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A GIS-BASED ASSESSMENT OF BIOHYDROGEN PRODUCTION POTENTIAL FROM AGRICULTURE CROP RESIDUES IN LIBERIA

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DEDICATION

I like to dedicate this Thesis to my lovely brothers (Nuah Y. Teah, Kwatolbor K. Teah, and Bouker Teah) and Sisters (Zlanner N. Teah and Matay Teah) for their understanding when they missed my presence as an elderly brother while I was busy undergoing my study.

I am gratified to sincerely dedicate this Thesis to my wife Mrs. Duoly D. Teah for her sincere time, support, and encouragement that she provided to me while away from home undergoing this study. My sincere delight goes to my parents Mr. and Mrs. Moses G. Teah whose valuable guidance and support have reached me this far from my childhood till now.

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I also appreciate the coordinator of the H_2 Graduate School Program (GSP) in Lome, Togo for the guidance throughout to the completion of this Thesis paper.

DECLARATION BY RESEARCHER

I, Teahtay TEAH, hereby declare that this Thesis paper; Title: **A GIS-based Assessment of biohydrogen production potential from agriculture crop residues in Liberia** is my original work and has not been submitted for the award of a degree in any other University or college. Additionally, I certify that the thesis I submitted was my own work and that I only used materials and reference sources that were approved.

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Signed: ___________________________________Date: _________________________

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Abstract

As the globe is moving toward the use of renewable energy sources in place of fossil fuels, Liberia as a developing nation has huge agricultural crop residues that can be valorized. Over 70% of the population (mainly in rural areas) provides informal employment through agriculture activities. Therefore, a lot of crop residues are generated from these activities and most of them are not used for energy purposes. In this regard, it can promote the use of agricultural crop residues for energy generation. This study explores the energy potential of the crop residues generated by Rice, Cassava, Banana, Sugar cane, Cocoa, Oil palm, and Plantain. The obtained data were integrated into a geographic information system (GIS) to provide spatial distribution results.

Nevertheless, several crop residues have competing uses such as livestock feeding and soil rejuvenation. It was gathered that the surplus residue potential revealed about 1,204, 033 t/yr (55.4% of gross) could be generated from gross crop residue.

The estimated annual bioenergy of 20, 276 TJ/yr or 81,430 Tons of biohydrogen potential from surplus crop residue with Nimba (23,143 Tons) producing the highest amongst the 15 counties. Biohydrogen happens to be the most efficient and cleanest form of energy which is produced through the process of dark fermentation.

Also, the total potential of electricity generation from all the sources is estimated to be about 5,632 GWh, representing approximately twenty times Liberia's total electricity production of 2021; implying that biomass sources could significantly contribute towards meeting the future energy requirement of the country.

Therefore, the information generated in this study is expected to aid a decentralized crop residue-based energy planning and policy by the counties, which would positively influence the overall renewable energy growth in Liberia.

Keywords: Liberia; Biohydrogen potential; Agriculture crop residue; Surplus residue; GIS

Title: Evaluation à base du SIG du potentiel de production de biohydrogène à partir des residus de cultures agricoles au Liberia.

Résumé

Alors que le monde s'oriente de plus en plus vers l'utilisation de sources d'énergie renouvelables à la place des combustibles fossiles, le Libéria, en tant que pays en développement, dispose d'énormes quantités de résidus de cultures agricoles peu valorisées. En effet, 70% de la population (principalement dans les zones rurales) fournissent des emplois informels par le biais d'activités agricoles. Par conséquent, ces activités génèrent de nombreux résidus de culture dont la plupart ne sont pas utilisés à des fins énergétiques. A cet égard, il est possible de promouvoir l'utilisation des résidus de cultures agricoles pour la production d'énergie. Cette étude explore le potentiel énergétique des résidus de culture générés par les cultures de riz, manioc, banane, canne à sucre, cacao, palmier à huile et banane plantain. Les données obtenues ont été intégrées dans un système d'information géographique (SIG) afin de fournir des résultats sur la distribution spatiale.

Néanmoins, plusieurs résidus de culture ont des utilisations concurrentes telles que l'alimentation du bétail et le rajeunissement du sol. Il a été constaté que le potentiel de résidus excédentaires a révélé qu'environ 1 204 033 t/an (55,4 % de la quantité brute) pourraient être générées à partir des résidus bruts de culture.

Le potentiel de bioénergie annuelle estimée à 20 276 TJ/an ou 81 430 tonnes d'équivalent en biohydrogène à partir de résidus de cultures excédentaires, Nimba (23 143 tonnes) produisant la plus grande quantité parmi les 15 régions. Le biohydrogène est la forme d'énergie la plus efficace et la plus propre, produite par le processus de fermentation à l'abris de la lumière.

En outre, le potentiel total de production d'électricité à partir de toutes les sources est estimé à environ 5 632 GWh, soit approximativement vingt fois la production totale d'électricité du Libéria en 2021. Par conséquent, les sources de biomasse pourraient contribuer de manière significative à la satisfaction des besoins énergétiques futurs du pays.

Les informations générées dans le cadre de cette étude devraient aider les régions à mettre en place une planification et une politique énergétiques décentralisées basées sur les résidus de culture, ce qui, à son tour, influencerait positivement la croissance globale des énergies renouvelables au Libéria.

Mots-clés: Liberia; Potentiel de biohydrogène; Résidus de cultures agricoles; Résidus excédentaires ; SIG

ABBREVIATIONS AND ACRONYMS

AWM	: Agriculture Waste Management
BMBF	: The Federal Ministry of Education and Research
EP	: Energy Potential
FAOSTAT	: Food and Agriculture Organization Statistics
GHG	: Green House Gas
GIS	: Geographic Information System
GOL	: Government of Liberia
GR	: Gross residue
GWh	: Gigawatt hour
IPCC	: Intergovernmental Panel on Climate Change
IRENA	: International Renewable Energy Agency
LHV	: Lower Heating Value
LISGIS	: Liberia Institute of Statistics and Geo-Information Services
NREL	: National Renewable Energy Laboratory
RF	: Recoverability Fraction
RPR	: residue to product ratio
SAF	: Surplus Availability Factor
SDGs	: Sustainable Development Goals
UNDP	: United Nations Development Programme
WASCAL	: West African Science Service Center on Climate Change and Adapted Land Use

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INTRODUCTION

BACKGROUND

The pressing obligation in finding substitutes for fossil fuels in the energy sector has intensified as a result of several climate disasters throughout the world that are enduring longer and causing significant material and human losses. The overuse of fossil fuel brings about climate extremes thereby causing global warming. One of the main sources of climate catastrophe is the energy sector which produced 90% of all carbon dioxide (CO_2) emission and roughly 75% of all greenhouse gas (GHG) emissions in 2018 (Aghahosseini et al., 2023). The Paris Agreement made reducing global warming a primary goal and governments committed to keeping temperatures below 2°C (Full et al., 2021). To achieve this difficulty in the energy sector as well as in the transportation and aviation industries, there is a need for a reduction in the use of fossil fuels and a transition to renewable energy sources. This degree of transformation requires the production of an essentially universal fuel source that is renewable and adaptable enough to be employed in a variety of sectors. By 2050, bioenergy from biomass may account for up to 1,548 EJ of which 96 EJ might come from waste and residues according to the IPCC making it the largest source of renewable energy (Guler et al., 2022).

Agricultural residues are underutilized and severely ignored energy sources since they are typically seen as waste around the globe, particularly in underdeveloped nations like Liberia. Bioenergy can be used in decentralized areas as renewable energy systems to power homes that are difficult to reach or to secure a stable electricity supply as well as transportation sectors that can balance from intermittent wind and solar power sources. This is especially important in order to better understand future energy supply systems with high shares of renewables.

Biomass (firewood, charcoal including crop residues) is nearly the primary energy source for heating and domestic cooking in all Sub-Sahara African countries. Liberia produces a variety of basic food crops including rice (the country's staple food), cassava, other roots and tubers (sweet potato, yam, and cocoyam), maize, vegetables, and groundnuts. After these crops have been harvested and processed various residues and byproducts remain as stalks, straws, and husks including shells with crop residues and agro-industrial byproducts.

More than 70% of the population in Liberia depend on agriculture as their main source of income making it a vulnerable sector to climate change. Surprisingly, 49% of Liberians are considered food insecure and 83% earning less than US$1.25 per day causing an unmitigated climate change that would ruin the industry and the nation (Boero, 2021).

Techniques based on geographic information systems (GIS) are frequently used to evaluate biomass potentials. Agricultural residues are categorized as husk, straw, cob stalks, peelings, and bagasse can result from the harvesting crop products (Zagrodnik & Łaniecki, 2017). These agricultural residue substances including hemicellulose, cellulose as well as lignin have high crystallization characteristics and prevent microbial breakdown and increased fermentative hydrogen production (Herzberg et al., 2019).

In one method, known as "biohydrogen production," microorganisms that can produce hydrogen utilize light or fermentation to convert organic molecules or water into hydrogen as part of their metabolic processes. Biohydrogen is produced in friendly settings using ecological practices. In order to lessen environmental contamination, it is also possible to combine these technologies with residue recycling. With the recycling yield the production of biohydrogen is seen as a method of hydrogen production with significant room for advancement that doesn’t have the propensity to damage the environment with the utilization of renewable energy.

According to the Sustainable Development Goals (SDGs), Liberia is trying to electrify the capital city to a 70 percent level and rural areas to a 35 percent level by 2030 although there is still more work to be done especially in rural areas (Africa Off-grid Project, 2020). The nation's entire economy including all of its commodities seriously jeopardizes energy security due to its heavy reliance on fossil fuels. According to (World Bank 2021), 29.8% of Liberians have access to electricity using the means of operation of 22.6 MW of diesel-based generators with extremely high production costs including 48 MW of heavy fuel oil-based generation is permitted under an emergency program for power generation which is likewise dominated by conventional fuels (Gesto energy consulting, 2016). There is a combined electricity capacity of 191 MW installed and around 98% of the nation's installed capacity is focused around the vicinity of Monrovia which has a total population of 1 million people and serves 35,000 customers with provisioning of service by the Liberia Electricity Corporation's (LEC). Due to the limited transmission and insufficient water supply for hydro plants during the dry season, less than 23 MW of Liberia's installed capacity is operational daily. Large establishments like hotels, restaurants and office buildings are compelled to operate their own on-site generators due to the grid's instability. Therefore, further expansion in the the agricultural sector as a crucial component will help contribute to the energy impediment that the country is encountering.

PROBLEM OF THE STUDY

This work places a lot of emphasis on hotspots and identifying the biohydrogen potential that can be extracted from agricultural crop residues for energy generation. Due to the lack of identification of agricultural crop residues in Liberia with the unknown locations of sites, a determination is anticipated to contribute significantly to energy generation in the near future. The application of a geographic information system (GIS) as a site selection tool has the contribution to concentrate on the determination of the best locations for the development of energy based on the expected yields from biohydrogen production or the distribution of agriculture residues to power plants.

It has not been used as a dynamic search engine to locate appropriate power plants, despite the spatial dispersion of agricultural crop residue potential and biohydrogen generation. Potential researchers and development partners will find it simpler to work in these sites after the effort to identify locations.

Despite growing interest to produce green hydrogen, agricultural waste still has a lot of untapped energy potential.

Most crop residues are fruitless in farms through burning or unmanaged decay which causes nitrogen leakage and eutrophication in nearby water bodies and contributes to odor and greenhouse gas emissions by releasing volatile and unburned hydrocarbons.

The apparent lack of organized information is seen to be one of the primary obstacles to the effective implementation of biohydrogen technology even if each of the restrictions has its own particular impact.

A database system providing crucial details and data on biohydrogen technology and feedstock like crop residues and their biohydrogen potential may act as a one-stop information hub for public and private organizations (Charles & Nzila, 2017).

Therefore, sustainable biohydrogen generation as well as mapping fueling stations by reducing transportation distances and related CO_2 emissions is crucial in meeting the problems encountered by the researcher.

OBJECTIVES AND QUESTIONS

This study aims to use a geographic information system (GIS) map to determine biohydrogen production potential from agricultural crop residues and identify suitable production sites as well as fueling stations in Liberia.

Specific objectives:

- Assess and map agriculture crop residues potential using GIS;
- Select by hotspot the calculation of biohydrogen production from agriculture crop residues;
- Identify suitable allocation for biohydrogen production plants and fueling stations.

The researcher seek to gather information on the production potential of biohydrogen from agriculture crop residues considering few questions below.

What are the residues from agricultural processes in the country that can help to boost the energy demand?

Where can these residues be found to have a potential for biohydrogen production?

Which sectors stand to benefit when biohydrogen is produced from crop residues?

Positive outcomes will spread knowledge of agricultural crop residues and encourage related research endeavors. Using agriculture waste for the production of energy in different sectors might have favorable effects on energy security with the energy mix and most importantly the nation's present reliance on conventional energy.

The gap in the study is the unavailability of research ever done in Liberia identifying biohydrogen production potential with the location of agriculture residues obtained.

STRUCTURE OF THE THESIS

The thesis is structured commencing with introduction and summarized by five original chapters.

The introduction that contains the study's background, statement of the problem, the objective of the study and structure of the thesis.

Chapter 1 is the state of knowledge on the production of biohydrogen from crop residues.

Chapter 2 is focused on the research methodology which contains the research design of the preparation and various characteristics by utilizing GIS-based identification of selected agriculture crop residues capable of having the potential to produce biohydrogen,

Chapter 3 contains the data presentation followed by its interpretation of the research results,

Chapter 4 contains the discussion and summary,

Chapter 5 is the conclusion including of recommendation of the research.

1 State of knowledge

1.1 ENERGY OVERVIEW

Right now, fossil fuels provide the majority of the world's energy needs. Since their natural reserves are limited fossil fuels are considered non-renewable energy sources. Each unit of their usage diminishes the size of their natural supplies. Additionally, it has a detrimental effect on the ecosystem. When fossil fuels are burned gases including carbon sulfur and nitrogen oxides as well as other particulate matter are released into the atmosphere generating the greenhouse effect and climate change (Pugazhendhi et al., 2017). Over-relying on fossil fuels as a source of energy is not a sustainable strategy. Thus, a strong emphasis on the development and use of renewable energy sources is very necessary to ensure sustainability in the energy industry. In reality much effort has been done globally in this area leading to the development of technology for the growth and application of various renewable energy sources (Namdarimonfared et al., 2023). The most crucial characteristic of these unconventional sources (Hydropower, solar energy, tidal energy, wind energy, geothermal energy, and bioenergy) is that they are all sustainable, clean and have no potential to harm the environment unlike fossil fuels (Kim et al., 2023). Biofuel has become a significant source of renewable energy because of how affordable it is and the potential benefits it offers to rural areas. The many types of bioenergy that have received a lot of interest include biogas, biodiesel, and bioethanol. There is however a relatively small amount of attention paid to biohydrogen a kind of bioenergy with enormous potential and use. As a result, this work discusses several elements of biohydrogen technologies including their generation and use. Any endeavor to provide a sustainable and economical way of energy generation carries great relevance given the current issues the globe faces from population growth and rising fuel prices (Yildirim & Ozkaya, 2023).

1.1.1 HYDROGEN AS A GREEN FUEL

Hydrogen is four times more energy dense and has lower heating value (LHV) than other fuels like coal, gasoline and methane including other traditional fuels (Gabisa & Gheewala, 2018). As a result, hydrogen is a clean fuel that burns more efficiently and produces less pollution and global warming than other fuels. Among the major gaseous fuels molecular hydrogen has the largest energy content per unit weight (157,631 MJ/kg) (Wang et al., 2022). Hydrogen is a carbon-free fuel since it finally oxidizes to water as a combustion byproduct. As a result, it has no impact on the emissions of greenhouse gases or other environmental issues like acid rain or ozone layer depletion (Lin et al., 2016). But the method by which it is now generated commercially poses a difficult problem in establishing H_2 as a possible source of energy.

H_2 gets produced from natural gas reforming, refinery/chemical off-gases (oil), coal and electrolysis in amounts of 48%, 30%, 18%, and 4% respectively according to (Mathimani & Pugazhendhi, 2019). Steam formation of natural gas gasification of coal and electrolysis of water is the traditional process for creating hydrogen for commercial usage. In addition to requiring very high temperatures (>840 °C) all of these processes are also incredibly energy-intensive and unfriendly to the environment (Siegrist et al., 2022). This situation necessitated the development of biohydrogen which is the result of the desire to manufacture hydrogen from sources other than coal that would be both inexpensive and environmentally beneficial.

1.1.2 BIOHYDROGEN PRODUCTION PROCESSES

The hydrogen that is produced by living things is known as Biohydrogen. The main procedures for producing Biohydrogen are described in (PANIGRAHI, 2019). Biophotolysis of water by algae dark fermentation; photo-fermentation of organic materials as well as sequential dark and photo-fermentation processes are the main methods used in producing Biohydrogen (Patel et al., 2021). Diverse forms of sustainable biomass may be converted by various microbes into hydrogen by the following categories: Green algae (*Chlamydomonas reinhardii* and *Chlamydomonas moewusii*), blue-green algae (*Anabaena variabilis, Anabaena cylindrical*, and *Oscillotoria miami BG7*), photosynthetic bacteria (*Rhodobacter sphaeroides, Rhodobacter capsulates*, *Rhodobacter palustris*, and *Rhodospirillum rubnum*) (Qyyum et al., 2022).
As shown in Figure 1, fermentation and photosynthetic are the two processes in producing biohydrogen. In so doing, this study focuses on dark fermentation.

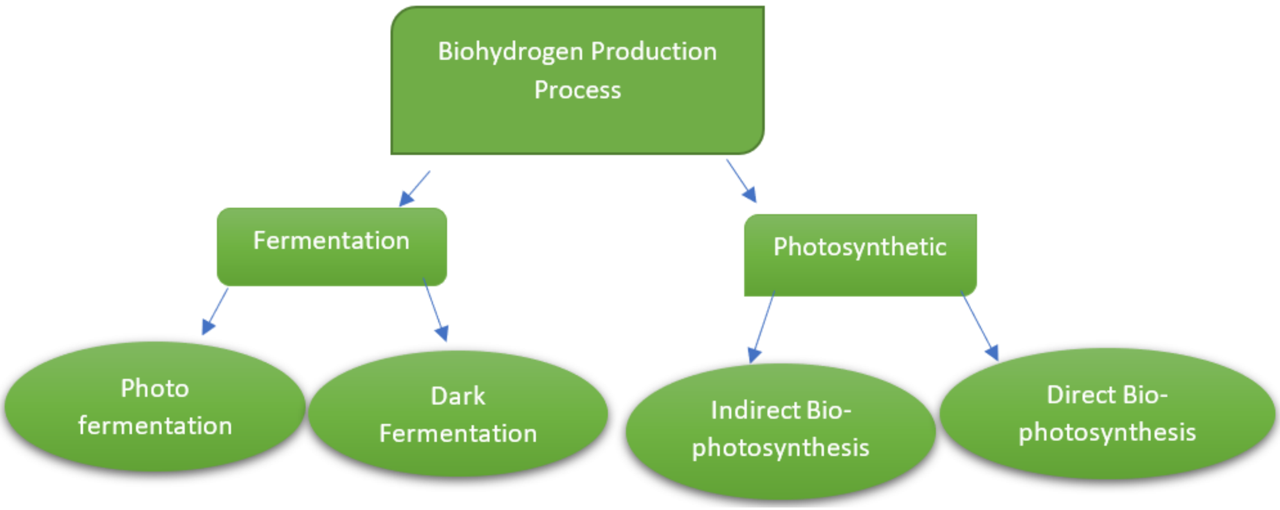

Figure 1. Methods for producing biohydrogen

The first form is photo-fermentation to produce biohydrogen in which photosynthetic bacteria break down organic materials and produce biohydrogen at the same time under anaerobic and light conditions. The second kind of fermentation is known as dark fermentation which takes place in anaerobic environments without light and includes bacteria and microalgae converting organic materials into Biohydrogen. Microalgae operates in anaerobic and light-rich environments to directly photolyze water to produce biohydrogen. Usually the organic matter feedstock (microalgae) used in this fermentation-based biohydrogen-generating method is starch, glucose or organic acids (Sivagurunathan et al., 2016; Villanueva-Galindo et al., 2023). The primary sources of fermentation substrates in the early development of biohydrogen-generating systems were agricultural residues (corn, sugarcane, potatoes, and other food crops) (Zagrodnik et al., 2022). Enzymes that produce hydrogen are essential to the biological process of creating hydrogen because they catalyze the chemical reaction:

$$2H^{+} + 2e^{-} \rightarrow \mathrm{H}_2$$

The three enzymes nitrogenase, Fe-hydrogenase and NiFe-hydrogenase are known to catalyze this process (Rangel et al., 2020). While nitrogenase is utilized in photo-fermentation processes, Fe-hydrogenase is employed in bio-photolysis processes. The subjection of the water can either be indirect or direct biophotolysis by algae. In direct biophotolysis, the photosynthetic process transforms solar energy into chemical energy that is utilized to disassemble the water molecule to make hydrogen molecules.

