since AD is a biological process. So, the emissions are linked to machinery and transport rather than the substrates. In addition, small amounts of ammonia (NH<sub>3</sub>) and Nitrous oxide (N<sub>2</sub>O) from digestate storage can further contribute to POF if not well managed (Seghetta et al., 2022). It points out that AD is clearly advantageous in terms of climate change mitigation and resource recovery, but its local air pollution impacts call for targeted measures like siting AD plants close to feedstock, covering digestate storage, and adopting cleaner grinding technology. The higher burden observed for carcinogenic human toxicity may also be attributed to the same factors (grinding and frequent diesel trips which emit trace levels of carcinogenic compounds).

With addressing these impacts, AD for biogas recovery stands out as the best scenario for waste treatment as the landfilling scenario presents many environmental impacts. Adopting that controlled waste treatment method will reduce yearly environmental burdens in many aspects, such as terrestrial acidification (88.99% reduction), climate change (70.80% reduction), particulate matter formation (74.27%), as well as freshwater and marine ecotoxicity. A clean environment, better air quality, freshwater and marine preservation are among all, the positive outcomes on the environment.

### **III.2.3.2. Impact of biogas as alternative for cooking**

Biogas, the first outcome of AD process, can be use as energy source for cooking. The data of its environmental impacts, as well as for firewood for cooking needs are presented in Appendix G and Figure 21. Between the two processes, firewood combustion showed the highest climate change impact ( $2.22 \times 10^{-1}$  kg CO<sub>2</sub>-Eq), terrestrial ecotoxicity, carcinogenic human toxicity, and photochemical oxidant formations. The impacts were not limited to that, but terrestrial acidification, marine ecotoxicity, and particulate matter formation are other higher impacts from firewood combustion compared to biogas combustion. This can be explained by the fact that biomass burning for cooking in west Africa setting is still at the traditional level where the

combustion is uncontrolled, mostly causing incomplete combustion linked with the emission of key atmospheric pollutants such as carbon monoxide (CO), hydrocarbons (HC), and particulate matter (dust) (Balmes, 2019). The same author explained that particles generated from wood combustion contain high concentrations of polycyclic aromatic hydrocarbons (PAHs), which are associated with health risks due to their carcinogenic and mutagenic properties. Moreover, the emissions of carbon monoxide (CO) pose serious health hazards: CO is highly toxic because it binds strongly to hemoglobin, impairing oxygen transport in the blood and possibly causing rapid death in cases of high exposure, especially during ignition phases or inefficient combustion (Idowu et al., 2023). The release of unburned hydrocarbons and dust, contribute to atmospheric pollution and can participate in photochemical reactions leading to the formation of complex, potentially harmful secondary pollutants. The presence of these pollutants can also contribute to smog formation. Then generally, firewood use was highly unsustainable, as it contributes directly to deforestation, indoor air pollution, and greenhouse gas emissions, thereby worsening both climate change and public health issues.

As for biogas combustion, it rather displayed higher freshwater ecotoxicity, and non-carcinogenic human toxicity. This last category is mainly influenced by emissions of substances such as heavy metals and inorganic compounds (NH<sub>3</sub>, H<sub>2</sub>S, NO<sub>2</sub>, etc.), which can cause chronic health effects without being directly linked to cancer. In the case of biogas, small amounts of these pollutants may be released during combustion or through leakages, especially since raw biogas (not purified) was considered (Werkneh, 2022). These negative signals did not contradict the broader benefits of switching away from firewood; they just highlighted the importance of using improved stove technologies and gas-cleaning systems to minimize emissions. Promoting these improvements would ensure that biogas systems not only displace firewood use but also deliver the maximum possible environmental gains.

### **III.2.3.3. Overall environmental impact of anaerobic digestion pathway**

The life cycle assessment (LCA) of the anaerobic digestion (AD) scenario demonstrated that when accounting for avoided burdens from firewood substitution and digestate use as biofertilizer, the system delivered net environmental benefits across most impact categories. As shown in Figure 22, avoided burdens exceeded baseline AD impacts in categories such as terrestrial acidification, freshwater ecotoxicity, and human toxicity, leading to negative net values. This means that the credits outweigh the burdens and yield a net environmental benefit. These findings align with other studies that highlight the crucial role of substitution credits in improving the environmental profile of AD systems (Balcioglu et al., 2022).

