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Bioenergy and Green Hydrogen Production in The Gambia: Potential for Energy Mix Integration

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ABSTRACT: This study evaluates the feasibility of incorporating alternative sustainable energy sources, specifically bioenergy and green hydrogen, into The Gambia's energy mix to support the nation's long-term energy development goals. The feedstocks analyzed include agricultural crop residues such as rice, cassava, groundnuts, maize, sorghum, oil palm fruit, seed cotton, and millet, as well as municipal solid waste (MSW). An assessment was conducted to calculate the theoretical potential generated from the organic components of both MSW and crop residues, utilizing data collected from 2017 to 2021 and projections extending to 2038. The results were employed to calculate potential yields of biomethane and electricity production, using Buswell's equation as a framework for determining biogas generation from various organic materials. Additionally, the potential for hydrogen production via steam methane reforming was evaluated using stoichiometric principles. The technical potential for electricity and hydrogen generation was then established based on their respective conversion efficiencies. This study is the first to comprehensively assess the technical potential for both bioenergy and green hydrogen production from crop residues and MSW in The Gambia. By quantifying yields of electricity (64.5 MW) and hydrogen (6.2 million kmol), and proposing a site-specific pilot project strategy, it bridges the gap between theoretical potential and practical implementation, providing a scalable roadmap for energy diversification in low-income nations. To address data management and infrastructure gaps, a strategy is proposed that includes automated data collection, awareness programs, and waste-to-energy initiatives, aimed at enhancing energy resilience and sustainability in The Gambia.

KEYWORDS: Municipal solid waste; crop residue; energy mix; green hydrogen; bioenergy; waste-to-energy

1 Introduction

1.1 Africa's Energy Transition and Projects

Energy plays a crucial role in the development of any nation, influencing its economy, social activities, infrastructure, and lifestyle. In many African countries, electrification has yet to reach 100%, particularly in rural areas. Sub-Saharan Africa, home to 14% of the global population in developing countries, accounts for nearly 40% of the population without access to electricity [1]. Despite this, Africa is endowed with abundant renewable resources, and several countries, such as Nigeria, Egypt, Ghana, South Africa, and Kenya, have begun tapping into these resources. In 2021, Kenya proposed a 12 MW, grid-connected municipal Waste-to-Energy (WTE) plant in Kabira, a suburb of Nairobi. This project aims to convert three types of biomass municipal solid waste (MSW), crop residues, and livestock waste into biogas or fuel ethanol, while also

generating electricity [2]. Similarly, Ghana has implemented a 400 kW hybrid WTE plant in Gyankobaa as a pilot project. This facility processes 50 t of MSW daily and aims to produce electricity, biogas, compost, green hydrogen, solar power (200 kW), and facilitate plastic recycling via pyrolysis. It also serves as a training center to build local capacity [3].

The exploration of integrating bioenergy and green hydrogen into the energy mix of various nations is gaining traction globally. This study focuses on The Gambia, emphasizing the unique political, environmental, socioeconomic, and climatic contexts that shape energy policy in the country. An implementation strategy is proposed, which is predicated on an assessment of the production potential of agricultural crop residues and MSW as viable sources for generating bioenergy and green hydrogen. This research further identifies critical gaps within the nation's energy policies and infrastructure. To address these deficiencies, targeted recommendations are presented for consideration by government entities, aimed at enhancing the sustainability and resilience of The Gambia's energy landscape.

1.2 Overview of The Gambia

The Gambia is a small country located in West Africa along the eastern seaboard of the Atlantic Ocean. According to [4], the country has a total area of 11,570 km^2 and it stretches 450 km inland along the banks of The Gambia River. The country is bordered on three fronts by Senegal and has a landscape classified under the category of savannah with low hills and a tropical climate. It has an estimated population size of 2.5 million, with 176 people per square kilometer, making it one of the most densely populated countries in Africa. 57% of the population is concentrated in the urban areas of the country [5]. The Gambia's economy relies heavily on tourism and agriculture. In 2021, the country's gross domestic product (GDP) was estimated at USD 2.078 billion. The agricultural, forestry, and fisheries sectors employ 9.2% of the working population, excluding subsistence farmers. Agriculture represents approximately 24% of the GDP, 72% of poor households, and 91% of extremely poor rural households. Additionally, The Gambia serves as a key transit and trade route for Senegal and other regional countries [6].