Hydrogenase is effectively inhibited by oxygen as a result of the oxygen concentration is kept below 0.1% to improve the enzyme's effectiveness. However, the oxygen and hydrogen production processes are divided into two steps in indirect biophotolysis as described below. The first step is to convert solar energy and absorb carbon dioxide to produce carbonhydrates; and second step, ferment the carbohydrates to produce biohydrogen.

In a dark fermentation the complex organic polymers are hydrolyzed into monomers by the fermentative bacteria using microorganisms that produce hydrogen they are further transformed into organic acids with smaller molecular weights and alcohols. In the dark fermentation process, hydrogen is obtained along with the acetic and butyric acids that are formed from the feedstock of carbohydrates.

In this technique, hydrogen may be formed without light using a number of carbon sources. This process also results in the production of useful byproducts including hydrogen, acetic acid, lactic acid, and butyric acid. The resultant gas must be separated since it is a combination of CO_2 and H_2. The H_2 output is likewise quite low. The dark fermentation technique has several drawbacks. The primary disadvantage of dark fermentation is its low hydrogen output, which is proportional to substrate consumption. However, the limitations with yield and byproducts can be remedied by incorporating nanomaterials to alleviate key issues in biohydrogen generation using dark fermentation. In the fermentation process known as photo-fermentation, organic substrates are transformed into hydrogen and carbon dioxide in the presence of light that does not involve oxygen.

The benefits of this method include the elimination of environmental contaminants by organic acids created during dark fermentation and the use of industrial waste with organic materials as a feedstock in other to produce hydrogen. However, industrial effluents can occasionally turn poisonous to fermenting bacteria necessitating pre-treatment (Sivagurunathan et al., 2016). The two-stage dark/photo fermentative hydrogen production is applied in hybrid technique that uses photoheterotrophic bacteria for the production of hydrogen and CO_2 from the organic acid produced during dark fermentation (Zagrodnik & Łaniecki, 2017). This procedure is more advantageous than using only dark fermentation.

Fossil fuel stocks are under extreme strain due to the current rise in energy demand which might lead to a serious energy crisis, soon therefore much focus has been placed on the development and use of renewable sources of energy in order to achieve sustainability in the energy sector and to reduce the environmental damage caused by the combustion of fossil fuels (Singh et al., 2022). Although hydrogen has the potential to be a renewable energy source the current methods of producing it are neither environmentally benign nor sustainable. With this, biohydrogen has a brighter future that will allow us to utilize effectively organic wastes as source materials and cut costs and pollution associated with current hydrogen generation technologies (Yaashikaa et al., 2022). Through this endeavor, a lot of effort has to be done to overcome several obstacles facing biohydrogen technology in order for it to be a possible renewable and environmentally friendly fuel in the future offering employment possibilities for young people.

The reactor layout process variables and operational circumstances have the greatest impact on the substrate conversion efficiency and biohydrogen generation potential of microbial biocatalysts during dark fermentation (Chen et al., 2023). Better bioreactors must be able to operate at lower hydraulic retention times and must also be able to control biomass washout as a result of the reduced retention times (Mohd Asrul et al., 2022). The performance of these processes depends on the reformation created for specific situations as well as the combinations of the reactors (Banu J et al., 2021).

1.2 AGRICULTURE RESIDUES POTENTIAL

The agriculture residues are categorized in crop residues (leaf litter, seed pods, stalks, stems, straws, husks, weeds, cobs), livestock waste (urine, dung, wash water, leftover milk, waste feed), poultry waste (spilled feed, feathers, droppings, bedding material), slaughterhouse waste (blood, hair, hides, flesh, bones, etc.), and agro-industrial waste (bagasse, molasses, peels) (Duque-Acevedo et al., 2020). Agriculture is one of the biological industries with the biggest biomass production which may be a crucial component of the bioeconomy. The agricultural waste management (AWM) based bioeconomic strategies can prevent the reckless/random burning of crop residues and the underutilization of livestock excrement to ensure food and health security waste valorization to produce value-added products, farmer's livelihood, employment opportunities for youth and sustainability in agriculture (Oliveira et al., 2020). Nearly all of the agriculture wastes (Aws) listed above are easily decomposable and the end products of the process will not only supply vital nutrients for plants but will also make the soil permeable.

In order to contribute to clean, safe and sustainable agriculture it will minimize greenhouse gas (GHG) emissions and the dependence on fossil fuels as well as develop green markets and job possibilities by turning agricultural wastes and byproducts into useful resources (Hamedani et al., 2018). According to (Haase et al., 2016; Lozano-García et al., 2020) emphasized the possibility of residual; (Quinta-Nova et al., 2017) assessed the potential of biomass from forests (Voivontas et al., 2017) based on the possibilities for biomass and determine the best site for a power plant. To identify eligible regions with biomass potentials they often superimpose several data layers (forest, farm, urban, slope, and road data). However, because of a lack of accurate and straightforward crop distribution maps aggregated suitable lands often only receive a statistical crop distribution (Bao et al., 2020). A general word for waste solids and liquids produced by farming during agricultural production raising livestock and poultry is "agricultural waste." (Sun & Cheng, 2020). Waste biomass has dominated the feedstocks used to produce biohydrogen in recent years due to worries about competing with humans for food and the high cost of production (Zheng et al., 2022). Flooding brought on by intense rainstorms already has a negative impact on farmers and food production systems but improved food security and increased efficiency in agricultural value chains might protect farmer livelihoods including the national economy and clean renewable energy by adjusting food production systems to climate change (Kuukpen, 2022).

Figure 2 shows that there are three processes involed in producing bioenergies from lignocellulose biomass (Agricultural residues).

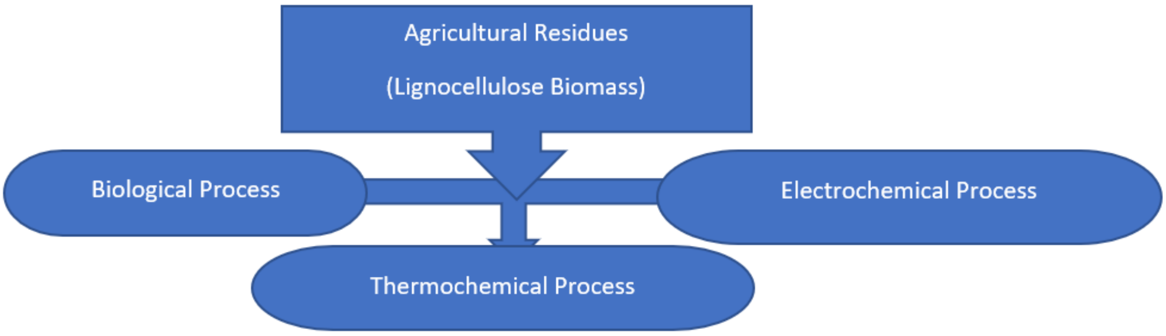

Figure 2. Hydrogen production processes from agricultural residues

Agriculture biomass mostly consists of lignocellulose which is composed of cellulose, hemicellulose and lignin. Cellulose accounts for 30–50% of the total biomass making it an ideal resource for microbial processing. According to studies lignocellulosic biomass may be strategically managed and valued to produce a variety of goods that are useful for both domestic and commercial usage and among them is the determination of compost (bio coal, biochar, bio bricks, biohydrogen, biomethane, bioethanol, biobutanol, organic acids, bioelectricity, etc). Additionally, it will continue to open up new doors for young people looking for work who are from farming communities all over the world (Feng et al., 2023).It has therefore been reported regarding the advantages and disadvantages of using biological agricultural residues as feedstocks for the generation of biohydrogen emphasizing that using agricultural waste as biohydrogen feedstock is an effective method of waste disposal that may reduce environmental damage and provide sustainable energy (Zheng et al., 2022). The public and farming communities need to be educated more about the unintended advantages of managing agricultural wastes biologically and biotechnologically such as improved human health and reduce or no soil air and water pollution with other sources of income. This would eliminate their irrational fears and preconceived preconceptions about ambiguous information.

1.3 Hotspot determination

Waste is a significant concern for the entire planet. In addition to the spread of infections fire risks water contamination and economic losses it is extremely hazardous to the environment and human health. A preassessment approach called land suitability evaluation helps to maximize the utilization of land in a promising but constrained location (Ramamurthy, 2020). The approach is very beneficial to optimize crop output per unit of land, labor and input since the restrictions range widely from environmental to socioeconomic aspects (Junginger, 2009).

Nevertheless, the criteria should not be regarded identically because the significance of each element considered varies.

The significance level of the taken-into-consideration criteria must be established in order to use land suitability analysis. To calculate the weights for land suitability analysis in the geographic information system (GIS) application multi-criteria decision analysis (MCDA) has been used extensively. The MCDA technique has been effectively used in the evaluation of land suitability for a variety of applications including selecting the best locations for solar systems and the production of biohydrogen (Yushchenko et al., 2018) and crops (Jeong, 2018). The analytic hierarchy process (AHP) approach which is frequently employed to derive factor weights that represent their relative importance was one of the most widely utilized MCDA algorithms in the research that found acceptable sites for crops (Özkan et al., 2020). The AHP consists of three steps: firstly, defining a goal, secondly, choosing criteria for the goal deciding on their weights as well as thirdly, evaluating the alternatives by adding up the scores of the criteria into goal scores based on the weights. The crucial stage of the AHP is the calculation of the weights of the criteria where pairwise comparisons of the criteria are utilized to determine their relative weight (Zhang et al., 2021). The AHP technique and GIS were used by (Ramamurthy, 2020) to evaluate the suitability of the land for maize in southern India. In their evaluation, they considered the depth of the soil as well as the growing season (soil surface texture, soil drainage, organic carbon, soil pH, slope, and elevation). In the semiarid terrestrial environment of the Central Anatolia Region, a similar set of criteria was applied to identify regions that were appropriate for agricultural activity (Chukwuma et al., 2021). Herzberg et al., (2019) MCDA was used to evaluate the land's potential for rice farming. The study's selection criteria were comparable to those used by (Jeong & Ramírez-Gómez, 2017). However, socioeconomic factors (such as the poverty rate and farming prowess) were also considered in their evaluation and used MCDA to evaluate the degree of land suitability which demonstrated that MCDA is an effective method for locating regions that are appropriate for agriculture (Yan et al., 2021). It is important to note that while these studies' findings show acceptable locations, as well as agricultural productivity which might be crucial in particular circumstances cannot be quantified.

1.3.1 GIS IDENTIFICATION

According to the United States Geological Survey, a geographic information system (GIS) is a computer system that analyzes and presents spatially related data (Sharmin et al., 2023). The implementation of farm waste recycling programs in the best locations with the best suitable capacities is not only essential for resolving some of the environmental problems connected to the rise of biological waste but it is also practically and financially possible (Celsa, 2022). Utilizing spatial information technologies like remote sensing and GIS to address the location of bioenergy plants appears to be a desirable practice given the considerable geographic identification of farms. Numerous researchers have therefore contributed to the utilization of GIS as an effective site-appropriateness tool demonstrating its ability to handle location-related issues (Bao et al., 2020; Selvaggi & Valenti, 2021).

The approach of garthering information comes in the weak of its dependent on tne national or regional impediments, with an emphasis on the local cities problems, such as population, transportation, the availability of resources including legislation. Kuby et al., (2023) have used a GIS-based regional hydrogen demand set-ups and filling station networks for the pathways planning of hydrogen fuel. Despite the fact that not much work that have focused on specifically this framework. The methodology considered by this author call for expansion of local hydrogen systems in reaching to the customers on time as well as the increasing hydrogen density.

National renewable energy Laboratory (NREL) in the USA, (Li et al., 2020) have contributed a study based on GIS to indentify the minimium hydrogen infrastructure to encourage customers have trust to purchase hydrogen vehicles.

The authors have offered a GIS approach for locating future hydrogen stations based on the characteristics of the demand in a few particular urban regions. The studies previously mentioned mostly concentrated on works that developed hydrogen infrastructure using a geographic information system (GIS) by itself.

In order to gain a deeper knowledge of events in specific contexts it uses data associated with a specific area. Additionally, GIS has shown to be a useful tool in biomass energy research for assessing and evaluating renewable energy resources since it identifies potential locations for bioenergy plants and makes it possible to determine the most commercially viable use of available feedstocks (Bharti et al., 2021). Analytical hierarchical process (AHP), an integrated decision-making technique based on geographic information systems has been utilized in previous studies to focus on the use of agricultural waste for bioenergy in which the feedstock used is feasible because of its origin which comes from agricultural residues (Messaoudi et al., 2019).

In recent years, the use of GIS tools has been acknowledged as being extremely helpful for mapping the spatial distribution of biomass potential and enabling the optimization of bioenergy production facilities. In the study (Selvaggi & Valenti, 2021; Ukoba et al., 2023) a GIS tool was used to evaluate the geographical distribution of the yearly potential of agroforestry waste as well as the potential of annual sustainable crop residues and optimize the outcome.

In the study (Jagriti Dabas, 2023), a GIS tool was used to evaluate the spatial distribution of yearly biogas potential from non-woody biomass of conservation areas and roadsides for biogas. The work's authors (Ukoba et al., 2023) evaluated the yearly theoretical and technical potential of chicken manure from different raising techniques in Polish districts using a GIS tool. The method for evaluating the yearly economic potential of biomass supply from crop leftovers was described by the author in the study (Chakraborty et al., 2022), and he utilized a GIS-based methodology to pinpoint the regions in China that are most likely to generate crop residue. The authors of the article Song et al., (2023) have proposed a GIS-based integrated strategy for identifying the biomass industry's most cost-effective expenditures. The suggested strategy includes specifying both storage and plant sites and mapping yearly biomass potential using GIS. Similar to the work of Romero et al., (2023), the authors used a GIS tool to evaluate the annual potential of corn stover, switchgrass and miscanthus to determine the viability of biofuel production and suitable locations for biorefineries in the USA. Similarly, the authors evaluated the annual potential of food waste, cattle slurry and wheat straw to determine the location of bioenergy facilities in the work (Omran & Baek, 2022) .

In the study by Selvaggi & Valenti, (2021), the authors used a GIS-based geographical index of feedstock-mixture availability for anaerobic co-digestion and the same feedstocks were taken into consideration.

Using a GIS tool, the authors of the study (Sciuto et al., 2022) determined the most economically advantageous places to inject biomethane into a natural gas pipeline based on the geographical distribution of the yearly potential from cattle slurry and grass silage. According to (Valenti et al., 2023) land use maps for the chosen hotspot zones were developed using a GIS tool for the yearly biomass potential assessment in India. Based on the theoretical yearly potential of various biomass resources and transportation distances the authors of the study (Seglah et al., 2023) performed a regional GIS-based technique to analyze feasible sites and capacities of bioenergy facilities. A study by (Sciuto et al., 2022) developed a model to address the multicriteria decision issue of choosing the best location for a bioenergy plant while considering factors like yearly slurry potential, population density, distance from heat sources and transportation-optimal locations.

1.3.2 DISTANCE POTENTIAL

Because biomass feedstock is a scattered resource with a low energy density transportation expenses might account for a huge amount of overall costs resulting in the usage of fossil fuels and their corresponding emissions. Therefore, transportation must be kept to a minimum and as a result some studies have used a sourcing radius of 25 km (Zheng et al., 2021). Updated regulations (Jayarathna et al., 2020) require the end user to be closed by which means that other economic variables will now determine the distance. Processing biomass can enhance energy density enabling more efficient conveyance and hence expanding the scope of production. It has been suggested to model logistics and processing together (Yalcinkaya, 2020) if torrefaction progresses past the demonstration stage and will become more significant (Zheng et al., 2022). Road network cultivation costs local availability patterns, the cost of cheaper substitutes such as wastes or residues yearly swings in transportation costs, feedstock prices, and spatial patterns of yields will all affect supply costs (French, 2019). To guarantee that green house gas (GHG) savings relative to the production of fossil fuels are sustained environmental factors should be addressed in addition to economic ones while limiting transport routes. Even if the transport radius for each individual plant will eventually vary this level of evaluation is inappropriate for consideration at the national level. A 40 km radius can be used to offer a broad assessment of potential depending on national laws incentives or industry requirements another radius could be better suitable for evaluation in another country. The need for locally sourced feedstock lowers the potential size of the biomass-only generation which does not fit well into traditional energy supply systems of efficient centralized generating at a large scale (Cintas et al., 2021). This necessitates a different strategy for biomass production in order to minimize feedstock transportation and maximize generating efficiency assessments of the future potential of bioenergy must take geographical variables for both supply and demand into consideration (Jeong & Ramírez-Gómez, 2017).

1.4 UTILIZATION (BIOHYDROGEN UTILIZATION) POTENTIAL

Since 1975, the need for hydrogen has been growing steadily with the majority of the demand coming from the manufacturing of ammonia. However, due to its characteristics which make it a key building ingredient in reducing fossil-derived energy sources utilized in hard-to-eliminate emission sectors the world's usage of hydrogen is predicted to dramatically expand (Hattori et al., 2022). Inferring that it is a direct energy source and has the capacity for energy storage in the form of chemical potential hydrogen is a synthetic energy carrier. Due to these qualities, hydrogen is a promising key component of the next generation of renewable energy systems (Acar & Dincer, 2018). Numerous processes (electrolysis, thermal water splitting, gasification, dark fermentation, photoelectrochemical cells, fossil fuel reforming, synthetic photosynthesis, aqueous phase reforming, and traditional reforming techniques) can be used to produce hydrogen. Depending on how much CO_2 they emit and how much of an influence they have on the environment these production methods can be categorized. Hydrogen production has been divided into four primary categories: brown, grey, blue, and green.

Figure 3 illustrates how these color codes are assigned according to the level of CO_2 emissions and capture.

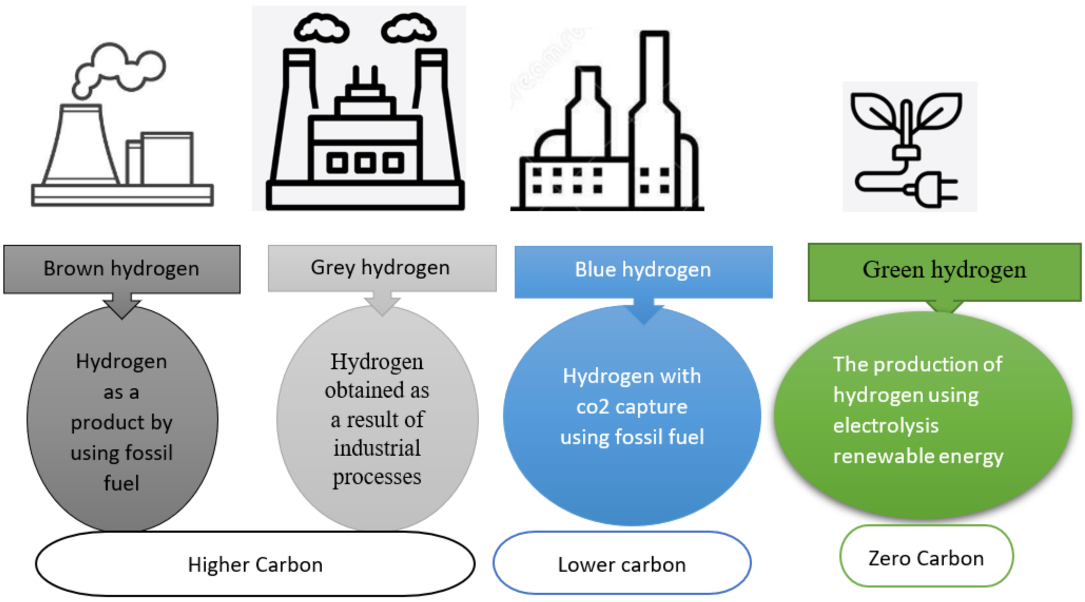

Figure 3. The differences in hydrogen production methods and how they impact carbon emissions

The generation of carbon and fossil fuels such as the gasification of coal which has the largest CO_2 emissions are included in the category of brown hydrogen. The term "grey hydrogen" refers to hydrogen that is generated industrially that is used by natural gas in the process of steam reforming which does not have carbon capture even though with considerable emission of CO_2. The category that emits the least CO_2 is called blue hydrogen, formed during the carbon capture process. The best way to manufacture hydrogen that is climate-neutral is by electrolysis using renewable energy which produces green hydrogen with no carbon dioxide emissions (Koul et al., 2022).