The most remarkable reductions were observed for particulate matter (PM) and especially photochemical oxidant formation (POF), where avoided burdens reached up to nearly 1000% compared to baseline impacts. This strong effect reflects the replacement of firewood combustion, which is a major source of NO<sub>x</sub>, CO, and particulate matter in traditional cooking

practices as discussed above. In the West African context where reliance on wood fuels contributes significantly to indoor air pollution and related health problems, this result underlines the potential of AD to improve both environmental performance and public health outcomes.

On the other hand, categories such as climate change (CC) and freshwater ecotoxicity (FET) showed smaller net gains. In these cases, the avoided burdens only partially compensated for the AD-related emissions. Thus, while AD presents clear advantages over landfilling and firewood combustion, further improvements in the system are necessary to optimize performance.

Overall, the findings indicate that accounting for avoided burdens turns AD from merely lower-impact into impact-avoiding in key impact categories. It confirmed that AD is not only a waste management solution but also a strategy for sustainable energy and environmental protection in West Africa. The significant avoided burdens highlighted its potential to mitigate deforestation by reducing firewood demand, while simultaneously lowering health-damaging emissions from traditional biomass use (Mmusi et al., 2021). This dual benefit (environmental protection and human health improvement) strongly supports the promotion of AD technologies as part of clean cooking and waste valorization strategies in the region.

#### **III.2.4. Economic assessment of the case study**

The economic analysis of the 30 m<sup>3</sup> biodigester showed promising results in Table 4, with a positive Net Present Value (NPV) of \$56,738.17, a Benefit–Cost Ratio (BCR) of 1.64, and a Payback Period (PP) of 3.20 years for a 20-year project lifetime. These indicators suggest that the investment is financially viable and can be undertaken under the current assumptions, as the project is expected to generate more benefits than costs over its lifetime. Compared to previous works, these values are lower in profitability. For example, Mohammed et al. (2017) reported a much higher BCR of 5.19 and a PP of 5 years for a large-scale 9000 m<sup>3</sup> biodigester in Ghana (with a discount rate of 23%). Similarly, Gabisa & Gheewala (2019) found a BCR of 2.0 and a PP of 2.38 years for a small 8 m<sup>3</sup> household digester in Ethiopia (discount rate of 4%).

The difference between these results and the present case study can be explained by several factors. First, economies of scale play a major role. Very large digesters like 9000 m<sup>3</sup> dilute fixed costs and achieve higher gas output per unit investment, which improves financial indicators. Conversely, household-scale digesters can benefit from low-cost construction and direct substitution of firewood, giving quick payback times. A medium-scale digester of 30 m<sup>3</sup>, like in this study, often falls in between, large enough to require significant investment, but too small to achieve strong economies of scale.

Secondly, local assumptions such as discount rate, feedstock availability, fuel substitution price, and labor costs strongly influence results. For example, the very high BCR in Mohammed et al. (2017) was partly due to using a high discount rate (23%) and stable feedstock supply from agro-industrial residues. In this study, the relatively modest BCR (1.64) are realistic with yam peels' handling, transport and grinding, impacting costs, while the market value of biogas and biofertilizer may not yet be fully recognized.

The Levelized Cost of Biogas (LCOB) was estimated at 0.89 \$/m<sup>3</sup>, which is higher than the 0.25 \$/m<sup>3</sup> reported for upgraded biogas in Southwestern Nigeria (Ogundari, 2023). This difference may be linked to variations in system design, feedstock supply chains, and local cost structures. When considering the cost of useful cooking energy, the analysis showed a net cost of 0.26 \$/kWh for biogas compared to 0.31 \$/kWh for firewood. This indicates that biogas is slightly cheaper than firewood. However, this comparison does not account for the significant hidden costs of firewood use, including the time burden of fuel collection and the environmental and health impacts associated with deforestation and indoor air pollution from traditional biomass use, which are significant in the West African context (Bede-Ojimadu & Orisakwe, 2020). With that, biogas becomes clearly preferable as cooking fuel. The daily production of 28.31 m<sup>3</sup> of biogas which represents approximately 168.88 kg of offset firewood, can meet a considerable amount of the cooking fuel needs by the women producing Tofu. This will therefore reduce reliance on unsustainable firewood harvesting, while providing cleaner energy access.

Overall, despite an LCOB above some literature values, the useful-energy cost of biogas is marginally lower than firewood, and the combined long-term economic and environmental benefits support biodigester deployment. For agro-industries, such as tofu producers and yam processors, biogas production represents a strategic opportunity to reduce cooking fuel expenditures and create new value chains in waste collection, digester operation and maintenance, and digestate utilization. Future research should integrate externalities such as avoided health expenditures, time savings from firewood collection, and carbon credits from emissions reductions, which could further improve the economic attractiveness of the system in West Africa.