1.3 The Gambia's Emissions and Energy Status

In 2020, The Gambia's total greenhouse gas (GHG) emissions were 4935 GgCO$_2$e, projected to increase to 6617 GgCO$_2$e by 2030 if no measures are taken [7]. The transport sector was responsible for 1026 GgCO$_2$e of GHG emissions in the energy sector, with the sub-sector emitting 345 GgCO$_2$e in 2020 and a projected increase to 1026 GgCO$_2$e by 2050. This increase can be attributed to the rising number of old cars and poor-quality fuels. GHG emissions from livestock were 434 GgCO$_2$e in 2020, expected to rise to 1085 GgCO$_2$e by 2050. Similarly, emissions from aggregate sources were 270 GgCO$_2$e in 2020, projected to reach 674 GgCO$_2$e by 2050, and emissions from forestry stood at 232 GgCO$_2$e in 2020, with a projected value of 578 GgCO$_2$e by 2050 [8]. While The Gambia's emissions are relatively low compared to global standards, electricity generation accounted for 241 GgCO$_2$e in 2020 and is expected to rise to 535 GgCO$_2$e by 2030 due to the use of light and heavy fuels in electricity production [7]. The country's electricity demand in urban areas was 1488 kWh per household per annum, compared to 792 kWh per household annually in rural areas [8]. Currently, only 60% of the population in the greater Banjul area has access to electricity, with rural areas having less than 30% access. The government aims to achieve universal electricity access for 80% of the population by 2025.

1.4 Waste Disposal and Management in The Gambia

Municipal solid waste in The Gambia is divided into organic and inorganic fractions, including food waste, agricultural waste, wood, animal waste, paper, plastics, latex, fabrics, and dirt [9]. Globally, organic

waste makes up about 46% of municipal solid waste, with paper (17%), plastics (10%), glass (5%), metals (4%), and other types of waste comprising the remaining (18%) [10]. While waste is ideally segregated at the source of production or collection, in The Gambia, segregation at the point of disposal is not widely practiced.

Waste is a significant source of greenhouse gas emissions. The waste sector in The Gambia produced 506 $GgCO_2e$ in 2020, with emissions expected to rise to 1184 $GgCO_2e$ by 2030 [7]. A 2014 study by the National Environmental Agency identified 95 dumpsites across the country, classified into the following regional volumes:

I   Banjul—4 Dumpsites, volume of 556.9 m^3
II   Kanifing Municipality—16 Dumpsites, volume of 14,384 m^3
III   West Coast region—20 Dumpsites, volume of 22,910 m^3
IV   Upper river region—29 Dumpsites, volume of 13,923 m^3
V   North Bank Region—13 Dumpsites, a volume of 9605 m^3
VI   Central River region—12 Dumpsites, a volume of 2448 m^3
VII   Lower River Region—4 Dumpsites, a volume of 494.9 m^3

This data highlights the country's lack of a standardized landfill [11]. The Gambia has identified several mitigation measures to improve waste management and reduce emissions, including waste prevention, recycling, banning biodegradable waste from dumpsites, organic waste recovery, increased landfill methane capture and oxidation, waste separation, and improvements at wastewater treatment and composting facilities [8,12].

1.5 The Gambia's Energy Development Goals and Targets

The Gambia's electricity generation is currently entirely dependent on fossil fuels, which are unsustainable and contribute to climate change and GHG emissions. To mitigate these negative effects and secure carbon credits, the government is prioritizing renewable energy sources, including solar PV systems, wind, mini-hydro systems, and biomass [7,12]. To meet national targets, the government, in partnership with others, has outlined several key renewable energy projects:

I   150 MW Regional Solar PV power plant in Soma (IPP)
II   20 MW Jambur solar PV project
III   10.5 MW Nationally Appropriate Mitigation Action (NAMA) solar PV project

According to the Ministry of Environment, Climate Change, and Adaptation's 2023 project mapping, The Gambia currently has eight energy and climate change adaptation projects, of which only one integrates clean cooking stoves with biogas. Given this focus on solar energy, there is an urgent need for investments in alternative renewable energy sources, particularly waste-to-energy and green hydrogen projects. The country's limited space and ongoing waste management challenges raise questions about the sustainability of an energy approach centered solely on solar power.