Blue hydrogen requires more purification before it can be used in a vehicle's fuel cell whereas green hydrogen is purer. Blue hydrogen on the other hand may be used in industries without being purified and the way it produces the energy is completely eliminating industry emissions by reasonably and widely lowering CO_2.

In 2019, 75 million tons of hydrogen were produced annually largely for use in chemical and refining processes (Downie, 2020). According to estimates, hydrogen and hydrogen-based fuels will supply 13% of global energy requirements in 2070 up from 1% in 2019 with the majority of the hydrogen being utilized in the chemical and transportation sectors and was stated that 70% of the hydrogen used in transportation in 2070 will come from shipping (52%) aviation (40%) and the balance road transport (Qyyum et al., 2022). Fuel cells for mobility and electrolysis production are two of the more sophisticated methodologies and initiatives working on a low-carbon hydrogen value chain. However, ammonia-fueled ships and hydrogen-fueled engines for land transportation (primarily for vehicles) are still at the prototype stage. This is crucial because crop and forest waste may be used to provide sustainable energy.

1.4.1 Potential Users

The potential for a significant contribution to the need for renewable energy in the future is shown by biohydrogen. It looks especially well-suited to decentralize relatively small-scale systems that are connected with commercial industrial and agricultural operations or waste processing facilities. Biohydrogen is now viewed as the adaptable fuel of the future having the ability to replace fossil fuels and is considered a crucial component of a sustainable global power supply. Among the variety of renewable H_2 production methods now has the strongest chance of becoming the best method. It has a high energy density and is a clean energy carrier (Dong et al., 2023). A very promising fuel for both mobile and stationary applications is hydrogen. In the presence of adequate catalysts, biohydrogen's strong electrochemical reactivity makes it perfect for use in fuel cells. In terms of utilization, biohydrogen is mostly employed in the production of food, metals treatment, fertilizer manufacturing, and oil refining. It has established uses in fuel cells, metal production and fabrication, aerospace, petroleum recovery and refining, and chemical processing (Haron et al., 2018). Biohydrogen can also be used in several ways (rotor coolant, shielding gas, reducing and hydrogenating agent, and food additive).

2 MATERIALS AND METHODS

2.1 STUDY AREA

Liberia is located in West Africa neighboring Côte d'Ivoire to the east, Sierra Leone to the west, Guinea to the north and to the south with the Atlantic Ocean that lies between longitudes 7°30 and 11°30 west as well as latitudes 4°18 and 8°30 north, as shown in Figure 4. Liberia is divided into fifteen (15) counties with approximately 5.2 million people in December 2022 (LISGIS 2022). Monrovia is the capital city, situated in one of the counties Montserrado which is also the country's commercial hub. The country's area is 111,379 km^2 with its land area of 96.32 km^2 as well as an agricultural area of 19.54 km^2 and including a forest area of 76.477 km^2 according to (FOA 2023)

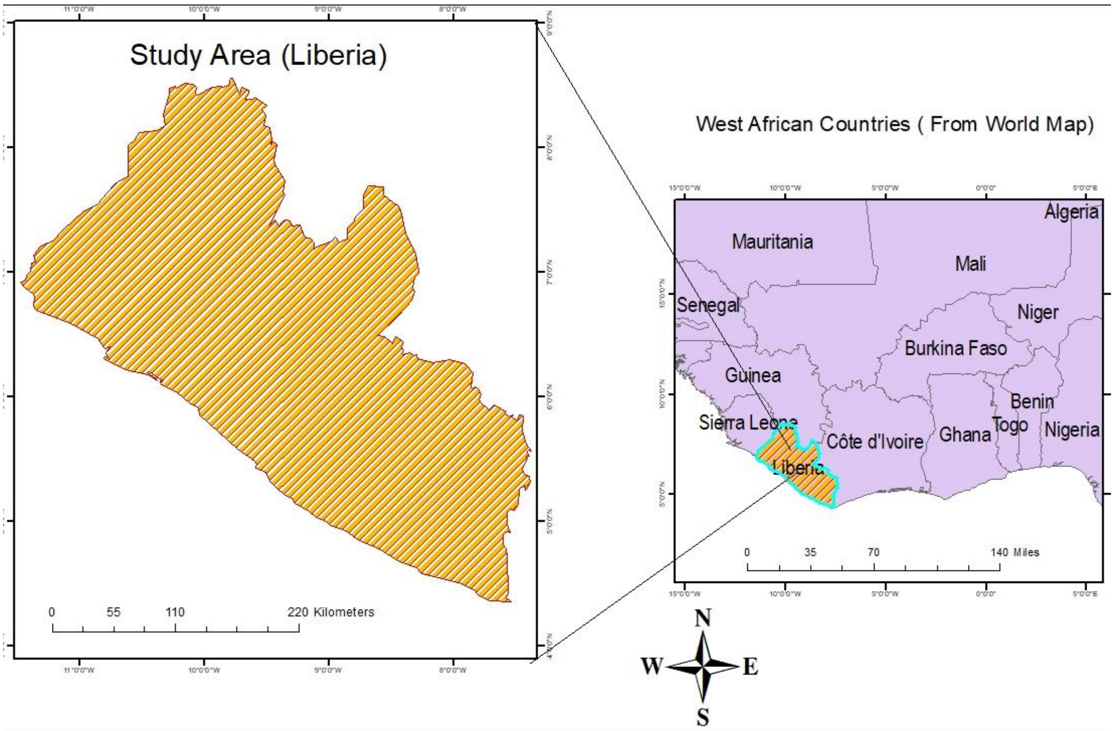

Figure 4. Diagram of the study area

2.2 Method

This study comprises the assessment of biohydrogen production potential from agriculture residues by hotspot analysis and determining agricultural residues production capacity and spatially optimized collection areas including transportation distances. All spatial-related tasks are performed using ArcGIS including QGIS software and its associated extensions such as the Spatial Analyst and Network Analyst as well as the use of Excel. In detail, the QGis software (Ver. 3.33), an open-source GIS software was used since it is a decision support tool appropriate for collecting, organizing, analyzing and localizing geographical data. It has been divided into theoretical assessment, site suitability and spatial statistics analyses. The theoretical analysis examines the availability of crop residues based on mathematical methods. The final suitability map of potential areas for setting biohydrogen plants is made by combining a restriction map and a suitability map. In the spatial statistics analysis, high-density areas of feedstocks are estimated through hotspot analysis that is designed contingent on feedstock intensity within significant areas.

ArcGIS software version 10.8.2, created by the Environmental Systems Research Institute in New York City, United States of America, was used to estimate the location and capacity of energy output from biohydrogen plants possibly having a series of fuel stations using hotspots. Figure 5 shows a step by step processes used to determine various results in this study.

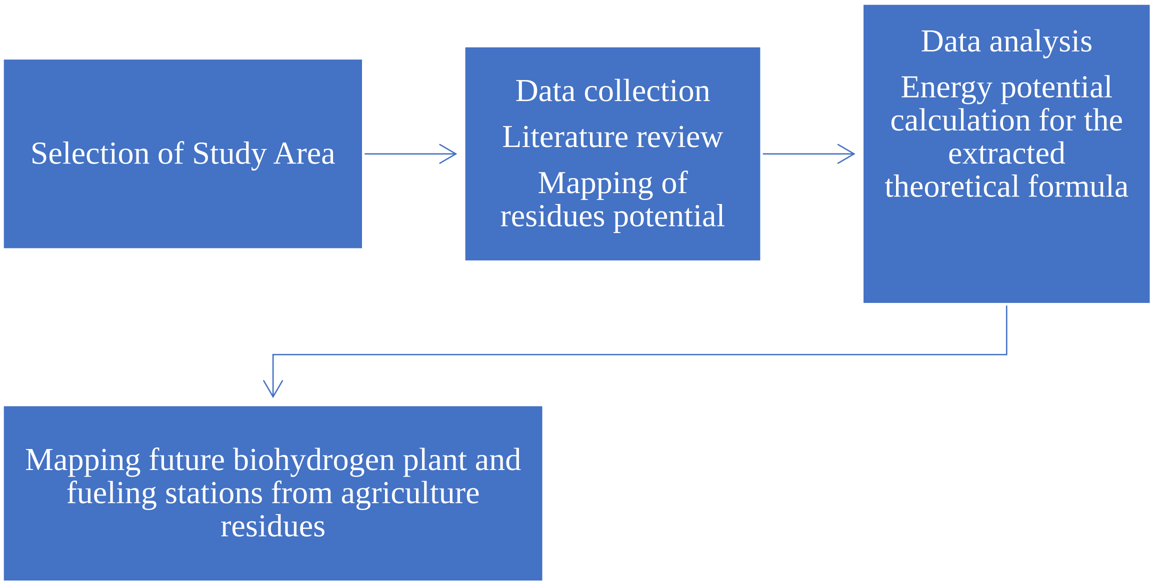

Figure 5. Methodology flow diagram for determining energy potential

2.2.1 Crop Selection

The major crops grown in these areas are rice, cassava, banana, sugar cane, oil palm, cocoa including plantain. The data were obtained from the Liberia Institute of Statistics and Geo-Information Services (LISGIS) (Agriculture team, 2017) and the Food and Agriculture Organization Statistics (FAOSTAT) reports ("World Food and Agriculture – Statistical Yearbook 2021," 2021). The study focused on all of the fifteen (15) counties in the Country to access the potential of biohydrogen production from agricultural crop residues. This data provides a better scope of the location of agriculture crop residues produced at the local and county levels. Estimating the residues' quantity and their energy potential in rural areas has added important environmental implications. Using spatial analysis GIS tools, the production areas were localized in the study areas and the most productive areas were considered. The crops selected are mostly grown by household farmers who carried on subsistence farming.

2.2.2 AGRICULTURE CROP RESIDUE POTENTIAL

In this study, the potential for agricultural crop residue accessibility in all of Liberia's counties was considered. Figure 7 demonstrates that the most widely grown crop types in Liberia were cassava, rice (the nation's primary diet), sugar cane, cocoa, plantains, bananas, and oil palm. At the national and county levels, Liberia's potential for gross and excess residue biomass, as well as its potential for bioenergy and biohydrogen were determined. To calculate crop residual biomass, statistics on Liberian agricultural crop production were used. The only crop included in the production statistics utilized for the estimation are those that were harvested during the main season (2017), according to the Liberia Institute of Statistics and Geo-Information Services (LISGIS).

2.2.3 QUANTIFICATION OF AGRICULTURE RESIDUES AVAILABILITY

During the data collection of agriculture crops, seven crop types where selected as crop production shown in Table 1. The presentation of crops diversifies according to household crop portfolio from various counties. As Table 1 shows, cassava and rice are the main crops grown by farming households (they account for 85.6% percent of households' crop portfolio each). The share of household-growing bananas is 3.0 percent (36,690 Tonnes) and plantain is 5.4 percent (65,724 Tonnes). In addition, cash crops are produced by 6 percent of the total selected crops which are cocoa, oil palm and sugar cane shown in Table 1.

It also shows that cassava, rice, banana, plantain and sugar cane are concentrated abundantly in Nimba, Lofa, Montserrado and Bong counties while Nimba, Bong, Lofa and Grand cape mount produced more cassava.

However, Agriculture team (2017) average yield of rice is 1.26 Metric tons (MT) per hectare at the national level and cassava yield is estimated at 5.28 tonnes per hectare.

While the yields per hectare vary among counties, the national average has been used to estimate the total production to be consistent with FOA methodology (Agriculture team, 2017). Cassava is estimated to be 335,179 Tonnes as well as rice 697,604 Tonnes, respectively. Cassava is more than rice due its many usages in the country like: gari, and several local foods produced from cassava.

Table 1. Crop production in Liberia per county in Tonnes/year

N.	County	Cassava	Rice	Banana	Plantain	Cocoa	Oil Palm	Sugar Cane
1	Bomi	27916	13413	640	891	137	307	204
2	Bong	120361	57830	3583	6,790	1304	164	5265
3	Grand Bassa	49797	23926	2225	4,013	829	0	3567
4	Grand Cape Mount	52366	25160	1043	1,686	237	1620	326
5	Grand Gedeh	20005	9612	1406	2,400	1281	76	18
6	Grand Kru	17255	8291	834	1,985	96	18	125
7	Lofa	86852	41730	6960	8,632	10421	1485	1170
8	Margibi	34997	16815	931	2,068	0	0	1598
9	Maryland	12681	6093	800	1,476	0	36	999
10	Montserrado	38109	18310	4555	7,336	363	998	2423
11	Nimba	166761	80124	9183	18,888	17097	7690	8660
12	River cess	18966	9113	951	3,014	276	132	194
13	Sinoe	22055	10597	2044	3,347	0	115	227
14	River Gee	12823	6161	752	1,326	855	41	175
15	Gbarpolu	16661	8005	783	1,872	454	38	174
	National	**697605**	**335180**	**36690**	**65724**	**33350**	**12720**	**25125**

2.3 BIOENERGY POTENTIAL OF AGRICULTURAL CROP RESIDUES

Estimating bioenergy from agriculture residues was followed by some procedures and methods adapted from Bharti et al., (2021) ; Tanyi & Adaramola (2023) ; and Tolessa (2023). The crop residues can be primary or secondary residues. Primary residues can be generated during crop harvesting and processing in farms as well as secondary residues generated during industries processes. Surplus residue potential is the residue that remains after any competing uses (including cow feed, animal bedding, heating and cooking fuel, and organic fertilizer), whereas gross residue potential is the overall amount of residue produced. The unused (surplus) availability portion is thereby used to produce bioenergy. A standard procedure is followed to estimate the gross and surplus potential which are discussed below.

2.3.1 GROSS RESIDUE POTENTIAL

Before the calculation of the biomass residue from crop production, the residue-to-product ratio for each crop residue from a county level was obtained from various literatures as shown in Table 2.

$$G_r = P * RPR \tag{1}$$

Where Gr corresponds to the gross residue produced (t year-1); P represents the biomass produced by each crop (t year-1); RPR corresponds to the residue-to-product ratio, which relates the generated biomass residue to the total produced biomass (dimensionless). The produced crop value was sourced from the LISGIS 2017 and FAOSTAT 2021 database, while the RPR values given in Table 2 were obtained from already published studies.

As was previously mentioned, the study considered 7 agricultural crops divided into 4 categories as root crop (Cassava), cereal(rice), cash crops (sugar cane, cocoa and oil palm), as well as fruits crop (Banana and Plantain) with the total of 18 residues. Figures 6 show samples of some of the residues used during this study.

Figure 6. Samples of crop residues used in this study from Liberia

Table 2 shows the 18 residue types (stalk, straw, husk, peelings, shell, pod, pruning, leaves, stem, tops, bagasse, fibers, fronds) and their respective residue-to-product ratios (RPR) range and average including their references. Accordingly, to reflect more climatic and agricultural conditions this study has covered numerous explored specific areas for crop residues in different countries around the World.

Table 2. Residue-to-crop ratio

Crop Group	Crop Type	Residues	RCR/RPR/CRR Range	Average	References
Root Crop	**Cassava**	Peels	0.25 - 0.91	0.58	(Milbrandt, 2009; Tanyi & Adaramola, 2023)
		Stalks	0.20 - 1.00	0.6	(Jekayinfa et al., 2020)
		Straw	1.10 - 2.00	1.55	(Tanyi & Adaramola, 2023)
Cereal	**Rice**	Husk	0.20 - 0.36	0.28	(Jekayinfa et al., 2020; Morato et al., 2019)
		tops	0.05 - 0.32	0.185	(Kemausuor et al., 2014)
	Sugar Cane	Leaves	0.05 - 0.32	0.185	(Morato et al., 2019; Tanyi & Adaramola, 2023)
		Bagasse	0.10 - 0.61	0.355	(Jekayinfa et al., 2020)
		Pods	1.5 - 2.10	1.8	(Kemausuor et al., 2014)
	Cocoa	Pruning	1.5 - 2.10	1.8	(Tanyi & Adaramola, 2023)
		Fibers	0.11 - 1.10	0.605	(Kemausuor et al., 2018 ;Tolessa, 2023)
		fronds	0.23 - 2.6	1.415	(Mujtaba et al., 2023)
Cash Crops	**Oil Palm**	Shells	0.05 - 1.00	0.525	(Tanyi & Adaramola,2023; Tolessa, 2023)
		Peels	0.25 - 0.45	0.35	(Gabisa & Gheewala, 2018; Patiño et al., 2016)
		Stem	4.0 - 5.6	4.8	(Siegrist et al., 2022)
	Banana	Leaves	0.25 - 3.5	1.875	(Patiño et al., 2016b; Tanyi & Adaramola, 2023)
		leaves	0.25 - 0.50	0.375	(O'Shea et al., 2017)
		Stem	3.91 - 5.00	4.455	(Tanyi & Adaramola, 2023)
Fruit Crops	**Plantain**	Peels	0.25 - 0.35	0.3	(Jekayinfa et al., 2020; Morato et al., 2019)

For better results, this study considered three major things to secure food security; soil conversion, animal feeding as well as moisture content. Soil organic matter (SOM) is important for providing nutrients to plants and maintaining the physical properties of the soil. Over the long term, removing excessive residues can lead to soil erosion and compaction (Singh & Kalamdhad, 2022). With this, some of the residues need to remain on the land. This study considered several pieces of literature in Table 2 as the residue left on the land for sustainable soil conservation. Typically, some agricultural waste is used as animal feed. Since there is no general information available on the use of residues in Liberia, in confirmative of the literature (Koua et al., 2022) has been used here instead, assuming the same animal feeding requirement. The residue moisture content depends on crop type and climate conditions. The moisture content affects conversion technology selection and the process design.

2.3.2 Surplus residue biomass potential

This study assumed that not all crop residue biomass would be available and suitable (because of variations in nature, competitive uses and technical limitations) for both bioenergy and biohydrogen production. The quantity of field-based residue that can be reasonably collected is calculated using the crop residue biomass recoverability fraction (RF) or surplus availability factor (SAF) (Gabisa & Gheewala, 2018) . The RF is the portion of residues that can realistically be used to generate bioenergy or biohydrogen after some of it has been used elsewhere (Halder et al., 2014) . The crop residue RF values were taken from relevant literature to estimate the surplus residue potential because of the lack of data specifically for Liberia. This information is provided in Table 3.

Table 3. The Surplus Availability Factor (SAF) and Lower Heating Value (LHV) for studied crops

Crop Type	Residue Type	SAF	LHV (MJ/KG)	Sources
	Peels	0.2	10.61	(Tanyi & Adaramola, 2023)
Cassava	Stalks	0.407	16.99	(Tanyi & Adaramola, 2023)
	Straw	0.684	8.83	(O'Shea et al., 2017)
Rice	Husk	0.83	12.9	(O'Shea et al., 2017)
	tops	0.8	15.8	(Tolessa, 2023)
Sugar	Leaves	0.8	15.8	(Tolessa, 2023)
Cane	Bagasse	1	6.43	(Gabisa & Gheewala, 2018)

	Pods	1	15.48	(Gabisa & Gheewala, 2018)
Cocoa	Pruings	1	15.48	(Mboumboue & Njomo, 2018)
	Fibers	1	19.94	(Tanyi & Adaramola, 2023)
	fronds	1	7.97	(Patiño et al., 2016)
Oil Palm	Shells	1	21.1	(Tanyi & Adaramola, 2023)
	Peels	1	17	(Tanwar et al., 2022)
	Stem	1	11.66	(Tanwar et al., 2022)
Banana	Leaves	1	11.37	(Tolessa, 2023)
	leaves	0.8	12.12	(Gabisa & Gheewala, 2018)
	Stem	0.8	10.9	(Kemausuor et al., 2014)
Plantain	Peels	1	12.56	(Tolessa, 2023)

Equation (2) is used to calculate the surplus residue potential:

$$SCRP = G_r * \ RF \tag{2}$$

where, surplus crop reisdue production (*SCRP)* is the potential of generated surplus crop residue from "*t*" number of crops, tons (t); *Gr* is the generated gross residue potential; and *RF* is recoverability factor of the crop.