### **III.3. Recommendations**

For further works, it is recommended to implement a pilot-scale biodigester directly at tofu production sites to validate the technical, environmental, and economic performance of the system under real operational conditions. This step would make it possible to assess parameters such as feeding frequency, process stability, and maintenance requirements, which cannot be

fully captured under laboratory conditions. Furthermore, analyzing the composition and quality of the biogas produced would provide valuable insights for optimizing gas utilization and ensuring compliance with clean energy standards.

In parallel, stakeholders and decision-makers should explore the integration of anaerobic digestion units within existing agro-industrial infrastructures, particularly in areas with abundant and continuous supply of feedstock such as Okara, yam peels, and other processing residues. Such integration would not only enhance waste management efficiency but also promote decentralized renewable energy generation, contributing to local energy independence and reduced reliance on traditional biomass. Finally, it is recommended to engage local authorities, private investors, and development partners to support the deployment of these systems, ensuring their long-term viability through adequate financing mechanisms, capacity building, and public awareness programs.

## Conclusion and Perspectives

This research was conducted in the context of growing energy insecurity, environmental degradation, and waste management challenges in West Africa, particularly in Benin and Togo where soybean processing generates large amounts of Okara. The findings demonstrate that co-digestion of Okara and yam peels is a viable strategy for sustainable waste valorization. The synergy between the two substrates improved biogas yields, especially at the 3:1 ratio and lower S/I ratio, showcasing the efficiency of resource recovery through anaerobic digestion. The readily biodegradable nature of the substrates, supported by pre-treatment, played a crucial role in the favorable results observed.

From an environmental perspective, the comparison between landfilling and AD underscored the benefits of adopting biodigesters. AD not only avoids methane emissions associated with uncontrolled decomposition but also delivers additional credits by displacing inorganic fertilizers through digestate use and reducing deforestation pressures through firewood substitution. The economic evaluation revealed that the useful energy cost of biogas was competitive with firewood. When broader environmental and social externalities are considered, biogas emerges as the more suitable option.

Overall, this work highlights that integrating bio-digestion into local agro-industrial value chains offers a promising strategy for waste valorization, renewable energy generation, soil health improvement, and climate change mitigation in Togo and Benin. Future research should focus on scaling up co-digestion systems, assessing long-term operational performance, and quantifying social benefits such as time savings and health improvements. These efforts will be crucial for advancing clean cooking solutions and promoting a circular bioeconomy in the region.

Based on the promising results of this study, future research should focus on continuous anaerobic digestion (AD) systems, which more accurately represent real operational dynamics than batch experiments. These reactors enable steady feeding and gas production, offering valuable insights into long-term stability, microbial adaptation, and process control. Studying such systems would also support the optimization of key operational parameters such as hydraulic retention time (HRT), organic loading rate (OLR), and mixing efficiency which are critical factors influencing biogas yield and quality. Integrating continuous AD into future investigations would thus provide a more realistic understanding of industrial-scale performance and the scalability of Okara and yam peels co-digestion in West African contexts. Furthermore, complementing the current economic assessment with social and technical feasibility analyses at community or industrial scale would help assess social acceptance, operational challenges, and the overall sustainability of the process. Finally, the outcomes of

this research could serve as a decision-support tool for policymakers, promoting the integration of anaerobic digestion into national waste management and renewable energy strategies to advance a low-carbon and circular economy.

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# APPENDIXES

## Appendix A: Ultimate analysis data

	<b>Okara</b>	<b>Yam peels</b>	<b>Units</b>
<b>Carbon (C)</b>	49.1	42.7	%w
<b>Hydrogen (H)</b>	7.16	6.32	%w
<b>Nitrogen (N)</b>	3.60	0.812	%w
<b>Oxygen (O)</b>	36.6	43.8	%w
<b>Sulfur (S)</b>	0.11	0.06	%w
<b>Potassium (K)</b>	0.35	1.91	%w
<b>Phosphorus (P)</b>	0.20	0.21	%w
<b>Calcium (Ca)</b>	0.65	0.12	%w
<b>Sodium (Na)</b>	0.26	0.018	%w
<b>Nickel (Ni)</b>	0.90	2.5	%w
<b>Iron (Fe)</b>	0.054	0.035	%w
<b>Aluminum (Al)</b>	0.019	0.045	%w
<b>Magnesium (Mg)</b>	0.15	0.084	%w
<b>Zinc (Zn)</b>	22.9	18.8	mg/kg
<b>Copper (Cu)</b>	4.74	8.60	mg/kg
<b>Lead (Pb)</b>	<0.31	0.35	mg/kg
<b>Manganese (Mn)</b>	24.5	33.5	mg/kg
<b>Chromium (Cr)</b>	2.28	5.73	mg/kg
<b>Cobalt (Co)</b>	<0.21	0.41	mg/kg
<b>C/N ratio</b>	13.64	52.59	-
<b>Gross Calorific Value</b>	20.535	17.239	MJ/kg
<b>Net Calorific Value</b>	18.984	15.862	MJ/kg