1.6 Current Status of Integrating Bioenergy and Green Hydrogen into the Energy Mix

The integration of bioenergy and green hydrogen into the energy system of countries represents a significant shift towards sustainable energy solutions [13]. The goal of this integration is to enhance energy security, optimize resource use, and reduce greenhouse gas emissions. Research shows that combining bioenergy with green hydrogen strengthens energy infrastructure. This combination improves energy storage and ensures a stable energy supply, addressing the intermittent nature of other renewable energy sources such as solar and wind energy [14,15]. While green hydrogen is most commonly produced through electrolysis

powered by solar or wind, it can also be produced from bioenergy methods that can be done biologically or thermochemically.

Dark fermentation is a well-established biological method for hydrogen production, with a net energy ratio of 1.9. In this process, anaerobic bacteria convert substrates in the absence of light [16]. This method can utilize both the organic fraction of municipal solid waste and agricultural residue. Unlike anaerobic digestion, which primarily aims to produce biogas, dark fermentation focuses on hydrogen production [17]. Several types of bacteria can be employed in dark fermentation; however, Clostridium and Enterobacter are the most commonly used. These bacteria can metabolize carbohydrates, proteins, and lipids to produce hydrogen, carbon dioxide, and organic acids through the acidogenic pathway.

Bio-photolysis is another biological method for hydrogen production, which can be categorized into two types. The first type is direct bio-photolysis, where water molecules are split using sunlight as an energy source, facilitated by the hydrogenase enzyme, to produce hydrogen without releasing greenhouse gases. The second type is indirect biophotolysis, performed by microalgae under anoxic conditions. In these conditions, microalgae can produce biohydrogen through fermentation or respiration. However, the indirect method is not continuous, as the return of the light period triggers photosynthetic growth, which inhibits hydrogenase activity [18].

Anaerobic digestion is a biological method that produces biogas from biomass. The conversion involves four main steps that normally take place in a digester. According to [19], the first stage, known as hydrolysis, is in charge of transforming complex insoluble organic matter into simple soluble molecules through the use of enzymatic hydrolysis microorganisms. This is then followed by the acidogenesis stage. During this phase, acid bacteria use both dissolved and bound oxygen in the solution to degrade the hydrolysis products into short-chained organic acids. Before moving to the third stage, called the acetogenesis phase, where essential products for methane generation are produced using acetogenic bacteria. During the final stage, methanogenesis occurs, in which products from the acetogenesis phase, namely acetic acid and hydrogen, are transformed into biomethane by methanogenic microorganisms. At the end of all the processes involved in AD, the main products produced are biogas and digestate. Gasification is a common thermochemical process that transforms biomass or other organic solid wastes into a gaseous product known as syngas. This syngas typically comprises hydrogen (H_2), methane (CH_4), carbon monoxide (CO), and carbon dioxide (CO_2). The conversion occurs by reacting carbonaceous feedstocks with gasifying agents such as air, oxygen, steam, or supercritical water within a gasifier, at temperatures ranging from 500°C to 1200°C. The most prevalent types of gasifiers include fixed bed gasifiers, fluidized bed gasifiers, and entrained flow gasifiers [20]. It can be categorized as either an autothermal reaction or an allothermal reaction. The auto-thermal reaction, often referred to as direct gasification, produces the necessary heat for the process internally, making it endothermic. In contrast, the allothermal gasification process, or indirect gasification, depends on externally generated heat to facilitate the reaction, rendering it exothermic.

1.7 Research Significance

Globally, the transition toward sustainable energy systems is accelerating, driven by commitments to decarbonization, energy security, and climate resilience. While much attention has been given to solar, wind, and hydropower, there is growing recognition of the role that waste-to-energy and hydrogen technologies can play, particularly in addressing energy access challenges in low-income and climate-vulnerable countries, as seen in Section 1.1.

In The Gambia, recent investments have primarily focused on solar photovoltaic installations and grid extension projects, supported by international development partners. While commendable, these efforts have not sufficiently diversified the national energy mix, leaving the country highly dependent on imported fossil

fuels and vulnerable to energy price shocks. Furthermore, existing projects often overlook locally available organic resources such as crop residues and MSW that could be harnessed for energy generation in both rural and peri-urban areas.