2.3.3 BIOENERGY POTENTIAL ESTIMATION

The bioenergy potential of agricultural residue biomass is estimated using the following calculation (Equation 3).

$$EP = SCRP * \ LHV \tag{3}$$

where EP is the potential of bioenergy from crops at particular in megajoule (MJ); *SCRP* is the surplus crop residue; LHV is the lower heating value of crop at the region. The lower heating values of the residues considered in this study were obtained from the literature as presented in Table 3. In addition, equation 3 was given by (Mboumboue & Njomo, 2018)for determining bioenergy potential.

2.3.4 BIOHYDROGEN POTENTIAL

Under anaerobic conditions, both facultative and obligate anaerobes carry out mixed acid fermentation. Dark fermentation is a term used to describe a process where no light energy is needed for the processes in contrast to photolysis and photo-fermentation. A benefit of this is that, unlike the need for light-dependent processes, hydrogen can be constantly produced (Cao et al., 2022). To calculate the crop residue's potential to produce hydrogen, it was considered that the composition of each residue is determined. Table 3 shows each of the 18 residues and their various components. In this process Clostridium spp. converts either to glucose ($C_6H_{12}O_6$) or sucrose ($C_{12}H_{12}O_{11}$) to acetic acid (CH_3COOH) including CO_2, and hydrogen with the use of [FeFe]-hydrogenases. Hydrogenase helps to transfer the electrons from Fd to H+ in the net reactions producing hydrogen (Dunbar et al., 2023) *:*

$$p_1C_XH_YO_Z + \ p_2H_2O \ \rightarrow n_1CH_3COOH \ + n_2CO_2 + \ n_3H_2$$

$$mH_2 = \frac{n_3}{p_1} * \frac{m_{C_XH_YO_Z}}{MC_XH_YO_Z} * MH_2 \tag{4}$$

where mH_2 is the mass of hydrogen produced from each crop residue in either tonnes or kg; n_3 is the number of moles of hydrogen after balancing the above equation, p_1 is the number of mole of glucose or sucrose from the residue examined; $m_{C_XH_YO_Z}$ is the mass of residue; $MC_XH_YO_Z$ refers to the molar mass of the carbohydrate and MH_2 is the molar mass of hydrogen. In other to obtain the hydrogen for each crop residue, the ultimate analysis of carbon, hydrogen and oxygen were taken into consideration as seen in Appendix 17. After determaining the organic content, it was balanced to obtain the number of moles for both the glucose(p_1) and hydrogen(n_3). The gathered moles are used in equation 4 to calculate each of the 18 residues in Table 3. There are no records for biohydrogen production process in Liberia, so in the case the formula (Al-Haddad et al., 2023) was used, which has also been used for hydrogen production through dark fermentation.

2.4 AGRICULTURE RESIDUES INTENSITY MAP

In this study, spatial distribution maps based on the total agriculture crop availability in Tonnes per year (t/yr), crop yield in t/ha/yr, the characterizations of the seven (7) crop residues, and the location of key counties. There are few stages that contributed to the usage of ArcGIS and QGIS; firstly, each residue from a crop was calculated from the crop produced to obtain gross residue (equation 1). Secondly, the value obtained from gross residue was used to estimate the surplus residues with the aid of equation 2. Thirdly, total surplus crop residue quantity were both evaluated for either bioenergy or biohydrogen production potential using both equations 3 or 4, after it was tabulated into MS Excel and converted into a form that cuould open in ArcGIS software for possible mapping. These steps were used for all of the maps in this study to generate using of data collected from agriculture crops in Liberia.

3 RESULTS

3.1 Gross crop residue potential

The annual gross crop residue produced with the help of crop production statistics taken into consideration the weight of the crop and then with the use of necessary crop-to-residue ratios is estimated that some 2,171,843 t/yr of selected agricultural crop residues for all fifteen counties (Figure 9). As shown in Figure 7, the crop residue production for cassava (both peels and stalks) was higher, while residues for sugar cane had the least due to the low production outcome. The crop residues followed the trend of cassava residues > rice residues > plantain residues > banana residues > cocoa residues > oil palm residues > sugar cane as shown in Figure 7. The proportion of fruits crop residues was 837,723 t/yr (34 %), followed by root residues with 34 % (823,173 Tonnes), another with cash crop residue of 170,646 Tonnes accumulating 7% and 25% for cereal (613,379 Tonnes).

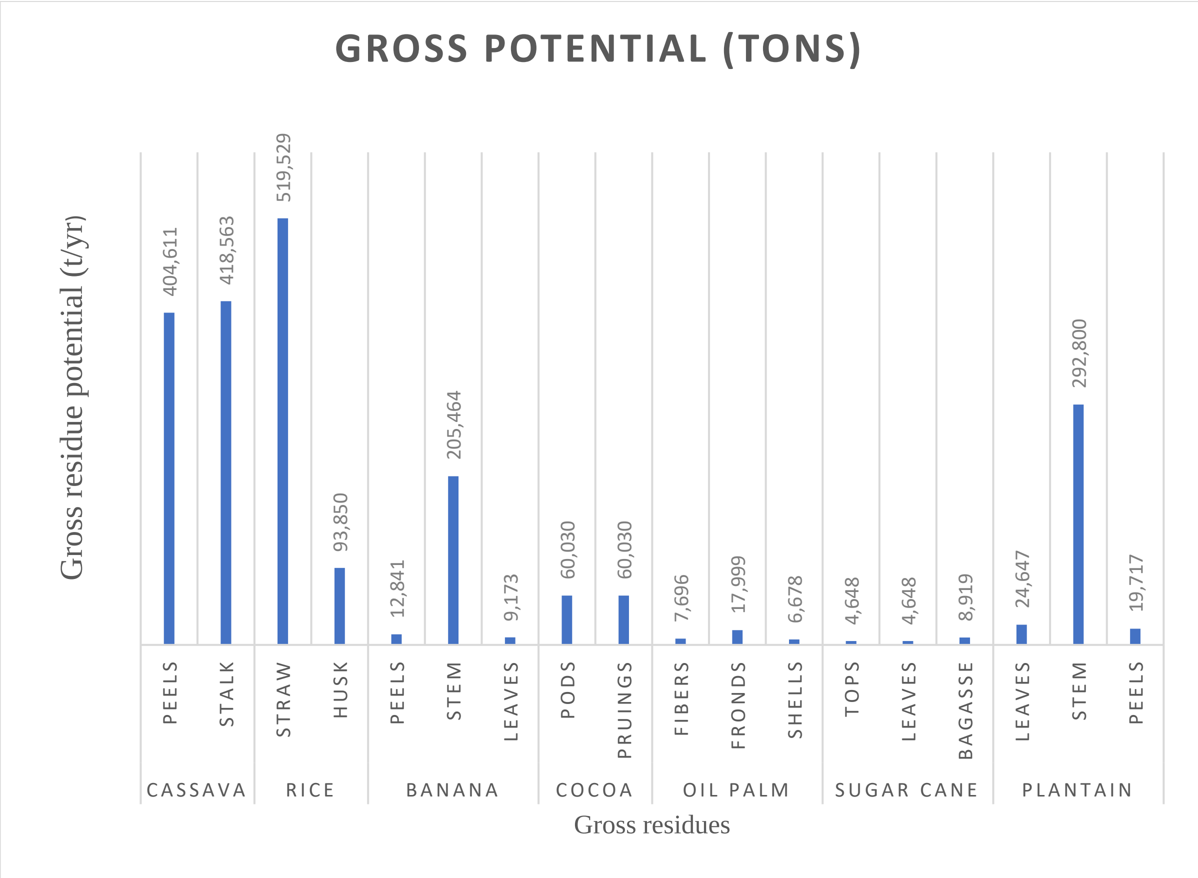

Figure 7. Gross agriculture crop residue potential

A as shown in Figures 8 and 9, among the fifteen counties, Nimba had the highest gross agriculture residues of 584,633 tonnes (27%) followed by both Bong County 14% (313,831 tonnes) and (308,428 tonnes) 14% in Lofa county as well as Maryland 39,461 tonnes (2%) and River Gee 2% (41,179 tonnes) being the least among the rest of the 12 counties (see also Appendixes 13,3,9 and 11,15).

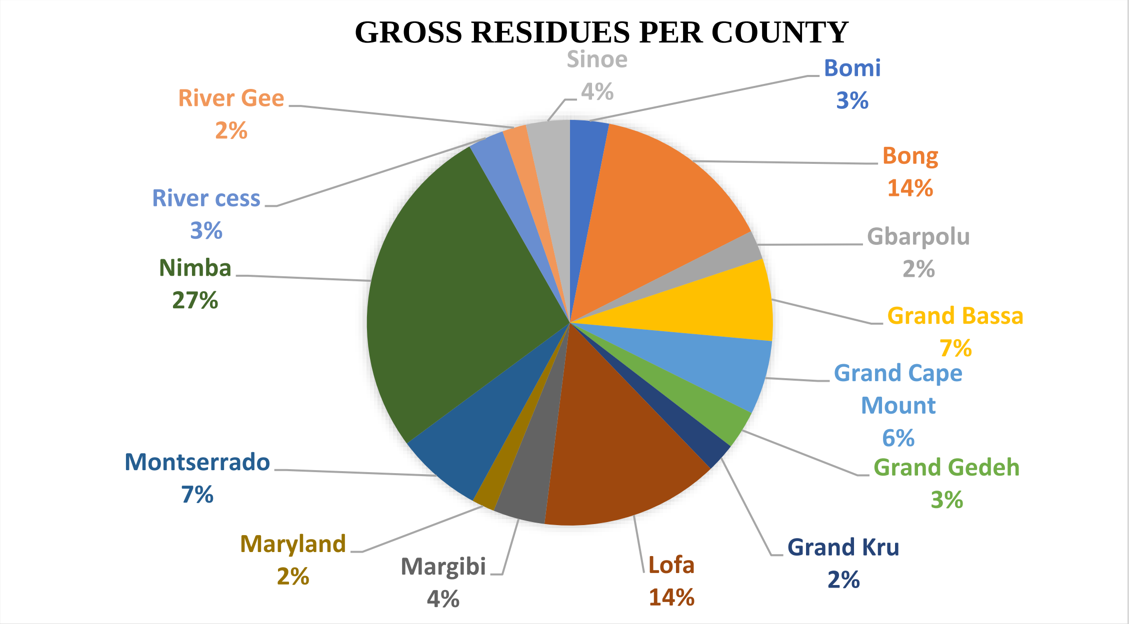

Figure 8. Total gross residue in Liberia per county

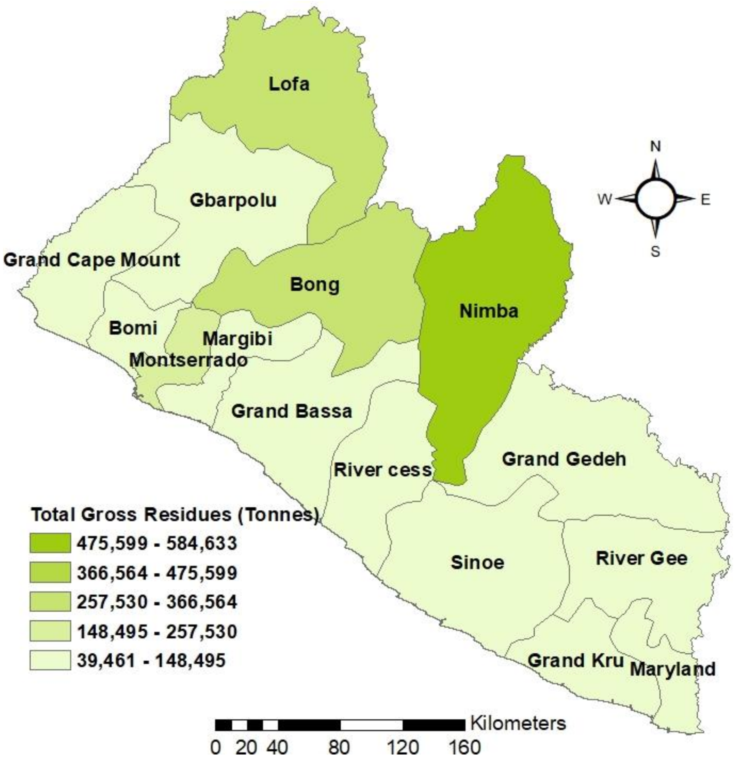

Figure 9 Gross Total Residues Per County

3.2 Surplus agriculture residues

Figure 10 shows the surplus residue potential portion of the selected crops. The total national surplus residue potential is approximately only 1,204,033 t/yr, indicating that 55.4% of the gross residue is available as surplus. The consideration parameters of approximately 44.6% (967,810 Tonnes) were used for soil fertilizer, animal feeding and cooking, respectively. Fruit contributes the highest amount of surplus residue (455, 655 Tonnes), followed by cereal crops (330, 587 Tonnes), root crops (251,277 Tonnes), and other cash crops (cocoa, oil palm and sugar cane) (166, 513 Tonnes) on a yearly basis shown in Figure 10.

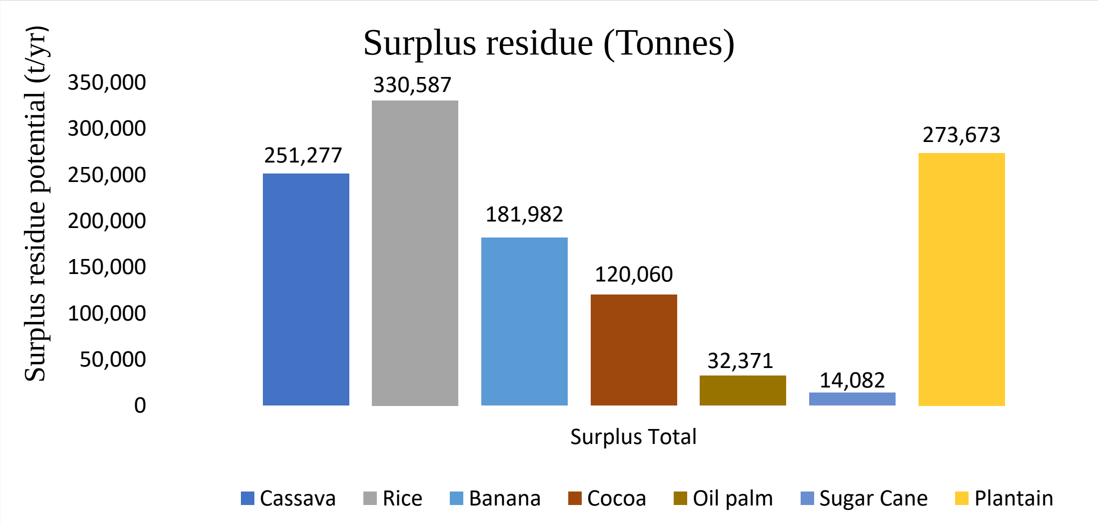

Figure 10. Surplus residue potential

At the individual group level, rice contributes the most surplus residue (27%), followed by plantain (23 %), cassava (21%), banana (15%), cocoa (10%), oil palm (3%), and sugar cane (1%) becoming the least among the studied crops as shown on figure 11.

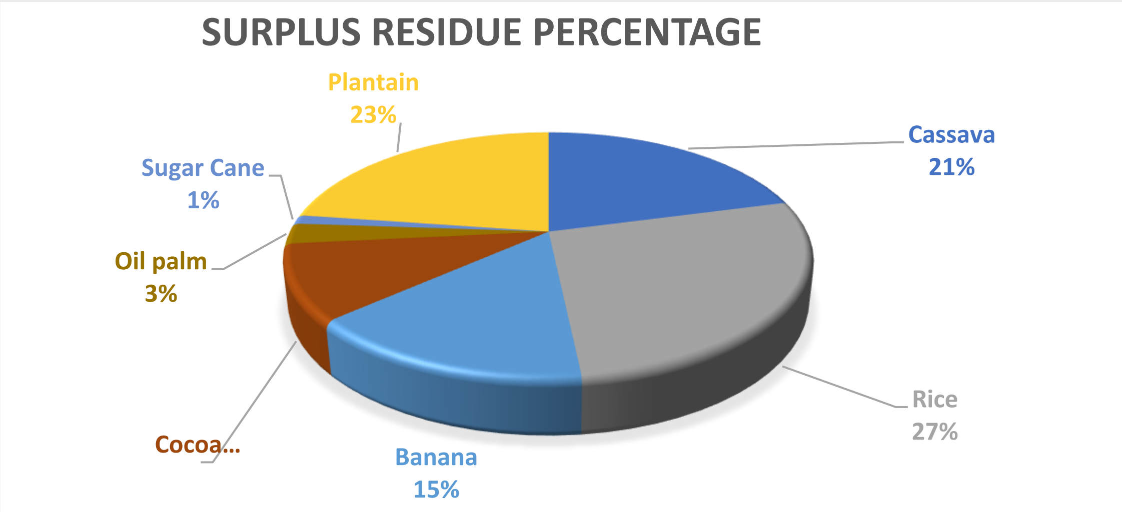

Figure 11. Surplus residue potential in percentage

Concerning the surplus residue potential spread up by counties, Nimba produces the highest amount (349,266 Tonnes) followed by Lofa (184, 858 Tonnes) and Bong (154,500 Tonnes) counties as shown in (Appendices 13, 3 & 9) with the lowest produced from Grand Kru (27,256 Tonnes), River Gee (23,227 Tonnes), and Gbarpolu (27, 404 Tonnes) amongst the fifteen counties studied. Crop group-wise surplus potential for all the counties of Liberia are presented in Figures 13-19. The calculation of each county is also seen in Appendices 2 to 16.