%w: percent by weight, on dry basis

## Appendix B: Settings for biogas tests

### ❖ Parameters of mono-digestion

Reactors N°	S/I	Substrates	Quantity (g)
M1-1	<b>0.5</b>	Okara	5.18
M1-2		Yam peels	5.27
B1		Inoculum / Blank	342.86
M2-1	<b>0.6</b>	Okara	5.18
M2-2		Yam peels	5.27
B2		Inoculum / Blank	285.71
C		Cellulose	3

### ❖ Parameters of co-digestion

Reactors N°	S/I	Mixing ratios	Okara (g)	Yam peels (g)	Inoculum (g)
C1-1	<b>0.5</b>	1:3	1.29	3.95	207.34
C1-2		1:1	2.59	2.63	207.34
C1-3		3:1	3.88	1.32	207.34
C2-1	<b>0.6</b>	1:3	1.29	3.95	172.79
C2-2		1:1	2.59	2.63	172.79
C2-3		3:1	3.88	1.32	172.79

## Appendix C: Biogas batch results

### 1. Mono-digestion

❖ Cumulative biogas yield (mL/g VS)

Days	Blank	Yam peels S/I=0.5	Okara S/I=0.5	Cellulose	Yam peels S/I=0.6	Okara S/I=0.6
0	0.00	0.00	0.00	0.00	0.00	0.00
1	8.04	232.45	196.68	287.08	225.29	197.61
2	16.54	354.53	371.00	498.59	353.60	364.72
3	24.38	385.41	457.23	577.25	384.16	463.45
4	32.30	403.20	506.85	637.24	400.10	509.00
5	40.58	414.43	535.22	662.76	409.84	533.98
6	49.50	421.89	552.45	672.69	416.28	548.53
7	57.71	429.40	564.77	679.24	422.12	557.50
8	64.25	436.40	574.35	685.51	428.04	565.41
9	70.07	441.56	581.15	690.78	433.42	572.21
10	75.41	446.16	586.62	695.16	436.72	577.35
11	80.31	449.66	591.01	699.20	439.41	581.05
12	85.41	452.81	594.04	701.72	441.48	582.70
13	89.98	455.34	596.40	705.01	443.39	584.67
14	94.20	458.00	599.00	707.23	445.12	585.99
15	97.86	460.10	601.10	709.51	446.70	587.35
16	101.81	461.14	602.38	710.55	447.43	587.81
17	105.19	462.61	603.50	711.53	448.29	588.24
18	108.36	463.16	604.10	711.54	448.83	588.58
19	111.28	463.36	604.89	712.04	449.38	588.91
20	114.01	463.45	605.27	712.05	450.27	589.38

<b>21</b>	117.08	463.88	605.24	711.89	450.61	589.57
<b>22</b>	119.55	463.93	605.52	711.98	451.00	590.03
<b>23</b>	121.99	464.15	605.80	712.29	451.59	590.62
<b>24</b>	124.20	464.86	606.75	711.98	451.83	590.93
<b>25</b>	126.38	465.52	607.28	711.66	451.70	590.95
<b>26</b>	128.37	465.82	607.88	711.43	452.14	591.24
<b>27</b>	130.47	466.13	608.30	711.48	451.73	591.54
<b>28</b>	132.30	466.56	608.97	712.09	452.02	591.90
<b>29</b>	133.84	467.89	609.95	712.51	452.52	592.25
<b>30</b>	135.19	468.82	610.58	713.25	453.28	592.73

❖ Weekly specific biogas production (mL/g VS)

<b>Period</b>	<b>Okara S/I=0.5</b>	<b>Okara S/I=0.6</b>	<b>Yam peels S/I=0.5</b>	<b>Yam peels S/I=0.6</b>
<b>0-7 days</b>	564.77	557.50	429.40	422.12
<b>8-14 days</b>	34.24	28.49	28.60	23.00
<b>15-21 days</b>	6.24	3.58	5.88	5.49
<b>22-30 days</b>	5.34	3.16	4.93	2.67