This research addresses a critical gap in The Gambia's energy planning by conducting the first integrated assessment of bioenergy and green hydrogen potential using nationally sourced biomass and waste data. Unlike previous studies that examine isolated technologies or rely on generalized regional models, this study provides a quantitative, country-specific evaluation of both theoretical and technical energy yields from crop residues and MSW, spanning from 2017 to 2021 with projections to 2038. It estimates a technical capacity of 64.5 MW in electricity and over 6.2 million kmol of hydrogen annually, highlighting significant untapped potential. Beyond energy estimation, the study employs GIS-based site analysis and proposes a three-phase implementation strategy, making it not only analytically robust but also actionable. In doing so, it offers a novel framework for integrated energy planning that is grounded in local context and can serve as a blueprint for other West African countries undergoing energy transitions. This combination of localized resource modeling, technical potential analysis, and spatial planning constitutes the core novelty and strategic importance of the study.

2 Methodology

2.1 Ultimate and Proximate Analysis

The ultimate analysis or elemental analysis is performed to quantify the carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S) content of biomass. This analysis is normally conducted with the use of an element analyzer such as the LECO CNS and Model 2400 CHNS-O, Perkin Elmer element analyzers, and the ASTM D 3173-85 or ASTM D 2243-00 methods [21–24]. Whereas, the proximate analysis quantifies the moisture content, dry matter, volatile materials, fixed carbon, and ash content in the feedstock. According to [22] To obtain the values of the specified parameters, the ASTM E 1617-94 and the ASTM E 1755-01 methods are used.

2.2 Residue-to-Product Ratio (RPR)

The residue-to-product ratio is a key metric in biomass studies that represents the proportion of crop residue generated relative to the main agricultural product. According to [25], the RPR values indicate how much biomass waste is generated per unit of harvested crop. These values can vary based on factors such as crop variety, soil fertility, and climatic conditions.

2.3 Theoretical Potential Calculation Methods

The theoretical potential of crop residues is calculated by multiplying the annual crop production by the residue-to-product ratio, as shown in Eq. (1). That of municipal solid waste is calculated by multiplying the annual production of municipal solid waste by the organic fraction of municipal solid waste percentage of the study site, as shown in Eq. (3). The theoretical Buswell's equation, shown below Eq. (5), was introduced in 1952 and is used to estimate the biogas potential of a given feedstock from anaerobic digestion. The values required while using the equation are the carbon, oxygen, hydrogen, nitrogen, and sulfur composition (ultimate analysis) of the specified biomass. To estimate the methane potential, a combination of Buswell's equation with the carbon content of the biodegraded material [26–28]. Steam methane reforming is an endothermic reaction that converts methane to hydrogen with the aid of steam. To determine the theoretical hydrogen potential of selected feedstocks theoretical methane potential is a branch of chemistry known as stoichiometry that involves the use of reactants and products in a chemical reaction to derive the quantity

of the element needed, in this case, hydrogen. Eq. (9) was obtained from [29,30] was used to estimate the hydrogen potential of the selected feedstocks for this research.