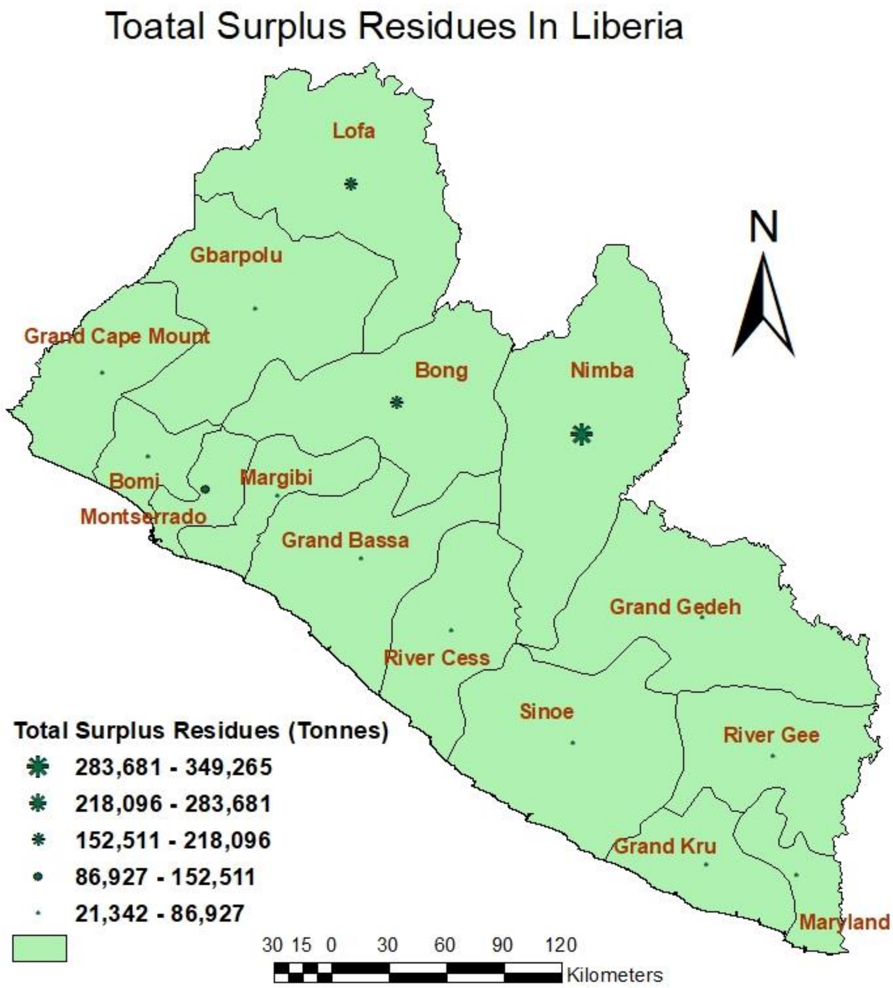

Figure 12. Total surplus residues by counties

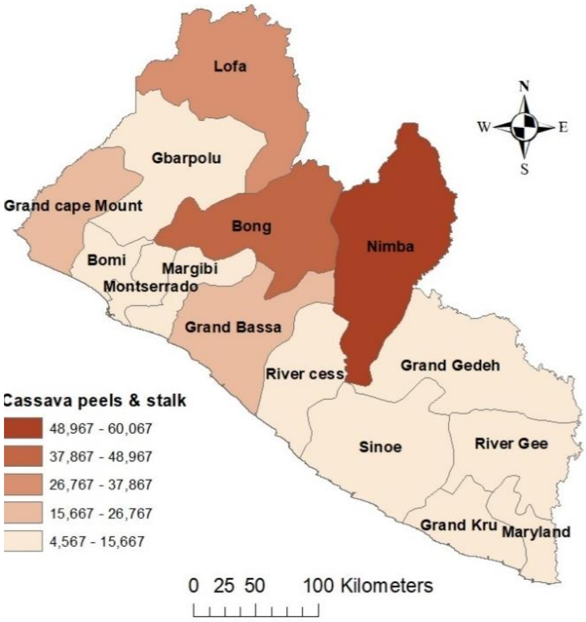

Figure 13. Surplus cassava residue

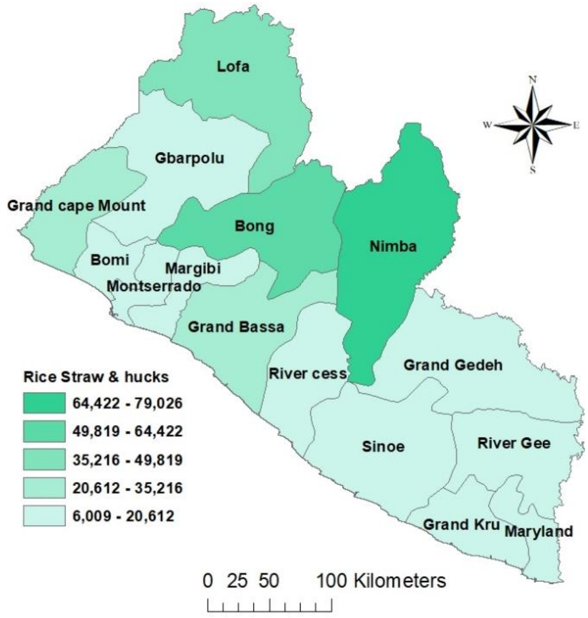

Figure 14 . surplus rice residue

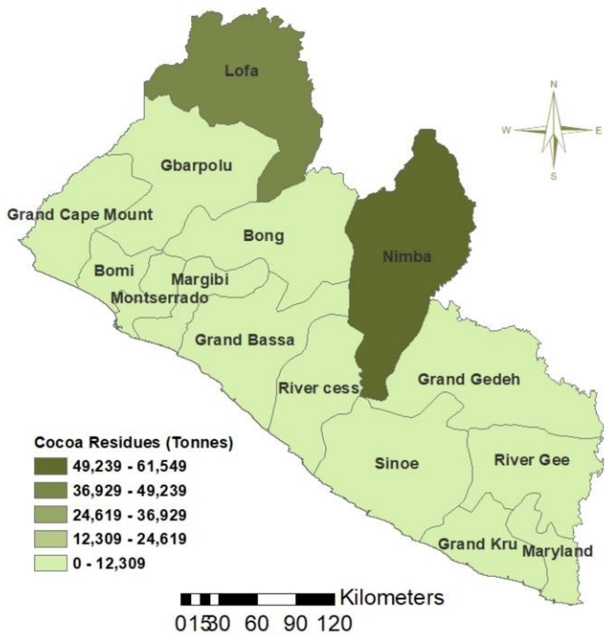

Figure 15. Surplus cocoa residues potential

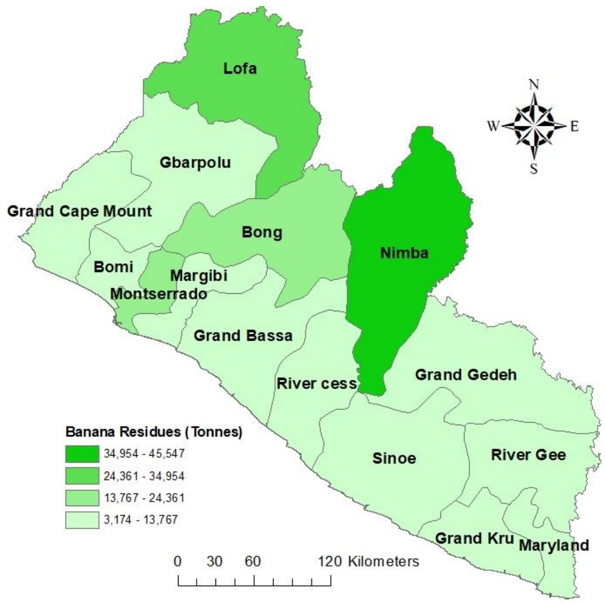

Figure 16. Surpuls banana residues potential

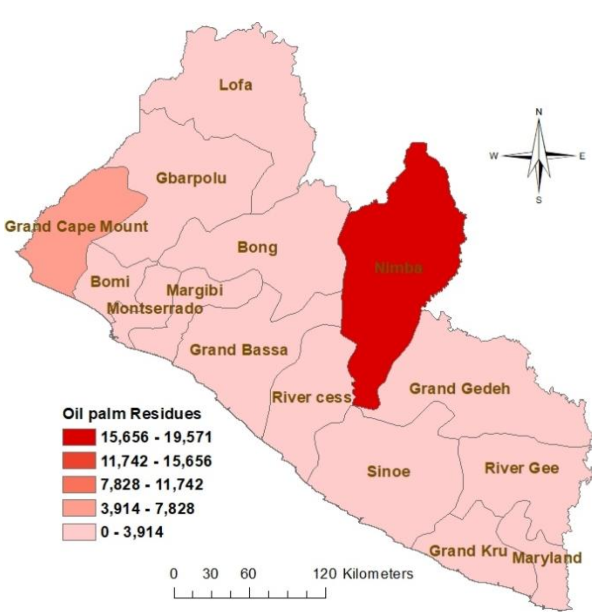

Figure 17. Surplus oil palm residues potential

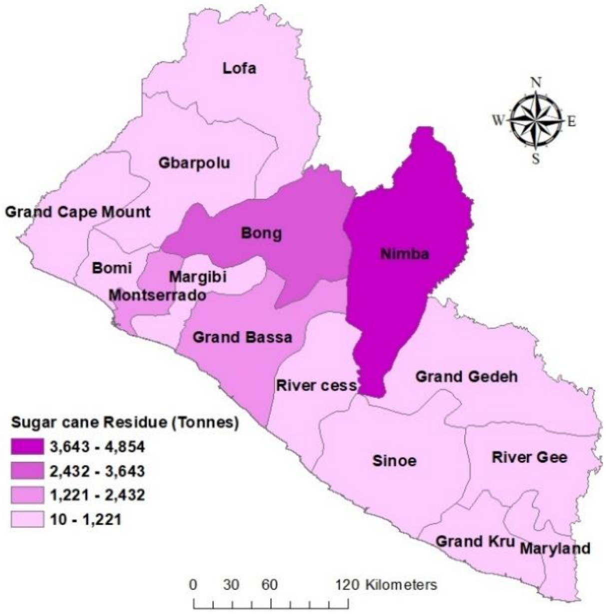

Figure 18. Surplus sugar cane residues potential

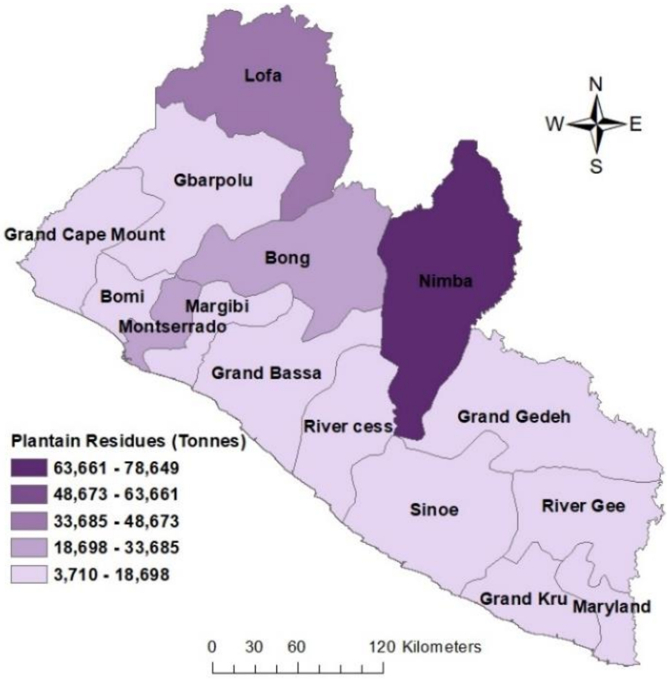

Figure 19. Surplus plantain residues potential

Figure 13 (see also Appendices 2-16) shows the total estimated amount of two surplus residues for cassava stalk (170,355t/yr) and cassava peels (80,922t/yr) which produces 251,277 t/yr considering the entire nation. Among the total, Nimba (23.9 %), Bong (17.2 %), Lofa (12.4 %) and Grand Cape Mount (7.5%) has the highest surplus with the possibility of producing energy. Cassava is largely used in the country for numerous food types.

Figure 14 shows that Nimba produces the highest (79,026 t/yr), followed by Bong 57,035 t/yr, and Lofa counties as well as the least coming from the rest of the counties and River Gee, Maryland counties becoming the very least among 12 counties.

Also, Figure 11. shows rice residue to be the highest among residue with 27.4% of 1,204,039 t/yr. With rice being the stable food for country, Liberia stands to even produce more than this number when it starts to produce in larger quantity.

As presented by Figure 15, cocoa is grown predominately on medium scale production system in Liberia. Pruning are either left in the field or used as firewood by households. This pruning process would yield about 60,030 t/yr as well as pods 60, 030 t/yr with the sum of 120,060 t/yr. with this amount, Nimba had the highest of 61,549 t/yr corresponding to 51.2%, followed by Lofa 37,515 t/yr (31.2%) and the least Maryland, Margibi and Sinoe 0% (also see Appendices 2-16).

It shows in Figure 16 that banana is one of the major products in Liberia serving as food crops. It is essential to food security during the hunger period and is cultivated by small-scale farmers in every county for household consumption as well as market supply. Surplus annual potential is 181,982 t/yr, which Nimba provides 25% (45,548 t/yr) >Lofa 34,522 t/yr (18.9%) > Montserrado 22,593t/yr (12.4%) > Bong 9.7% (17,772t/yr) and (also see Appendices 2-16).

Figure 17 shows that Nimba and Grand cape mount have the highest oil palm residues followed by Lofa, Montserrado, Grand Gedeh, Gbarpolu, River Gee, Grand Kru and Maryland counties had the least oil residues. The surplus of the three different residue for oil palm includes fronds (17, 998 t/yr) > Fiber (7,695 t/yr) shell (6,678 t/yr) and the total residues of (32,371 t/yr) which can also be seen in Appendices 2-16. According to data from LISGIS 2017, Grand Bassa and Margibi counties lack data on oil palm production. Oil palm cultivation is done on small household farms and medium- to large-scale in recent times.

Sugar cane is well grown in Liberia due to the pleasant climatic condition but the estimated surplus is 14,082 t/yr which is the least among all of the crops studied. A manuet quantity is produced for local consumption and the syrup are sold locally. In addition, it is mainly harvested for cane juice (liquor) that is traded around the Ivory Coast border and is an important income source. In so doing, Figure 18 shows Nimba (4,854 t/yr) > Bong (2,951 t/yr), Grand Bassa (1,999 t/yr) and Montserrado has the highest surplus residues and Grand Kru (70 t/yr) > Grand Gedeh (10 t/yr) the least (see also Appendices 2 to 16).

Another major cash and food crop in Liberia that every county produces at least a little of is plantain. It helps in fighting food insecurity during hunger season. Therefore, it is not by mistake the second highest surplus residue in the study with 273, 674t/yr corresponding to 22.7% among the residue selected for this study. As shown in Figure 19 (see also Appendices 2-16), Nimba remains the topmost county 78,649 t/yr (28.7%) > Lofa (35, 943 t/yr) > Montserrado (30, 347 t/yr) > Bong (28, 273 t/yr)> Grand Bassa (16, 710 t/yr) and three least counties Maryland (6,146 t/yr) >River Gee (5, 521 t/yr) > Bomi (3, 710 t/yr).

3.3 Bioenergy potential

Based on the surplus portion of residue, the annual correspondent bioenergy potential was estimated as (20,276 TJ/yr), equivalent to 5,632 GWh of electricity. The variations in yield, cropped area, and surplus of residue are some major factors resulting in surplus residue potential amongst the counties. Furthermore, Figure 20 shows that crop residues with the highest bioenergy potential are rice, cassava, plantains, banana and cocoa with estimated bioenergy potentials of 5,517 TJ/y> 4,648 TJ/y > 4,398 TJ/y > 2,921 TJ/y and 2,161 TJ/y are the major selected surplus crop potential in Liberia.

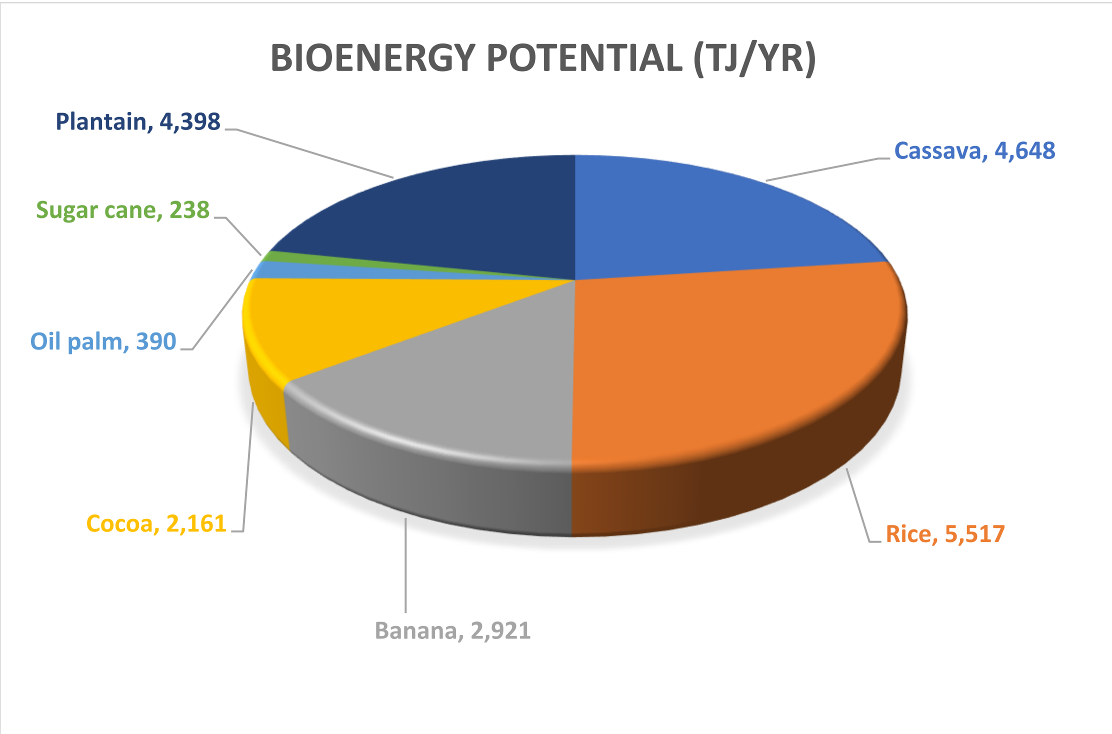

Figure 20. Bioenergy potential from crop residues

Counties-wise variation in bioenergy potential ranges from the highest Nimba (5,851 TJ/yr) to the lowest (357 TJ/yr) in Maryland Figure 21 (see also Appendix 11). It is also observed that counties like Lofa and Bong presented a range of 5,119 -5,485 and 4,753 -5118 Tonnes of bioenergy production potential, respectively. Grand Cape, Montserrado and Grand Bassa represented values between 3,653 – 4,752 Tonnes of potential from surplus residues which are also shown in Appendices 5,12 and 6, respectively. As shown in Figure 21, nine counties categorized in the assortment between 357 – 3,653 Tonnes bioenergy potential. The high energy contents of these crops can be attributed to their high production quantities, residue-to-product ratios and heating values of their residues.

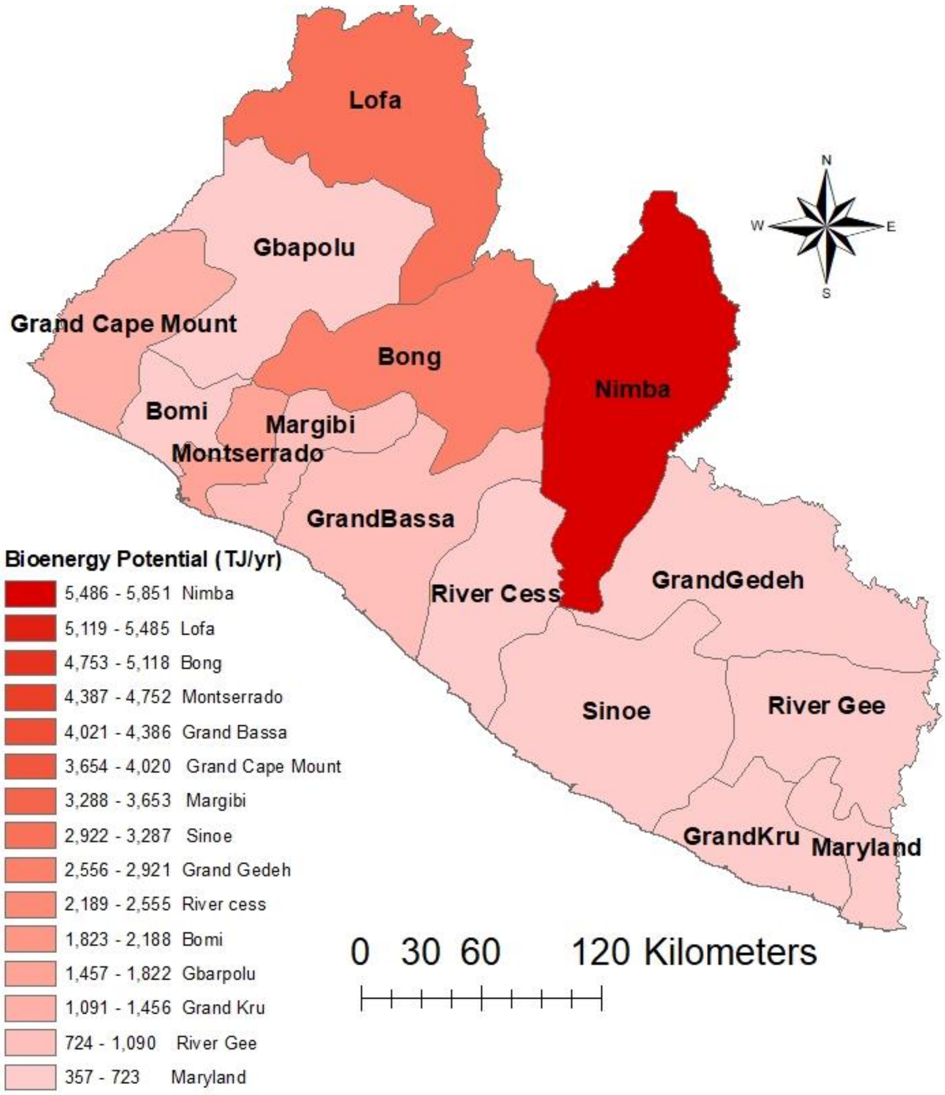

Figure 21. Bioenergy potential per county in Liberia

3.4 BIOHYDROGEN POTENTIAL

As shown in Figure 22, the corresponding biohydrogen content is about 81,430 Tonnes, equivalent to 81,430,275 Kg. The leading residues include cassava stalk and peels, rice straw, plantain stem and banana stem is shown in Figure 22. In addition, it is shown in Figure 23 that again Nimba County has the highest hydrogen potential at 23,144,000kg after converting 2,171,843 t/yr of surplus residues to biohydrogen.