2. Co-digestion

❖ Cumulative biogas yield (mL/g VS)

<b>Day</b>	<b>Blank</b>	<b>Cellulose</b>	<b>Ratio 1:3 S/I=0.5</b>	<b>Ratio 1:1 S/I=0.5</b>	<b>Ratio 3:1 S/I=0.5</b>	<b>Ratio 1:3 S/I=0.6</b>	<b>Ratio 1:1 S/I=0.6</b>	<b>Ratio 3:1 S/I=0.6</b>
<b>0</b>	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
<b>1</b>	1.56	34.37	112.56	102.52	83.16	128.61	113.45	87.57
<b>2</b>	3.80	228.01	251.81	239.83	215.54	282.71	267.10	228.06
<b>3</b>	6.04	396.36	342.11	335.76	314.39	394.19	386.18	348.44

<b>4</b>	8.08	506.15	438.65	438.76	423.26	487.31	491.20	463.46
<b>5</b>	10.90	582.89	502.73	511.88	515.06	518.52	535.28	518.09
<b>6</b>	14.26	631.27	522.02	537.66	550.67	537.59	560.77	547.55
<b>7</b>	18.16	662.81	536.68	555.73	573.40	554.31	577.22	567.51
<b>8</b>	23.68	679.13	545.20	566.59	587.28	563.90	584.82	577.42
<b>9</b>	28.87	682.51	550.27	572.54	593.13	567.63	588.30	580.79
<b>10</b>	32.36	685.96	556.09	578.70	598.65	572.22	593.17	586.02
<b>11</b>	34.27	691.71	561.22	584.27	603.98	577.95	599.07	591.73
<b>12</b>	36.01	693.27	565.69	589.11	609.10	583.11	605.06	597.42
<b>13</b>	38.42	697.00	571.01	594.45	614.81	588.44	611.51	603.68
<b>14</b>	40.49	699.82	574.59	598.19	619.31	591.80	615.58	608.28
<b>15</b>	42.07	701.85	577.91	601.42	623.10	594.72	618.80	611.79
<b>16</b>	43.77	704.23	580.75	604.37	626.47	597.34	621.77	614.34
<b>17</b>	45.18	706.62	583.34	606.80	629.18	599.65	624.79	617.06
<b>18</b>	45.84	708.11	585.75	608.92	631.99	602.68	627.99	620.44
<b>19</b>	46.67	707.96	587.61	610.90	634.52	604.90	630.38	623.01
<b>20</b>	47.54	708.50	589.61	612.55	637.05	607.03	632.45	625.50
<b>21</b>	49.41	708.65	591.83	614.48	639.94	609.25	634.85	628.25
<b>22</b>	50.28	709.54	593.83	616.18	642.47	611.14	636.50	630.85
<b>23</b>	51.28	710.43	595.75	618.16	644.79	612.97	638.14	633.45
<b>24</b>	51.90	711.69	597.69	620.01	647.06	614.83	639.87	635.96
<b>25</b>	52.15	712.72	599.45	621.82	649.01	616.48	641.70	638.32
<b>26</b>	52.52	713.64	601.19	623.56	650.82	617.82	643.28	640.07
<b>27</b>	53.52	713.59	603.59	625.60	653.41	619.10	644.92	641.83
<b>28</b>	54.14	714.97	606.00	628.13	655.89	620.54	646.29	643.09
<b>29</b>	54.60	716.11	607.82	630.53	658.71	621.78	647.71	644.20

<b>30</b>	54.80	716.81	609.10	632.34	661.00	622.80	648.72	645.10
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❖ Weekly specific biogas production (mL/g VS)

<b>Days</b>	<b>Ratio 1:3 S/I=0.5</b>	<b>Ratio 1:1 S/I=0.5</b>	<b>Ratio 3:1 S/I=0.5</b>	<b>Ratio 1:3 S/I=0.6</b>	<b>Ratio 1:1 S/I=0.6</b>	<b>Ratio 3:1 S/I=0.6</b>
<b>0-7 days</b>	536.68	555.73	573.40	554.31	577.22	567.51
<b>8-14 days</b>	37.90	42.46	45.91	37.48	38.35	40.77
<b>15-21 days</b>	17.25	16.28	20.63	17.46	19.27	19.97
<b>21-30 days</b>	17.27	17.86	21.05	13.55	13.88	16.85

## Appendix D: Data manually input for environmental analysis

Functional unit: Okara+Yam peels with 25%DM.