2.4 Study Site and Feedstocks

The Gambia is divided into five administrative regions whose names originate from their position with the River Gambia that runs across the length of the country. The names of the regions are as follows: Central River Region (CRR (North and South)), Lower River Region (LRR), Upper River Region (URR), North Bank Region (NBR), and West Coast Region (WCR) [12]. These regions are further divided into eight districts, namely Banjul, Brikama, Kanifing, Kerewan, Mansa Konko, Kuntaur, Janjanbureh, and Basse, as shown above in Fig. 1. This study focuses on municipal solid waste and the crop residue generated by the country as a whole. The Gambia's economy is mainly dependent on agricultural activities and tourism. The agricultural sector contributes 24% of the country's gross domestic product (GDP) [31]. The agricultural products mainly produced in the country are livestock, crops, and fisheries. Crop residues in The Gambia are mainly obtained from farms or gardens. It normally includes rice straw, wheat straw, rice husk, corn stover, stalks and leaves from tomatoes, pepper, coconut shells, sugarcane bagasse, and so forth, depending on the region and climatic conditions. They are mostly left on the fields after harvests and used for fodder and landfill material, or burned in many places. These practices can lead to carbon emissions and leaching [32].
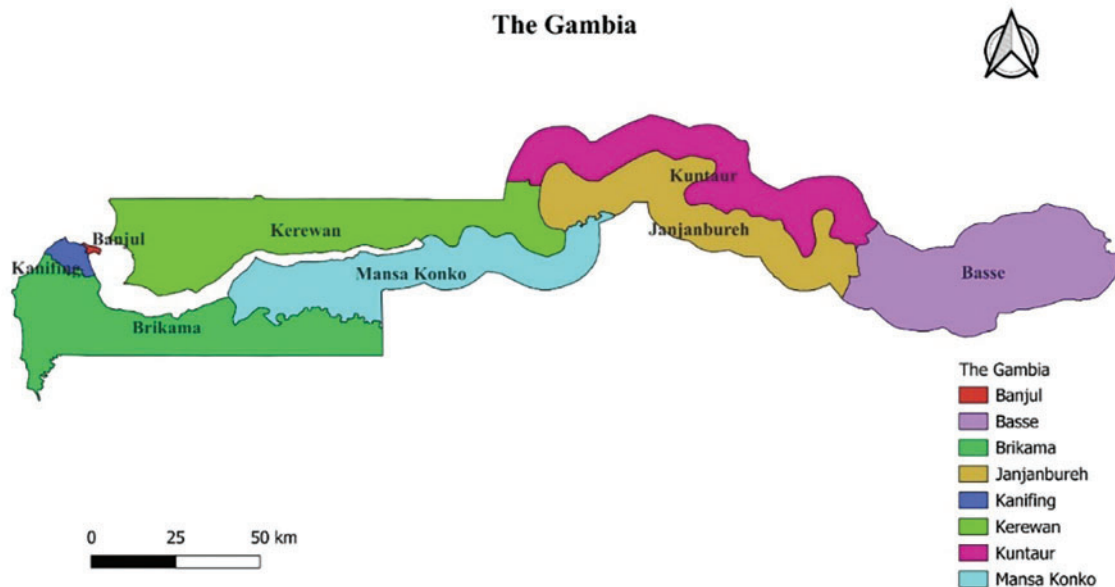

Figure 1: Study site highlighting the eight districts of The Gambia

The agricultural residue is mostly inexpensive, renewable lignocellulosic fiber resources that can be used as an alternative to woody lignocellulosic biomass. These residues have similar structure, composition, and properties to those of other plant fibers and make them suitable for composite, textile, pulp, and paper applications [33].

These residues can be used for composting and the generation of biogas, biofuels, and green hydrogen. This research is focused on the use of biogas production through anaerobic digestion to calculate the country's potential for generating biomethane, electricity, and hydrogen.

Crops produced in The Gambia are divided into two categories, the first being cash crops, which include groundnuts, millet, sorghum, seed cotton, and oil palm fruit. The second category is subsistence crops, which include rice, cassava, okra, onions, tomatoes, and other vegetables. Table 1 highlights the fourteen feedstocks used to estimate the study site's biogas, biomethane, biohydrogen, and electricity production potential.

2.5 Secondary Data Collection and Compilation

Data for this study, presented in Tables 1 and 2 with additional supporting data provided in Table 3 were obtained from FAOSTAT (Food and Agriculture Organization Corporate Statistical Database), peer-reviewed articles, and official sources including The Gambia's Ministry of Agriculture, Ministry of Environment, Ministry of Energy, the Kanifing Municipal Council, and the Brikama area council. FAOSTAT serves as a comprehensive global database that systematically collects, processes, and disseminates agricultural data, including detailed statistics on crop production. In the context of The Gambia, the process of submitting crop production data to FAOSTAT is handled by the Ministry of Agriculture, which oversees a structured methodology involving national statistical agencies in collaboration with FAO. Data collection in The Gambia relies on diverse sources, including farm surveys, census reports, and administrative records, encompassing key agricultural metrics such as area harvested, total production, and yield per hectare. Upon compilation, the data is formatted and submitted to FAO through standardized templates designed to ensure consistency and uniformity across submissions. The FAO subsequently undertakes verification and validation procedures, cross-referencing the submitted data for accuracy and rectifying any discrepancies in coordination with Gambia's agricultural authorities.

Following the validation process, the verified data is integrated into the FAOSTAT database, making it publicly available. During the data collection phase for this study, correspondence was sent to the public institutions listed above, which provided valuable information regarding the geographical distribution of farms and dumpsites, as well as policies and ongoing projects. Notably, it was identified that the data lacked quantitative details specifying the types and volumes of crops produced, which presents a significant limitation to the study, as it indicates that not all agricultural products cultivated within the nation are comprehensively represented in the FAOSTAT database. Data represented in Tables A1–A5, found in the Appendix, provides annual crop production data sourced from literature [34].