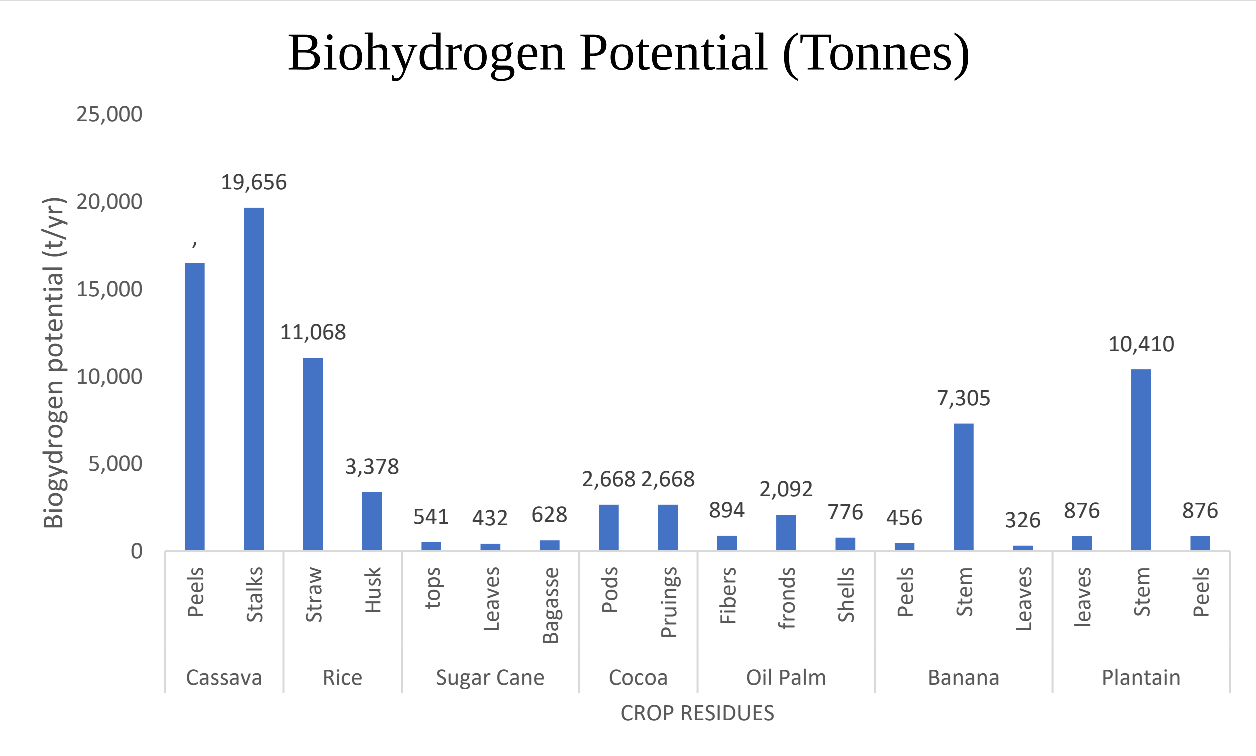

Figure 22. Biohydrogen production potential from crop residues

Deducing from equation (4), approximately 81,430 Tonnes of biohydrogen potential from surplus residue. In Figure 23 among the fifteen counties; Nimba, Lofa, Bong, Montserrado and Grand Bassa produces high quantity of hydrogen from surplus residues in other of 23,143.7 Tonnes > 11,605 Tonnes > 11,342 Tonnes > 5,625 Tonnes > 5,188 Tonnes. The next counties production potential ranges from Grand Cape Mount (4,876 Tonnes) > Margibi (3,222 Tonnes) > Sinoe (2,717 Tonnes) > Bomi (2,459 Tonnes) > Grand Gedeh (2,429 Tonnes). Figure 23 also shows the lowest five counties that produced low amount of hydrogen from agriculture crop residues.

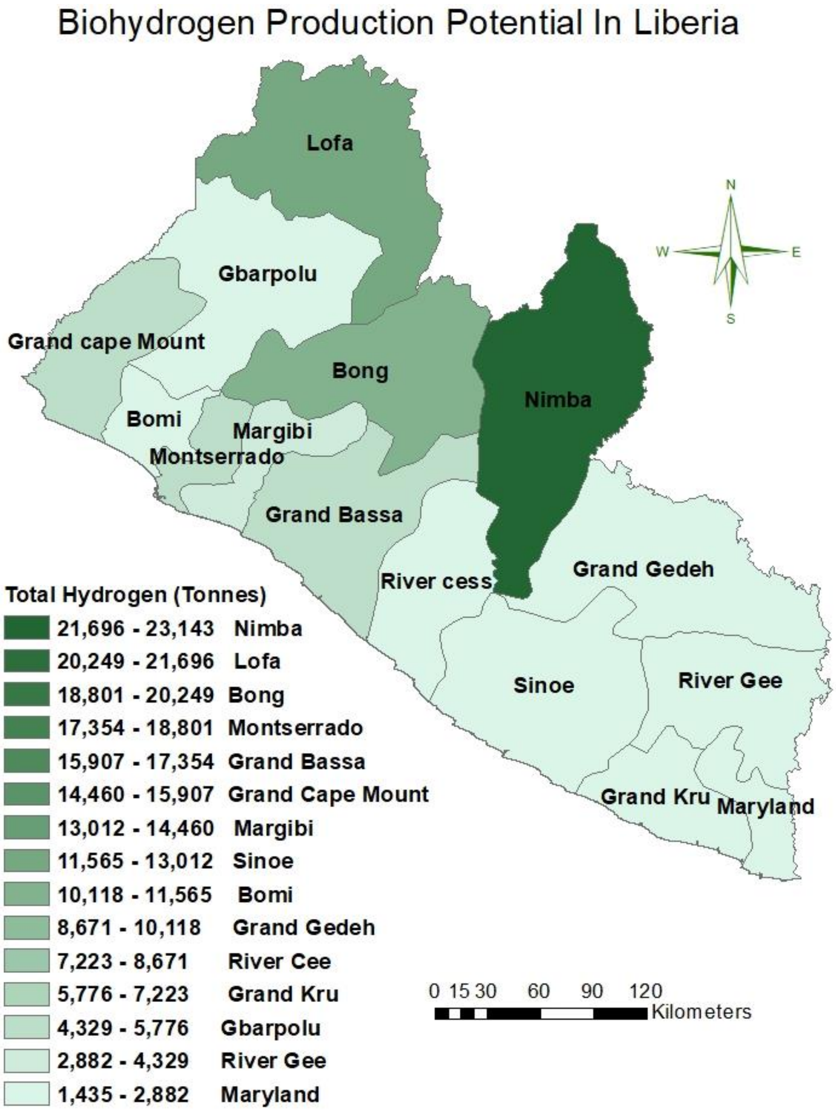

Figure 23. County-wise biohydrogen production potential from agriculture crop residues

3.5 Hotspot and fueling stations from hydrogen production

The areas shown in Figure 24 have therefore been considered to be favorable for energy and power potentials as well as Figure 25 is conducive for biohydrogen fueling. As a result, this energy will help businesses, and the transportation sector, and provide houses with electricity. There are several parameters to in suggesting power plant.

In Table 4, consideration of population is very essential and also drives to meet the selection of location for fueling stations. In addition, an average distance between the main cities is also considered with advantageously national roads. It further projects possible power plant in accordance to easy assescibility and with the connection to biger cites.

Table 4. Power plant and fueling stations determination

No.	County	Population	Cities	Crop residue distribution on power Plant
1	Bomi	133,668	Tubmanburg	Power plant 4
2	Bong	467,502	Gbarnga	Power plant 2
3	Gbarpolu	95,995	Bopolu	Power plant 5
4	Grand Bassa	293,557	Buchanan	Power plant 6
5	Grand Cape Mount	178,798	Robersport	Power plant 5
6	Grand Gedeh	216,692	Zwedru	Power plant 7
7	Grand Kru	107,342	Barclayville	Power plant 7
8	Lofa	367,376	Voinjama	Power plant 3
9	Margibi	304,946	Kakata	Power plant 4
10	Maryland	172,202	Harper	Power plant 7
11	Montserrado	1,920,914	Bensonville	Power plant 4
12	Nimba	621,841	Sanniquellie	Power plant 1 & 2
13	River cess	90,777	River cess	Power plant 6
14	River Gee	124,653	Fish Town	Power plant 7
15	Sinoe	150,358	Greenville	Power plant 7
	Total	5,246,621		

As shown in Figure 24, seven power plants are marked for proposed biohydrogen production. These areas are suitable due to the huge amount of residue found after determining the biohydrogen potential in each of the spotted locations. Power plant one (P1) is located in the densely crop residue location of Nimba which has the capacity of producing approximately 23, 143 Tons of biohydrogen. This is followed by power plant 2 situated in Bong with 11,342 Tons of which the towns near Bong from Nimba can accommodate due to its huge potential of residues in Nimba. P3 being situated in the far east northern county of Lofa, will serve the entire county with its biohydrogen potential of 11,605 Tons. P4 is suituated in Montserrado that will serve Migibi, Bomi and part of Bong counties. Grand Cape Mount and Gbarpolu counties will supply power plant 5 (P5) due to low surplus residue potential. Due to the high content of biohydrogen from cassava residue and Grand Cape Mount producing a considerable amount, it will bring relief to the surrounding by collecting residues to produce. The south-central part of the country is cardinal in performing major impact to collect crop residues from Grand Bassa and River Cess as well as other counties from the north. From Figure 24, all the southeastern counties can join to have one power plant that can ease residue collection and production. Having a low residue amount from the five counties, joining them may meet the production potential from P7.

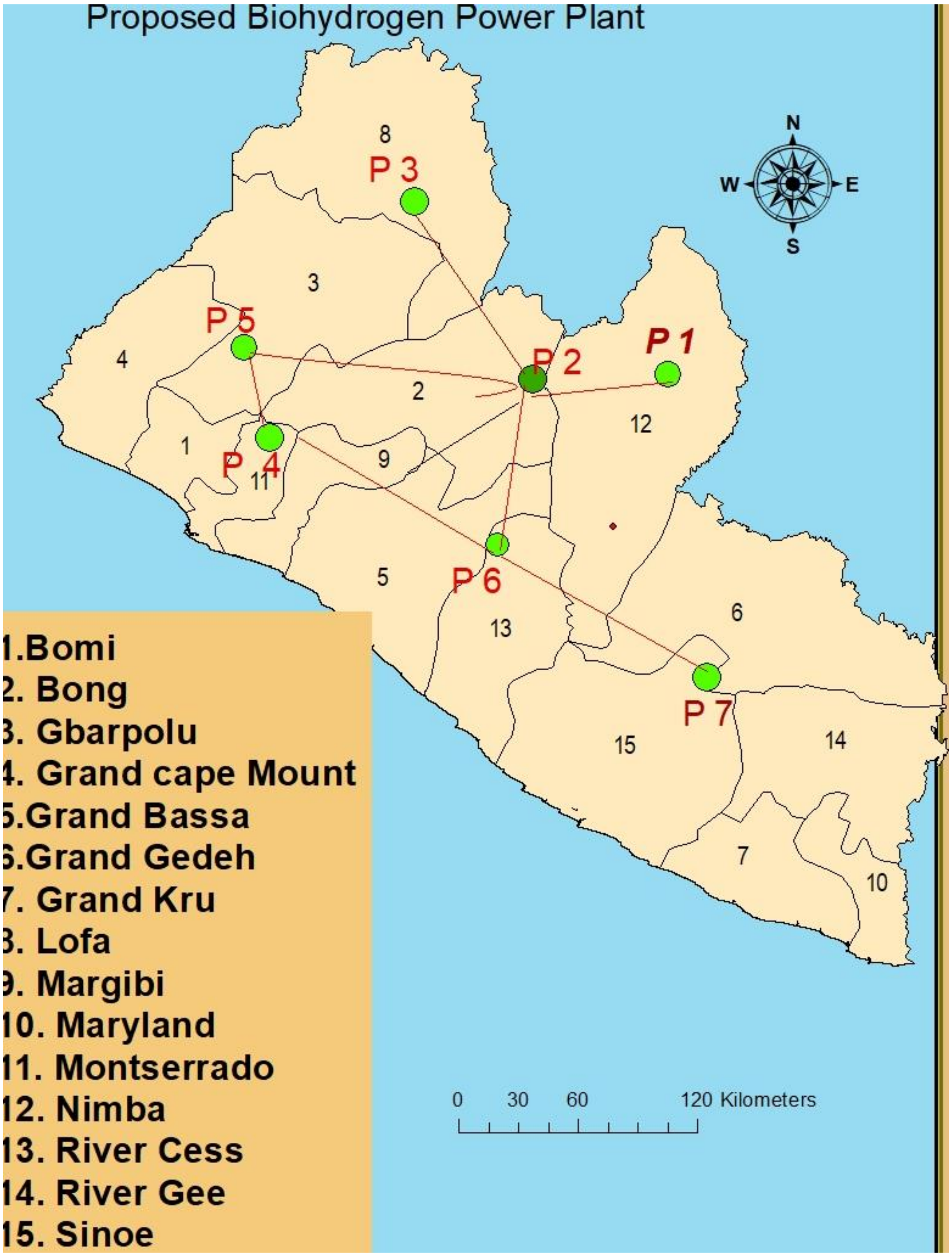

Figure 24. Biohydrogen power plant allocation

Result of fueling stations were plotted in various counties in form of green and white color with the use of ArcGIS 10.8.2. Figure 25. Shows the spatial distribution of fueling station that would assist in transitioning into clean energy mostly in the transportation sector. The identification of population is cardinal to fueling station selection as shown in Table 4. Twenty fueling stations were identified with the highest in Montserrado (three stations) and Nimba (three stations). The population was considered in the selection. Monrovia is situated in Montserrado thereby allowing it to be one the highest in contrast to Nimba which produces huge amount of biohydrogen. Other stations are placed in Bong, Margibi and Lofa counties not more than three. For the south-central regions have theirs in its county's capital cities. The south eastern region have four biohydrogen fueling stations that can supply their clean energy needs and improve access to renewable energy.

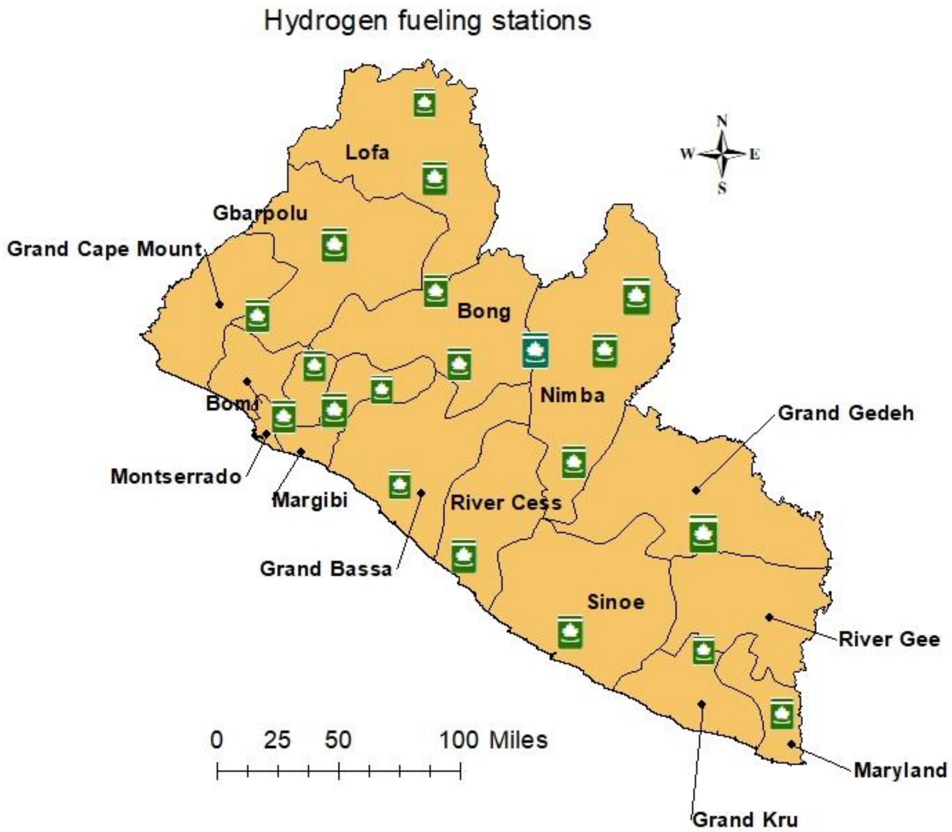

Figure 25. Biohydrogen proposed fueling stations

4 DISCUSSION

4.1 GROSS RESIDUES POTENTIAL

The primary crop residues in Liberia's agriculture system considered seven crops divided into four crop types as shown in Table 2. After the harvesting period or during processing, residues from these crops that are applicable to bioenergy and biohydrogen include straw, stalk, peels, tops, husk, stem, leaves, pods, pruning, bagasse, frond, shell, and fiber. Based on the residues-to-product ratio (RPR), the gross residues in the farming system are estimated on a yearly basis. Based on 18 crop residues produced by the 7 crop types, Liberia's total gross crop residues potential is estimated to be around 2,171,843 Tonnes in 2017. Rice straw had the highest gross residue followed by the rest (cassava stalk, cassava peels, plantain stem, banana stem, rice husk, cocoa pruning, cocoa pods, plantain leaves, plantain peels, oil palm fronds, banana peels, banana leaves, sugar cane bagasse, oil palm fiber, oil palm shells, sugar cane leaves, and sugar cane tops). Casava is the highest 823, 173 t/yr if plantain and banana residues are not combined 837,723 t/yr followed by rice 613,379 t/yr and 170,646 t/yr (sugar cane, cocoa and oil palm) shown in Figure 7. The result confirms that root and fruits are the crops with the highest residue potential, although cereal residue alone was the second topmost residue generated. Preview research (Agriculture team, 2017) revealed when the authors compared cereal and root potential that taken higher quantities of only cereal residue were produced in Liberia than root residues which came second. The counties with the topmost gross residue potential (selected agriculture crop residues) yields were Nimba, Bong and Lofa as well as the least most River Gee, Maryland, and Grand Kru.

The counties with a high gross residue potential can be considered for future research or surveys related to residue biomass. The availability of the different types of residues in the regions agrees with the findings of (Milbrandt, 2009), who reiterated that there are potential crop residues in Liberia that is possible of producing bioenergy for the country.

4.2 SURPLUS RESIDUE

A little over half of the total gross residue can be sustainably used for energy generation. According to (Gielen et al., 2019), concorded that half of the crop residue can be adequately retrieved and the other half is economically collected. To retain several residue resources for soil conversion and purpose creates the possibility of using the surplus potential as raw materials for energy generation (Molina-Guerrero et al., 2020).