### 1. Landfill scenario

	Unit	Value
<b><i>Input</i></b>		
Okara+Yam peels	kg	1
Transport	tkm	25
Landfill area	m <sup>2</sup>	0.00357
<b><i>Output</i></b>		
CH <sub>4</sub> emissions	kg	0.0169
NH <sub>3</sub> emissions	kg	6.8518.10 <sup>-5</sup>

### 2. Anaerobic digestion scenario

	Unit	Value
<b><i>Input</i></b>		
Okara+Yam peels	kg	1
Transport	tkm	10
Electricity (grinding)	kWh	0.00328
Energy GCV in biomass	MJ	4.3732
<b><i>Output</i></b>		
Biogas	m <sup>3</sup>	0.13043
Digestate	kg	0.1121
CH <sub>4</sub> emissions (non-fossil)	kg	0.0045

### ❖ Estimated parameters for co-digestion

Average parameters	Value
MC (%)	78.41
TS (%)	21.59
VS (%)	96.16
AC (%)	03.84

### 3. Biogas combustion

	Unit	Value
<b><i>Input</i></b>		
Biogas	m <sup>3</sup>	0.13043
<b><i>Output</i></b>		
Heat	MJ	1.6036
CO <sub>2</sub> emissions	kg	0.1307
CH <sub>4</sub> emissions	kg	9.1408.10 <sup>-5</sup>
CO emissions	kg	0.00018
N <sub>2</sub> O emissions	kg	8.6597.10 <sup>-6</sup>

### 4. Firewood combustion

	Unit	Value
<b><i>Input</i></b>		
Wood	kg	0.7799
<b><i>Output</i></b>		
Heat	MJ	1.6036
CO <sub>2</sub> emissions	kg	5.8037
CH <sub>4</sub> emissions	kg	0.0065
CO emissions	kg	0.1727
N <sub>2</sub> O emissions	kg	4.6910.10 <sup>-5</sup>

### 5. Inorganic fertilizers

	Unit	Value
<b><i>Input</i></b>		
Nitrogen fertilizer	kg	0.0017
Phosphorus fertilizer	kg	0.00091
Potassium fertilizer	kg	0.0012

## Appendix E: Results of the Environmental Analysis using OpenLCA Software

### 1. Environmental impact of landfilling and anaerobic digestion (AD) for biogas production

<b>Impact category</b>	<b>Reference unit</b>	<b>Landfilling</b>	<b>AD</b>
Acidification: terrestrial	kg SO <sub>2</sub> -Eq	1.73 x 10 <sup>-4</sup>	1.90 x 10 <sup>-5</sup>
Climate change	kg CO <sub>2</sub> -Eq	5.55 x 10 <sup>-1</sup>	1.62 x 10 <sup>-1</sup>
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	7.48 x 10 <sup>-3</sup>	2.02 x 10 <sup>-3</sup>
Ecotoxicity: marine	kg 1,4-DCB-Eq	1.03 x 10 <sup>-2</sup>	2.68 x 10 <sup>-3</sup>
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	7.70 x 10 <sup>-2</sup>	5.37 x 10 <sup>-2</sup>
Energy resources: non-renewable, fossil	kg oil-Eq	1.31 x 10 <sup>-3</sup>	1.13 x 10 <sup>-3</sup>
Eutrophication: freshwater	kg P-Eq	4.42 x 10 <sup>-5</sup>	1.99 x 10 <sup>-5</sup>
Eutrophication: marine	kg N-Eq	8.39 x 10 <sup>-4</sup>	1.29 x 10 <sup>-6</sup>
Human toxicity: carcinogenic	kg 1,4-DCB-Eq	1.06 x 10 <sup>-3</sup>	2.84 x 10 <sup>-3</sup>
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	2.44 x 10 <sup>-1</sup>	4.72 x 10 <sup>-2</sup>
Ionizing radiation	kBq Co-60-Eq	4.22 x 10 <sup>-5</sup>	6.55 x 10 <sup>-5</sup>
Land use	m <sup>2</sup> *a crop-Eq	2.80 x 10 <sup>-3</sup>	1.59 x 10 <sup>-4</sup>
Material resources: metals/minerals	kg Cu-Eq	6.61 x 10 <sup>-5</sup>	9.31 x 10 <sup>-5</sup>
Ozone depletion	kg CFC-11-Eq	6.92 x 10 <sup>-10</sup>	4.11 x 10 <sup>-7</sup>
Particulate matter formation	kg PM2.5-Eq	2.95 x 10 <sup>-5</sup>	7.58 x 10 <sup>-6</sup>
Photochemical oxidant formation: human health	kg NO <sub>x</sub> -Eq	2.63 x 10 <sup>-5</sup>	3.07 x 10 <sup>-5</sup>
Photochemical oxidant formation: terrestrial ecosystems	kg NO <sub>x</sub> -Eq	2.72 x 10 <sup>-5</sup>	3.14 x 10 <sup>-5</sup>
Water use	m <sup>3</sup>	7.70 x 10 <sup>-6</sup>	7.37 x 10 <sup>-5</sup>