Even though cassava produces the most gross residue of any crop, it produces less surplus residue than rice. This is because cassava residues (peels and stalks) have more competing uses (cattle feeding as well as cooking fuel) than rice (straw and husk). Surplus residue potential from plantain and banana (horticultural crops) is also significant in Liberia and is estimated as 273,587 Tonnes and 181,982 Tonnes, respectively.

4.3 AGRICULTURE CROP RESIDUE POTENTIAL FOR BIOENERGY AND BIOHYDROGEN POTENTIAL

The agriculture crop residue energy production is estimated considering the potential biomass resource and conversion technology. The surplus residue bioenergy potential of each residue in Liberia is presented in Figure 20 and shown by county in Figure 21.

The total annual bioenergy potential for all the residues was 20, 276 TJ/yr (5,632 GWh) and 81,541 Tonnes for hydrogen, respectively. The approximately 20,276 TJ/yr energy potential of crop residues is significantly greater than the 2, 100 TJ/yr energy potential in 2009 (Milbrandt, 2009). This can be attributed to the increase in crop productivity of the selected crops and the length of time it has taken. Due to the scarcity of information for the past 14 years, there is no recent study on Liberia's energy system to produce bioenergy from agricultural residues.

Furthermore, the highest energy potential comes from rice straw (4,073 TJ/yr) followed by plantain stem (3,747 TJ/yr) and cassava stalk (2,982 TJ/yr), respectively. It was also determined that sugar cane bagasse (118 TJ/yr) > sugar cane tops (61 TJ/yr) and Sugar cane leaves had the least energy potential. Sugar cane had the least because of the very low crop production in Liberia during this time as shown on Table 1.

It clearly depicts that rice is mostly grown in Liberia than all of the crops. In accordance with (Agriculture team, 2017) , one of the main crops grown by farming households which make up 74% of all home crop production is rice.

The Northern region has the largest regional variation in the yearly bioenergy potential from surplus residue, ranging from 5,851 TJ/yr to 357 TJ/yr (Figures 21). The key determinants of variation in surplus residue potential and subsequently linked bioenergy potential across the nation include cropping pattern, cropped area and yield, and a surplus fraction of residue.

As shown in Figure 21, the northern regions (Nimba, Bong, and Lofa) contribute approximately 57.2 % bioenergy potential. Other parts of the country representing 12th counties generated the remaining 42.8%. This is because these three counties (Nimba, Lofa and Bong) are more involved in agriculture with the added advantage of fertile areas and produce the majority of crops and residues. This clearly demonstrates that these regions of the country have a tremendous amount of bioenergy potential, to a considerable point where they have the capacity to provide massive amounts of bioenergy to other regions. According to (IRENA, 2022), Liberia uses about 297 GWh of energy annually. With this quantity, it is a huge energy resource that can be used to generate electricity. Indeed, according to the study by (Tanyi & Adaramola, 2023), the efficiency of power plants is very important as the residue moisture content plays a pivotal role.

On the other hand, the calculation of hydrogen's annual potential from surplus residues is 81,430 Tonnes corresponding to 81,430,000 kg.

In a study by (Sandikie, 2015) the Government of Liberia (GoL) has set a target of increasing electrification rates to 70% in the capital Monrovia and 35% of rural areas by 2025.

As shown in Table 5, cassava (36,140 tonnes) had the topmost hydrogen production potential of all of the seven selected agricultural crops. The rest of the crop residue potential is followed by rice (14,446 tonnes) > plantain (12,163 tonnes) > banana (8,088 tonnes) > cocoa (5,336 tonnes) >oil palm (3,764 tonnes) and least being sugar cane (1,602 tonnes). Authors like (Dunbar et al., 2023) who researched the dark fermentation process for producing H_2 concorded that cassava has a higher yield of starch and therefore would give higher production potential. Several works done in the literature (Bentsen et al., 2014; Koua et al., 2022), explained multiple sequential processes that could produce more yield of sugar cane. But due to it only being grown for small-scale consumption in Liberia, it has lesser production.

With the use of equation 4, the county's biohydrogen production potential was determined by calculating each of the 18 residues considered in this study as well as the ultimate analysis (see Appendix 17) was considered. After obtaining each biohydrogen production potential, it was summed to obtain the total biohydrogen production potential for the county. These steps were followed by all 15 counties to gather the biohydrogen production potential. With this, Nimba produces the topmost amount of biohydrogen with 23,143 tonnes followed by Lofa (11,605 tonnes) and 11,342 tons (Bong county). The remaining 12 counties with lower hydrogen production are Montserrado (5,625 tonnes) > Grand Bassa (5,188 tonnes) > Grand cape mount (4, 876 tonnes) > Margibi (3,222 tons) > Sinoe (2,717 tons) > Bomi (2,459 tons) > Grand Gedeh (2,429 tonnes) > River Cess (2,234 tonnes) > Gbarpolu (1,823 tonnes) > Grand Kru (1,832 tonnes) > River Gee (1,500 tonnes) and Maryland (1,435 tonnes). In agreement, (Africa Off-grid Project, 2020) identified Nimba county to be the leading in agriculture crop production and the highest amount of crop residue biomass can be obtained. Aiming at the application of biogas which can be further processed to biohydrogen from cassava peels, (Fagbenle & Olukanni, 2022) evaluated the acid-producing bacteria will initially produce acids during fermentation. Acetic acid, H_2 gas, and some volatile fatty acid (VFA), such as butyric acid and propionate will all be produced because of that acid production.

From Table 5 about 1.2 million tons of agriculture crop residues were available for biohydrogen production in 2017. These residues had the potential of producing 81 thousand tonnes of hydrogen which could be used for transportation, electricity consumption in Liberia. Using the estimation methodology used by (Tanyi & Adaramola, 2023), this quantity of biohydrogen is more than 5 times Liberia's total gasoline consumption of 3.48 thousand barrels per day in 2020 (Africa Off-grid Project, 2020). Alternatively, it could also yield between 1.1 to 1.3 billion liters per year of hydrogen which could be used in reducing the demand for biofuel consumption. Considering the electricity generation, crop residues could generate 5,632 GWh, which is 20.6 times the entire country's electricity consumption of 279 GWh in (IRENA, 2022).

Table 5. Hydrogen production potential per crop residue in Liberia (equation 4).

County	Cassava Residues	Rice Residues	Sugar cane Residues	Cocoa Residues	Oil palm Residues	Banana Residues	Plantain Residues	Total Hydrogen (Tonnes)
Bomi	1446	578	13	22	92	142	166	2,459
Bong	6235	2492	313	208	48	790	1256	11,342
Gbarpolu	865	345	11	72	11	173	346	1,823
Grand cape Mount	2713	1084	20	38	479	231	311	4,876
Grand Bassa	2579	1032	212	133	0	491	741	5,188
Grand Gedeh	1036	413	1	204	22	309	444	2,429
Grand Kru	894	357	7	15	6	185	368	1,832
Lofa	4500	1798	69	1668	438	1534	1598	11,605
Margibi	1814	724	97	0	0	205	382	3,222
Maryland	657	262	58	0	10	176	272	1,435
Montserrado	1974	788	146	59	296	1003	1359	5,625
Nimba	8,639	3,456	517	2,736	2,275	2,024	3,496.7	23,143
River cess	982	393	10	44	38	209	558	2,234
River Gee	663	266	11	137	12	166	245	1,500
Sinoe	1143	458	13	0	35	449	619	2,717
Total	36,140	14,446	1,498	5,336	3,762	8,087	12,161.7	81,430

As shown in Table 6, all processes involved in the production of biohydrogen are given. These are results from 7 crop residues identified for this study followed by using of equation 1,2,3, and 4 to obtain both the potential for bioenergy and biohydrogen. Each of the 18 residues from the 7 crops were calculated accordingly.

Table 6. Energy production potential from all crop residues

Crop	Eq.	Gross residue	Eq.	Surplus Residue	Eq.	H_2	Eq.	Bioenergy
Cassava		823,173		251,277		36,140		4,648
Rice		613,379		330,587		14,446		5,517
Banana		227,477		181,982		8,088		2,921
Cocoa		120,060		120,060		5,336		2,161
Oil palm	$G_r = P * RPR$	32,371	$SCRP = G_r * RF$	32,371	$mH_2 = \frac{n_3}{p_1} * \frac{m_{C_xH_yO_z}}{MC_xH_yO_z} * MH_2$	3,764	$EP = SCRP * LHV$	390
Sugar cane		18,215		14,082		1,602		238
Plantain		610,246		273,673		12,163		4,398
Total		2,444,921		1,204,032		81,539		20,273

Table 7 below shows the summary crop residue potential to produce bioenergy and biohydrogen. The corresponding gross residue is 2, 171,843 t/yr and surplus residue of 1,204,033 t/yr considering 55.4 % taken from gross residue. Regarding the energy potential, bioenergy 20,276 TJ/yr and biohydrogen 81,430 Tonnes were both determined.

Table 7. Summary of crop residues and energy potential in Liberia

	Unit	Amount
Gross Residue	t/yr	2, 171, 843
Surplus Residue	t/yr	1,204,033
Percent Surplus	%	55.4
Bioenergy potential	TJ/yr	20,276
Biohydrogen Potential	Tons	81,430

4.4 THE ALLOCATION OF THE POWER PLANT AND AND FUELING STATIONS FROM BIOHYDROGEN PRODUCTION

As shown in figure 24 and 25, there are seven proposed power plant facilities and twenty fueling stations by the biomass collected by each county which determines the power and energy potential (there are no accessibility restrictions or transportation distances). According to the crop surplus residue per county, power plant facilities can be distributed amongst these seven locations due to it’s potential as Nimba (23,143 Tonnes) Lofa (11,605 Tonnes) Bong (11, 342), Grand cape mount Bomi and Gbarpolu counties 9,158 Tonnes; Montserrado and Margibi (8,847 Tonnes), Grand Bassa and River (7,422 Tonnes) as well as Maryland, Grand Gedeh, Grand Kru, Sinoe and River Gee counties (9,913 Tonnes).

4.5 SUMMARY DISCUSSION

In Liberia, fossil fuels account for 43% of electricity output as of 2021 while hydropower makes for 57% (IRENA, 2022). Therefore, it is undisputed that there is an opportunity to extend the usage of renewable energy sources, with a particular focus on bioenergy and its concentration on biohydrogen production. Due to the abundance of biomass-based energy sources in the nation, Liberia can also grow its green hydrogen sector by considering biohydrogen. By doing this, the country will be able to lessen its reliance on oil imports while also boosting the dependability of utilizing shared renewable sources to support its energy system. The development of the future hydrogen economy depends on the production of hydrogen from renewable sources. As a plentiful, sustainable, and clean energy source biomass has the potential to be crucial in the hydrogen manufacturing process. Due to its extensive agricultural and forestry operations, Liberia produces an enormous quantity of biomass residues that can be used for energy generation each year—roughly 1,204,033 Tonnes of selected crop residues. By using a dark fermentation method, this significant amount of biomass can be converted into a hydrogen-rich gas. This study examines the possibility of producing biohydrogen while considering several variables that affect the process of conversion efficiency. Dark fermentation doesn't require the use of fossil fuels, can be produced at room temperature and pressure and requires less energy than other sources, dark fermentation is a desirable process. Dark fermentation has proven to be the most efficient way of generating biohydrogen. Dark fermentation techniques are quick, create large yields, and do not release combustible oxygen. However, carbon dioxide must be captured and separated, and the oxygen must be kept away from the involved enzymes. Genetic modification could be used to boost hydrogen production, according to (Al-Haddad et al., 2023).

As shown in Table 5, all gross residues are not to be used because some play an essential role in animal feeding and soil conservation. With this, from the amount of 2,171,843 t/yr, only 55.4% (1,204,033 t/yr) were considered suitable for energy production.

It is reasonable to conclude from the study's results that the leftover biomass found in Liberia's counties can be used as an energy source to supplement conventional power sources for both transportation and electricity production. It is also advised to do a thorough analysis of the feedstock value chains for bioenergy and food security in order to fully understand the possibilities of biomass energy availability. Quantifying the amount of bioenergy and biohydrogen that will be produced is also necessary, as well as determining the most productive feedstocks and the best locations in the nation to grow them. This should be looked at to maintain food security while also reducing energy poverty. It should be simple to access and regularly updated for researchers in diverse locations. Numerous crucial challenges, such as collection, processing, and storage procedures, soil health, appropriate conversion technology that improves fuel qualities, and fuel replacement economics, which are predicted to vary between Liberian counties, must be addressed regarding the utilization of agricultural residues as bioenergy. The generated agricultural residue must be made nearby for use by facilities. The supply chain for residue, which includes gathering, storing, and transporting residue from the field to the bioenergy production facility, is impacted by feedstock costs. Crop residues have a low energy density or are bulky, making them challenging to transport, store, manage, and convert. Costs for shipping and harvesting are key considerations when planning bioenergy production from crop residue. When these are handled, the production and distribution of hydrogen across the country as seen in Figures (24 and 25) would significantly be in the rightful trajectory.

It is impossible to determine how much agriculture crop residue is actually available in Liberia for the production of electricity or additional fuel for transportation. Given the way of life of Liberian households, it is highly likely that a sizable portion of the wastes discovered are already being used as animal feed, on farms, or for cooking and water heating. As such, specific resources demand in-depth analyses for any projects that are under consideration.

5 CONCLUSION

The study estimated the bioenergy and biohydrogen potential from crop residues considering 18 crops residues produced by 7 crops from all 15 counties in Liberia. Statistical information on crop production was collected from the LISGIS and agriculture team conducted in 2017. The major agriculture crops identified as potential sources of energy are rice, cassava, plantain, banana, cocoa, oil palm, and sugar cane. Overall, the country produces 2,171,843 tonnes of gross residues annually, of which 1,204,033 tonnes annualy (55.4 % of gross) are available as surplus. Nimba produces the highest surplus residue in the country (29%), followed by (Lofa 15.3%), Bong (12.8%) and Maryland (1.7%) being the least among the fifteen counties. Of all the crops, rice produces the most surplus residue due to the largly unsue of both the straw and the hucks, followed by cassava and plantains.

At the national level, the bioenergy potential from surplus residue is roughly 20,276 TJ/yr which varies by county ranging from 5,851 TJ/yr to 357 TJ/yr. The comparable bioenergy power generation is 5,632 GWh, which is more than the nation's current electricity supply of 4.9% (279 GWh).

Dark fermentation has proven to be the most efficient way of producing biohydrogen. The biohydrogen potential from the surplus residues is 81,430 Tonnes (81,430,100 kg), ranging from 23,143 to 1,435 Tonnes. Additionally, twenty fueling stations and seven power plants were considered to contribute to the nationwide use of environmentally friendly fuel.

Estimated bioenergy and biohydrogen potential at the national, county, and crop levels in this study is expected to aid policy decisions and county-wise biohydrogen planning.

Furthermore, a value chain analysis can be conducted in Liberia to compare the energy potential using crop residues and fossil fuels. Also, the thorough literature review of the residue-to-product ratio, surplus availability fraction, and lower heating values of agriculture crop residue offer experts in the field an excellent basis for launching related studies. It also highlights the lack of up-to-date data on biomass potential and recommends ground data collection.

Additionally, with the aid of biomass energy-based in the community power generation could be used to electrify rural areas. This will make use of the crop residues produced in rural areas and help to mitigate excessive CO_2 emsion to give rise to clean environment.

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Appendix

Appendix 1

Data Permission

Dear Sir/Madame,

I am Teahtay Teah, a master's student in Bioenergy/Biofuels and Green hydrogen Technology at the University of LOME and doing my research at the University of Rostock, Germany under the program West African Science Service Center on Climate Change and Adapted Land Use (WASCAL). I am seeking permission to receive information from the Ministry of Agriculture on agricultural crop available in Liberia.

This research is intended for my master's program thesis. The research topic is **A GIS-based Assessment of Biohydrogen Production Potential from Agriculture Crop Residues in Liberia.** As the world is pressed with the obligation of finding substitutes for fossil fuels in the energy sector as well as the result of several climate disasters, a green energy source will be advantageous to our country, Liberia. Most agricultural residues are fruitless in farms through burning or unmanaged decay, which causes nitrogen leakage and eutrophication in nearby water bodies and contributes to odor and greenhouse gas emissions by releasing volatile and unburned hydrocarbons.

This work seeks to emphasize the identification of hotspots to produce biohydrogen extracted from agricultural crop residues as well as determine locations or sites for energy generation in the near future.

Despite growing interest in creating green hydrogen, agricultural waste still has a lot of untapped energy potential. This work will also uncover those impediments that have the propensity to hinder investment in biohydrogen production due to a lack of information about where they can access agricultural crop residues in huge quantities in Liberia. It will also give potential researchers and developing partners find it simpler to work in these sites after the effort to identify locations and the biohydrogen potential since the world now is focused on climate-related activities.

In view of this, Liberia has been a very green country as well as agricultural crop residues that could help the energy crisis wasted on a daily basis could strengthen the energy demand to meet up with SDG 7 (Affordable and clean energy), 13 (Climate action), and many more.

Therefore, I am seeking information that will guide and make my research reliable. I am further confident that the data that will be provided by the Ministry is up to date and will help me obtain accurate information. Below are a few things that are highly needed to make my thesis credible and contribute to the research activities in Liberia.

1. The list of all agricultural crops and the quantity of each produced
2. Quantity of each agricultural crop produced from all counties in Liberia

At the end of this research, I would have the opportunity to share the finding with you for further reference. If you require any further information, please do not hesitate to contact me on WhatsApp at +231777318010 or email teahtay.t@gmail.com, or teahtay.teah@uni-rostock.de. Thank you for your time and consideration in this matter.

Yours sincerely

Teahtay Teah

Master Student

Bioenergy/Biofuels and Green Hydrogen Technology

Appendix 2: *Bomi county bioenergy potential from agriculture crop residues*

Bomi County							
Crop Type	Residues	RCR	Gross (t/yr)	SAF	Surplus	LHV(MJ/KJ)	EP (TJ/yr)
Cassava	Peels	0.58	16191	0.2	3238	20.6	66
	Stalks	0.6	16749	0.407	6817	17.5	119
Rice	Straw	1.55	20790	0.49	10187	16	162
	Husk	0.28	3755	0.81	3042	19	57
Banana	Peels	0.35	224	0.8	179	17	3
	Stem	5.6	3584	0.8	2867	16	45
	Leaves	0.25	160	0.8	128	16	2
Cocoa	Pods	1.8	246	1	246	18	4
	Pruings	1.8	246	1	246	18	4
Oil palm	Fibers	0.605	185	1	185	16	2
	fronds	1.415	434	1	434	8	3
	Shells	0.525	161	1	161	18.5	2
Sugar cane	tops	0.185	37	0.81	30	16	0.5
	Leaves	0.185	37	0.8	30	16	0.5
	Bagasse	0.355	72	0.74	53	18	0.9
Plantain	leaves	0.375	334	0.8	267	16	4
	Stem	4.455	3969	0.8	3175	16	50
	Peels	0.3	267	1	267	17	4

APPENDIX 3. Bong County bioenergy potential from agriculture crop residues

Bong County

Crop Type	Residues	RCR	Gross (t/yr)	SAF	Surplus	LHV(MJ/KJ)	EP (TJ/yr)
Cassava	Peels	0.58	69809	0.2	13961	20.6	287
	Stalks	0.6	72216	0.407	29392	17.5	514
Rice	Straw	1.55	89636	0.49	43921	16	702
	Husk	0.28	16192	0.81	13115	19	249
Banana	Peels	0.35	1254	0.8	1003	17	17
	Stem	5.6	20064	0.8	16051	16	256
	Leaves	0.25	895	0.8	716	16	11
Cocoa	Pods	1.8	2347	1	2347	18	42
	Pruings	1.8	2347	1	2347	18	42
Oil Palm	Fibers	0.605	99	1	99	16	1.5
	fronds	1.415	232	1	232	8	1.8
	Shells	0.525	86	1	86	18.5	1.5
Sugar Cane	tops	0.185	974	0.81	788	16	12
	Leaves	0.185	974	0.8	779	16	12
	Bagasse	0.355	1869	0.74	1383	18	24
Plantain	leaves	0.375	2546	0.8	2037	16	32
	Stem	4.455	30249	0.8	24199	16	387
	Peels	0.3	2037	1	2037	17	34

APPENDIX 4. Gbarpolu County bioenergy potential from agriculture residues

Gbarpolu County							
Crop Type	Residues	RCR	Gross (t/yr)	SAF	Surplus	LHV(MJ/KJ)	EP (TJ/yr)
Cassava	Peels	0.58	9663.38	0.2	1932.68	20.6	39
	Stalks	0.6	9996.6	0.407	4068.62	17.5	71
Rice	Straw	1.55	12407.8	0.49	6079.8	16	97
	Husk	0.28	2241.4	0.81	1815.53	19	34
Banana	Peels	0.35	274.05	0.8	219.24	17	3.7
	Stem	5.6	4384.8	0.8	3507.84	16	56
	Leaves	0.25	195.75	0.8	156.6	16	2.5
Cocoa	Pods	1.8	817.2	1	817.2	18	1.4
	Pruings	1.8	817.2	1	817.2	18	1.4
Oil Palm	Fibers	0.605	22.99	1	22.99	16	0.4
	fronds	1.415	53.77	1	53.77	8	0.4
	Shells	0.525	19.95	1	19.95	18.5	0.4
Sugar Cane	tops	0.185	32.19	0.81	26.0739	16	0.4
	Leaves	0.185	32.19	0.8	25.752	16	0.4
	Bagasse	0.355	61.77	0.74	45.7098	18	0.8
Plantain	leaves	0.375	702	0.8	561.6	16	8.9
	Stem	4.455	8339.76	0.8	6671.81	16	106

	Peels	0.3	561.6	1	561.6	17	9.5

APPENDIX 5. Grand Cape Mount County bioenergy potential from agriculture residues

Grand Cape Mount County							
Crop Type	Residues	RCR	Gross (t/yr)	SAF	Surplus	LHV(MJ/KJ)	EP (TJ/yr)
Cassava	Peels	0.58	30372	0.2	6074	20.6	125
	Stalks	0.6	31419	0.407	12787	17.5	223
Rice	Straw	1.55	38998	0.49	19109	16	305
	Husk	0.28	7044	0.81	5706	19	108
Banana	Peels	0.35	365	0.8	292	17	4.9
	Stem	5.6	5840	0.8	4672	16	7.4
	Leaves	0.25	260	0.8	208	16	3.3
Cocoa	Pods	1.8	426	1	426	18	7.6
	Pruings	1.8	426	1	426	18	7.6
Oil Palm	Fibers	0.605	980	1	980	16	1.5
	fronds	1.415	2292	1	2292	8	1.8
	Shells	0.525	850	1	850	18.5	1.5
Sugar Cane	tops	0.185	60	0.81	48	16	0.7
	Leaves	0.185	60	0.8	48	16	0.7
	Bagasse	0.355	115	0.74	85	18	1.5
Plantain	leaves	0.375	632	0.8	505	16	8.1
	Stem	4.455	7511	0.8	6008	16	96
	Peels	0.3	505	1	505	17	8.5

APPENDIX 6. Grand Bassa County bioenergy potential from agriculture residues

Grand Bassa County							
Crop Type	Residues	RCR	Gross (t/yr)	SAF	Surplus	LHV(MJ/KJ)	EP (TJ/yr)
Cassava	Peels	0.58	28882	0.2	5776	20.6	118
	Stalks	0.6	29878	0.407	12160	17.5	212
Rice	Straw	1.55	37085	0.49	18171	16	290
	Husk	0.28	6699	0.81	5426	19	103
Banana	Peels	0.35	778	0.8	623	17	10
	Stem	5.6	12460	0.8	9968	16	159
	Leaves	0.25	556	0.8	445	16	7

Cocoa	Pods	1.8	1492	1	1492	18	26
	Pruings	1.8	1492	1	1492	18	26
Oil Palm	Fibers	0.605	0	1	0	16	0
	fronds	1.415	0	1	0	8	0
	Shells	0.525	0	1	0	18.5	0
Sugar Cane	tops	0.185	659	0.81	534	16	8.5
	Leaves	0.185	659	0.8	527	16	8.4
	Bagasse	0.355	1266	0.74	937	18	16
Plantain	leaves	0.375	1504	0.8	1203	16	19
	Stem	4.455	17877	0.8	14302	16	228
	Peels	0.3	1203	1	1203	17	20

APPENDIX 7. Grand Gedeh County bioenegy potential from agriculture crop residues

Grand Gedeh County							
Crop Type	Residues	RCR	Gross (t/yr)	SAF	Surplus	LHV(MJ/KJ)	EP (TJ/yr)
Cassava	Peels	0.58	11602	0.2	2320	20.6	47
	Stalks	0.6	12003	0.407	4885	17.5	85
Rice	Straw	1.55	14898	0.49	7300	16	116
	Husk	0.28	2691	0.81	2180	19	41
Banana	Peels	0.35	492	0.8	393	17	6.6
	Stem	5.6	7873	0.8	6298	16	100
	Leaves	0.25	351	0.8	281	16	4.4
Cocoa	Pods	1.8	2305	1	2305	18	4.1
	Pruings	1.8	2305	1	2305	18	4.1
Oil palm	Fibers	0.605	45	1	45	16	0.7
	fronds	1.415	107	1	107	8	0.8
	Shells	0.525	39	1	39	18.5	0.7
Sugar cane	tops	0.185	3	0.81	2	16	0.04
	Leaves	0.185	3	0.8	2	16	0.04
	Bagasse	0.355	6	0.74	4.7	18	0.08
Plantain	leaves	0.375	900	0.8	720	16	11
	Stem	4.455	10692	0.8	8553	16	136
	Peels	0.3	720	1	720	17	12

APPENDIX 8. Grand Kru County bioenergy potential from agriculture crop residues

Grand Kru County							
Crop Type	Residues	RCR	Gross (t/yr)	SAF	Surplus	LHV(MJ/KJ)	EP (TJ/yr)
Cassava	Peels	0.58	10,007	0.2	2001	20.6	41
	Stalks	0.6	10,353	0.407	4213	17.5	73
Rice	Straw	1.55	12,851	0.49	6297	16	100

	Husk	0.28	2,321	0.81	1880.4	19	35
Banana	Peels	0.35	291	0.8	233	17	3.9
	Stem	5.6	4,670	0.8	3736	16	59
	Leaves	0.25	208	0.8	166.8	16	2.6
Cocoa	Pods	1.8	172	1	172.8	18	3.1
	Pruings	1.8	172	1	172.8	18	3.1
Oil palm	Fibers	0.605	10	1	10.89	16	0.1
	fronds	1.415	25	1	25.47	8	0.2
	Shells	0.525	9	1	9.45	18.5	0.1
Sugar cane	tops	0.185	23	0.81	18	16	0.2
	Leaves	0.185	23	0.8	18.5	16	0.2
	Bagasse	0.355	44	0.74	32	18	0.5
Plantain	leaves	0.375	744	0.8	595	16	9.5
	Stem	4.455	8843	0.8	7074	16	113
	Peels	0.3	595	1	595	17	10

APPENDIX 9. Lofa County bioenergy potential from agriculture crop residues

Lofa County							
Crop Type	Residues	RCR	Gross (t/yr)	SAF	Surplus	LHV(MJ/KJ)	EP (TJ/yr)
Cassava	Peels	0.58	50,374	0.2	10074.8	20.6	207542
	Stalks	0.6	52,111	0.407	21209.3	17.5	371162
Rice	Straw	1.55	64,681.5	0.49	31693.9	16	507103
	Husk	0.28	11,684.4	0.81	9464.36	19	179823
Banana	Peels	0.35	2436	0.8	1948.8	17	33129.6
	Stem	5.6	38976	0.8	31180.8	16	498893
	Leaves	0.25	1740	0.8	1392	16	22272
Cocoa	Pods	1.8	18757.8	1	18757.8	18	337640
	Pruings	1.8	18757.8	1	18757.8	18	337640
Oil Palm	Fibers	0.605	898.425	1	898.425	16	14374.8
	fronds	1.415	2101.275	1	2101.28	8	16810.2
	Shells	0.525	779.625	1	779.625	18.5	14423.1
Sugar Cane	tops	0.185	216.45	0.81	175.325	16	2805.19
	Leaves	0.185	216.45	0.8	173.16	16	2770.56
	Bagasse	0.355	415.35	0.74	307.359	18	5532.46
Plantain	leaves	0.375	3237	0.8	2589.6	16	41433.6
	Stem	4.455	38455.56	0.8	30764.4	16	492231
	Peels	0.3	2589.6	1	2589.6	17	44023.2

APPENDIX 10. Margibi County bioenergy potential from agriculture crop residues

Margibi County							
Crop	Residues	RCR	Gross (t/yr)	SAF	Surplus	LHV(MJ/KJ)	EP

Type							(TJ/yr)
Cassava	Peels	0.58	20298.26	0.2	4059.65	20.6	83628.8
	Stalks	0.6	20998.2	0.407	8546.27	17.5	149560
Rice	Straw	1.55	26063.25	0.49	12771	16	204336
	Husk	0.28	4708.2	0.81	3813.64	19	72459.2
Banana	Peels	0.35	325.85	0.8	260.68	17	4431.56
	Stem	5.6	5213.6	0.8	4170.88	16	66734.1
	Leaves	0.25	232.75	0.8	186.2	16	2979.2
Cocoa	Pods	1.8	0	1	0	18	0
	Pruings	1.8	0	1	0	18	0
Oil Palm	Fibers	0.605	0	1	0	16	0
	fronds	1.415	0	1	0	8	0
	Shells	0.525	0	1	0	18.5	0
Sugar Cane	tops	0.185	295.63	0.81	239.46	16	3831.36
	Leaves	0.185	295.63	0.8	236.504	16	3784.06
	Bagasse	0.355	567.29	0.74	419.795	18	7556.3
Plantain	leaves	0.375	775.5	0.8	620.4	16	9926.4
	Stem	4.455	9212.94	0.8	7370.35	16	117926
	Peels	0.3	620.4	1	620.4	17	10546.8

APPENDIX 11. Maryland County bioenergy potential from agriculture crop residues

			Maryland County				
Crop Type	Residues	RCR	Gross (t/yr)	SAF	Surplus	LHV(MJ/KJ)	EP(TJ/Yr)
Cassava	Peels	0.58	7,354	0.2	1471	20.6	30302.5
	Stalks	0.6	7608.6	0.407	3096.7	17.5	54192.3
Rice	Straw	1.55	9444.15	0.49	4627.63	16	74042.1
	Husk	0.28	1706.04	0.81	1381.89	19	26256
Banana	Peels	0.35	280	0.8	224	17	3808
	Stem	5.6	4480	0.8	3584	16	57344
	Leaves	0.25	200	0.8	160	16	2560
Cocoa	Pods	1.8	0	1	0	18	0
	Pruings	1.8	0	1	0	18	0
Oil Palm	Fibers	0.605	21.78	1	21.78	16	348.48
	fronds	1.415	50.94	1	50.94	8	407.52
	Shells	0.525	18.9	1	18.9	18.5	349.65
Sugar Cane	tops	0.185	184.815	0.81	149.7	16	2395.2
	Leaves	0.185	184.815	0.8	147.852	16	2365.63
	Bagasse	0.355	354.645	0.74	262.437	18	4723.87
Plantain	leaves	0.375	553.5	0.8	442.8	16	7084.8
	Stem	4.455	6575.58	0.8	5260.46	16	84167.4

	Peels	0.3	442.8	1	442.8	17	7527.6

APPENDIX 12. Montserrado Conuty bioenergy potential from agriculture crop residues

Montserrado County							
Crop Type	Residues	RCR	Gross (t/yr)	SAF	Surplus	LHV(MJ/KJ)	EP (TJ/yr
Cassava	Peels	0.58	22103.2	0.2	4420.64	20.6	91065.3
	Stalks	0.6	22865.4	0.407	9306.22	17.5	162859
Rice	Straw	1.55	28380.5	0.49	13906.4	16	222503
	Husk	0.28	5126.8	0.81	4152.71	19	78901.5
Banana	Peels	0.35	1594.25	0.8	1275.4	17	21681.8
	Stem	5.6	25508	0.8	20406.4	16	326502
	Leaves	0.25	1138.75	0.8	911	16	14576
Cocoa	Pods	1.8	653.4	1	653.4	18	11761.2
	Pruings	1.8	653.4	1	653.4	18	11761.2
Oil Palm	Fibers	0.605	603.79	1	603.79	16	9660.64
	fronds	1.415	1412.17	1	1412.17	8	11297.4
	Shells	0.525	523.95	1	523.95	18.5	9693.08
Sugar Cane	tops	0.185	448.255	0.81	363.087	16	5809.38
	Leaves	0.185	448.255	0.8	358.604	16	5737.66
	Bagasse	0.355	860.165	0.74	636.522	18	11457.4
Plantain	leaves	0.375	2751	0.8	2200.8	16	35212.8
	Stem	4.455	32681.9	0.8	26145.5	16	418328
	Peels	0.3	2200.8	1	2200.8	17	37413.6

APPENDIX 13. Nimba County bioenergy potential from crop residues

Nimba County							
Crop Type	Residues	RCR	Gross (t/yr)	SAF	Surplus	LHV(MJ/KJ)	EP(TJ/yr)
Cassava	Peels	0.58	96721.4	0.2	19344.3	20.6	398492
	Stalks	0.6	100057	0.407	40723	17.5	712653
Rice	Straw	1.55	124192	0.49	60854.2	16	973667
	Husk	0.28	22434.7	0.81	18172.1	19	345270
Banana	Peels	0.35	3214.05	0.8	2571.24	17	43711.1
	Stem	5.6	51424.8	0.8	41139.8	16	658237
	Leaves	0.25	2295.75	0.8	1836.6	16	29385.6
Cocoa	Pods	1.8	30774.6	1	30774.6	18	553943
	Pruings	1.8	30774.6	1	30774.6	18	553943
Oil Palm	Fibers	0.605	4652.45	1	4652.45	16	74439.2
	fronds	1.415	10881.4	1	10881.4	8	87050.8
	Shells	0.525	4037.25	1	4037.25	18.5	74689.1

Sugar Cane	tops	0.185	1602.1	0.81	1297.7	16	20763.2
	Leaves	0.185	1602.1	0.8	1281.68	16	20506.9
	Bagasse	0.355	3074.3	0.74	2274.98	18	40949.7
Plantain	leaves	0.375	7083	0.8	5666.4	16	90662.4
	Stem	4.455	84146	0.8	67316.8	16	1077069
	Peels	0.3	5666.4	1	5666.4	17	96328.8

APPENDIX 14. River Cess County bioenergy potential from agriculture crop residues

River Cess County							
Crop Type	Residues	RCR	Gross (t/yr)	SAF	Surplus	LHV(MJ/KJ)	EP (TJ/yr)
Cassava	Peels	0.58	11000.3	0.2	2200.06	20.6	45321.2
	Stalks	0.6	11379.6	0.407	4631.5	17.5	81051.2
Rice	Straw	1.55	14125.2	0.49	6921.32	16	110741
	Husk	0.28	2551.64	0.81	2066.83	19	39269.7
Banana	Peels	0.35	332.85	0.8	266.28	17	4526.76
	Stem	5.6	5325.6	0.8	4260.48	16	68167.7
	Leaves	0.25	237.75	0.8	190.2	16	3043.2
Cocoa	Pods	1.8	496.8	1	496.8	18	8942.4
	Pruings	1.8	496.8	1	496.8	18	8942.4
Oil Palm	Fibers	0.605	79.86	1	79.86	16	1277.76
	fronds	1.415	186.78	1	186.78	8	1494.24
	Shells	0.525	69.3	1	69.3	18.5	1282.05
Sugar cane	tops	0.185	35.89	0.81	29.0709	16	465.134
	Leaves	0.185	35.89	0.8	28.712	16	459.392
	Bagasse	0.355	68.87	0.74	50.9638	18	917.348
Plantain	leaves	0.375	1130.25	0.8	904.2	16	14467.2
	Stem	4.455	13427.4	0.8	10741.9	16	171870
	Peels	0.3	904.2	1	904.2	17	15371.4

APPENDIX 15. River Gee County bioenergy potential from crop residues

River Gee County							
Crop Type	Residues	RCR	Gross (t/yr)	SAF	Surplus	LHV(MJ/KJ)	EP(TJ/yr)
Cassava	Peels	0.58	7437.34	0.2	1487.47	20.6	30641.8
	Stalks	0.6	7693.8	0.407	3131.38	17.5	54799.1
Rice	Straw	1.55	9549.55	0.49	4679.28	16	74868.5
	Husk	0.28	1725.08	0.81	1397.31	19	26549
Banana	Peels	0.35	263.2	0.8	210.56	17	3579.52
	Stem	5.6	4211.2	0.8	3368.96	16	53903.4
	Leaves	0.25	188	0.8	150.4	16	2406.4
Cocoa	Pods	1.8	1539	1	1539	18	27702
	Pruings	1.8	1539	1	1539	18	27702

Oil Palm	Fibers	0.605	24.805	1	24.805	16	396.88
	fronds	1.415	58.015	1	58.015	8	464.12
	Shells	0.525	21.525	1	21.525	18.5	398.213
Sugar cane	tops	0.185	32.375	0.81	26.2238	16	419.58
	Leaves	0.185	32.375	0.8	25.9	16	414.4
	Bagasse	0.355	62.125	0.74	45.9725	18	827.505
Plantain	leaves	0.375	497.25	0.8	397.8	16	6364.8
	Stem	4.455	5907.33	0.8	4725.86	16	75613.8
	Peels	0.3	397.8	1	397.8	17	6762.6

APPENDIX 16. Sinoe County bioenergy potential from agriculture crop residue

Sinoe County							
Crop Type	Residues	RCR	Gross (t/yr)	SAF	Surplus	LHV(MJ/KJ)	EP (TJ/yr)
Cassava	Peels	0.58	12791.9	0.2	2558.38	20.6	52702.6
	Stalks	0.6	13233	0.407	5385.83	17.5	94252
Rice	Straw	1.55	16425.4	0.49	8048.42	16	128775
	Husk	0.28	2967.16	0.81	2403.4	19	45664.6
Banana	Peels	0.35	715.4	0.8	572.32	17	9729.44
	Stem	5.6	11446.4	0.8	9157.12	16	146514
	Leaves	0.25	511	0.8	408.8	16	6540.8
Cocoa	Pods	1.8	0	1	0	18	0
	Pruings	1.8	0	1	0	18	0
Oil Palm	Fibers	0.605	69.575	1	69.575	16	1113.2
	fronds	1.415	162.725	1	162.725	8	1301.8
	Shells	0.525	60.375	1	60.375	18.5	1116.94
Sugar Cane	tops	0.185	41.995	0.81	34.016	16	544.255
	Leaves	0.185	41.995	0.8	33.596	16	537.536
	Bagasse	0.355	80.585	0.74	59.6329	18	1073.39
Plantain	leaves	0.375	1255.13	0.8	1004.1	16	16065.6
	Stem	4.455	14910.9	0.8	11928.7	16	190859
	Peels	0.3	1004.1	1	1004.1	17	17069.7

APPENDIX 17. Ultimate analysis for crop residues

Crop	Residue	C	H	O	S	N
	Peels	22.1	13.5	37	1.82	2.38
Cassava	Stalks	48.8	6.7	43.4	0	1.1
	Straw	28.55	5.98	65.71	0.1	0.7
Rice	Husk	44.13	5.9	50.4	0.6	1.2
	tops	48.6	6.5	36		
	Leaves	48.6	6.5	36	0.08	
Sugar Cane	Bagasse	48.6	5.81	42.72	0.04	0.2
	Pods	44.48	6	49.1	0.2	3
Cocoa	Pruings	44.48	6	49.1	0.2	3
	Fibers	47.5	6	36.7	0.3	1.4
	fronds	48.9	6.3	36.7	0.1	0.7
Oil Palm	Shells	50	5.6	35	0.1	0.7
	Peels	40	5.1	49.01	0.03	1.4
	Stem	42	5.7	54.7		1.4
Banana	Leaves	39	5	55.8		0.7
	leaves	38	4.7	55.9		0.8
	Stem	39	5.4	54.8		1.5
Plantain	Peels	40	5.1	49.01		0.8