## 2. Environmental impact of firewood and biogas combustion

<b>Impact category</b>	<b>Reference unit</b>	<b>Firewood combustion</b>	<b>Biogas combustion</b>
Acidification: terrestrial	kg SO <sub>2</sub> -Eq	$7.78 \times 10^{-4}$	$6.36 \times 10^{-4}$
Climate change	kg CO <sub>2</sub> -Eq	$2.22 \times 10^{-1}$	$5.38 \times 10^{-2}$
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	$2.47 \times 10^{-4}$	$3.66 \times 10^{-3}$
Ecotoxicity: marine	kg 1,4-DCB-Eq	$5.59 \times 10^{-3}$	$2.78 \times 10^{-3}$
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	$4.70 \times 10^{-1}$	$1.37 \times 10^{-1}$
Energy resources: non-renewable, fossil	kg oil-Eq	0	$6.96 \times 10^{-3}$
Eutrophication: freshwater	kg P-Eq	$1.08 \times 10^{-5}$	$1.44 \times 10^{-5}$
Eutrophication: marine	kg N-Eq	0	$1.16 \times 10^{-4}$
Human toxicity: carcinogenic	kg 1,4-DCB-Eq	$1.24 \times 10^{-2}$	$5.82 \times 10^{-3}$
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	$2.48 \times 10^{-2}$	$8.68 \times 10^{-2}$
Ionising radiation	kBq Co-60-Eq	0	$8.26 \times 10^{-4}$
Land use	m <sup>2</sup> *a crop-Eq	0	$6.21 \times 10^{-2}$
Material resources: metals/minerals	kg Cu-Eq	0	$5.36 \times 10^{-4}$
Ozone depletion	kg CFC-11-Eq	$4.83 \times 10^{-7}$	$5.64 \times 10^{-7}$
Particulate matter formation	kg PM2.5-Eq	$4.11 \times 10^{-4}$	$1.28 \times 10^{-4}$
Photochemical oxidant formation: human health	kg NO <sub>x</sub> -Eq	$2.01 \times 10^{-3}$	$1.66 \times 10^{-4}$
Photochemical oxidant formation: terrestrial ecosystems	kg NO <sub>x</sub> -Eq	$2.01 \times 10^{-3}$	$1.70 \times 10^{-4}$
Water use	m <sup>3</sup>	$5.75 \times 10^{-4}$	$1.05 \times 10^{-2}$

### 3. Emissions from inorganic fertilizers

<b>Impact category</b>	<b>Nitrogen fertilizer</b>	<b>Phosphorus fertilizer</b>	<b>Potassium fertilizer</b>
Acidification: terrestrial	$3.93 \times 10^{-5}$	$2.26 \times 10^{-5}$	$2.28 \times 10^{-5}$
Climate change	$1.41 \times 10^{-2}$	$2.44 \times 10^{-3}$	$2.47 \times 10^{-3}$
Ecotoxicity: freshwater	$5.87 \times 10^{-4}$	$5.48 \times 10^{-4}$	$5.90 \times 10^{-4}$
Ecotoxicity: marine	$7.61 \times 10^{-4}$	$7.05 \times 10^{-4}$	$7.59 \times 10^{-4}$
Ecotoxicity: terrestrial	$2.47 \times 10^{-2}$	$2.38 \times 10^{-2}$	$2.75 \times 10^{-2}$
Energy resources: non-renewable, fossil	$2.59 \times 10^{-3}$	$6.25 \times 10^{-4}$	$6.14 \times 10^{-4}$
Eutrophication: freshwater	$2.15 \times 10^{-6}$	$2.76 \times 10^{-6}$	$1.23 \times 10^{-6}$
Eutrophication: marine	$8.72 \times 10^{-7}$	$1.23 \times 10^{-7}$	$7.82 \times 10^{-8}$
Human toxicity: carcinogenic	$1.72 \times 10^{-3}$	$8.92 \times 10^{-4}$	$1.09 \times 10^{-3}$
Human toxicity: non-carcinogenic	$1.18 \times 10^{-2}$	$1.20 \times 10^{-2}$	$1.18 \times 10^{-2}$
Ionising radiation	$1.35 \times 10^{-4}$	$1.58 \times 10^{-4}$	$8.83 \times 10^{-5}$
Land use	$1.55 \times 10^{-4}$	$1.22 \times 10^{-4}$	$1.57 \times 10^{-4}$
Material resources: metals/minerals	$1.01 \times 10^{-4}$	$1.45 \times 10^{-4}$	$9.33 \times 10^{-5}$
Ozone depletion	$1.86 \times 10^{-7}$	$8.71 \times 10^{-10}$	$8.53 \times 10^{-10}$
Particulate matter formation	$1.11 \times 10^{-5}$	$9.94 \times 10^{-6}$	$8.32 \times 10^{-6}$
Photochemical oxidant formation: human health	$1.78 \times 10^{-5}$	$9.19 \times 10^{-6}$	$9.29 \times 10^{-6}$
Photochemical oxidant formation: terrestrial ecosystems	$1.88 \times 10^{-5}$	$9.41 \times 10^{-6}$	$9.60 \times 10^{-6}$
Water use	$1.30 \times 10^{-4}$	$3.47 \times 10^{-5}$	$3.91 \times 10^{-5}$

4. Net impact of anaerobic digestion pathway (impact considering the avoided burdens)

<b>Impact category</b>	<b>Reference unit</b>	<b>AD Plant impact</b>	<b>Net AD Plant impact</b>
Acidification: terrestrial	kg SO <sub>2</sub> -Eq	6.55 x 10 <sup>-4</sup>	-2.08 x 10 <sup>-2</sup>
Climate change	kg CO <sub>2</sub> -Eq	2.16 x 10 <sup>-1</sup>	-2.48 x 10 <sup>-2</sup>
Ecotoxicity: freshwater	kg 1,4-DCB-Eq	5.68 x 10 <sup>-3</sup>	3.70 x 10 <sup>-3</sup>
Ecotoxicity: marine	kg 1,4-DCB-Eq	5.47 x 10 <sup>-3</sup>	-2.35 x 10 <sup>-3</sup>
Ecotoxicity: terrestrial	kg 1,4-DCB-Eq	1.91 x 10 <sup>-1</sup>	-3.55 x 10 <sup>-1</sup>
Energy resources: non-renewable, fossil	kg oil-Eq	8.09 x 10 <sup>-3</sup>	4.26 x 10 <sup>-3</sup>
Eutrophication: freshwater	kg P-Eq	3.40 x 10 <sup>-5</sup>	1.70 x 10 <sup>-5</sup>
Eutrophication: marine	kg N-Eq	1.17 x 10 <sup>-4</sup>	1.16 x 10 <sup>-4</sup>
Human toxicity: carcinogenic	kg 1,4-DCB-Eq	8.66 x 10 <sup>-3</sup>	-7.44 x 10 <sup>-3</sup>
Human toxicity: non-carcinogenic	kg 1,4-DCB-Eq	1.34 x 10 <sup>-1</sup>	7.37 x 10 <sup>-2</sup>
Ionising radiation	kBq Co-60-Eq	8.92 x 10 <sup>-4</sup>	5.10 x 10 <sup>-4</sup>
Land use	m <sup>2</sup> *a crop-Eq	6.23 x 10 <sup>-2</sup>	6.18 x 10 <sup>-2</sup>
Material resources: metals/minerals	kg Cu-Eq	6.29 x 10 <sup>-4</sup>	2.90 x 10 <sup>-4</sup>
Ozone depletion	kg CFC-11-Eq	1.00 x 10 <sup>-6</sup>	0
Particulate matter formation	kg PM2.5-Eq	1.36 x 10 <sup>-4</sup>	-3.05 x 10 <sup>-4</sup>
Photochemical oxidant formation: human health	kg NO <sub>x</sub> -Eq	1.97 x 10 <sup>-4</sup>	-1.85 x 10 <sup>-3</sup>
Photochemical oxidant formation: terrestrial ecosystems	kg NO <sub>x</sub> -Eq	2.01 x 10 <sup>-4</sup>	-1.85 x 10 <sup>-3</sup>
Water use	m <sup>3</sup>	1.05 x 10 <sup>-2</sup>	9.77 x 10 <sup>-3</sup>