Table 1: Selected feedstock with RPR and OFMSW percentage

Specified feedstock	Residue to product ratio (RPR)	References
	OFMSW percentage	
Rice straw	1.66	[35,36]
Rice husk	0.26	[35,36]
Maize stalks	1.59	[35,36]
Maize husk	0.2	[35–37]
Maize cob	0.29	[35,36]
Cassava stalks	0.06	[35]
Groundnut shells	0.37	[35,36]
Groundnut straw	2.15	[35,36]
Millet stalks	1.83	[35,36]
Oil palm fruit kernel shell	0.07	[35]
Oil palm fruit fibers	0.14	[35]
Sorghum stalks	1.99	[35,36]

(Continued)

Table 1 (continued)

Specified feedstock	Residue to product ratio (RPR)	References
	OFMSW percentage	
Seed cotton stalks	2.755	[38]
OFMSW	50%	[39]

Table 2: Conditions required for crop growth, projected temperature, and annual rainfall for the year 2038 in The Gambia

Estimated average temperature 2038	The temperature required for the growth of the crop	Estimated annual rainfall 2038	Annual precipitation for crop growth	Crop type	References
19°C–34°C	21°C–37°C	70–100 cm	115–300 cm	Rice	[40–42]
19°C–34°C	25°C–28°C	70 -100 cm	50–100 cm	Maize	[43]
19°C–34°C	25°C–30°C	70–100 cm	100–300 cm	Cassava	[44]
19°C–34°C	20°C–30°C	70–100 cm	45–125 cm	Groundnuts	[45]
19°C–34°C	26°C–29°C	70–100 cm	50–90 cm	Millet	[46]
19°C–34°C	20°C–40°C	70–100 cm	125–200 cm	Oil palm fruit	[47]
19°C–34°C	20°C–30°C	70–100 cm	45–65 cm	Sorghum	[48]
19°C–34°C	21°C–37°C	70–100 cm	85–110 cm	Seed cotton	[49]

Table 3: MSW total theoretical potential

Year	Population	Per capita generation of MSW	No. of days in the year	MSW t/annum	OFMSW	MSW Theoretical Potential t/annum
2017	2.21	0.53	365	427.5245	0.5	213.76225
2018	2.28	0.53	365	441.066	0.5	220.533
2019	2.34	0.53	365	452.673	0.5	226.3365
2020	2.42	0.53	365	468.149	0.5	234.0745
2021	2.49	0.53	365	481.6905	0.5	240.84525
2022	2.56	0.53	365	495.232	0.5	247.616
2023	2.63	0.53	365	508.7735	0.5	254.38675
2028	3.01	0.6	365	659.19	0.5	329.595
2033	3.42	0.6	365	748.98	0.5	374.49
2038	3.84	0.6	365	840.96	0.5	420.48

2.6 Calculations

2.6.1 Crop Residue and Municipal Solid Waste Theoretical Potentials

Theoretical crop residue potential

$$Theoretical\ crop\ residue\ potential = Annual\ crop\ production * RPR \tag{1}$$

For this research, the estimation of theoretical crop residue potential was conducted by using the following steps:

Step One:

Determine the annual crop production of the selected feedstock from the literature. Due to unavailable data for the years 2022 and 2023, the data in Tables A1–A5 in the Appendix and Table 2 were used as a reference to estimate the projected annual crop production for the year 2038.

Step Two:

Calculate the theoretical crop residue potential using equation one and the data in Tables A1–A7.

Step Three:

The values obtained from step two were then summed up to get the total theoretical crop residue potential for the years 2017 to 2021 and 2038.

Annual municipal solid waste production

$$Annual\ MSW\ production = Population * Per\ capita\ generation * Number\ of\ days\ in\ the\ year \tag{2}$$

Municipal solid waste theoretical potential

$$MSW\ \ Theoretical\ potential = OFMSW * MSW \tag{3}$$

To obtain the municipal solid waste theoretical potential for this research, the following steps were taken:

Step One:

To calculate the country's generation of municipal solid waste for each of the specified years, equation two was used by multiplying the population value by each corresponding year with the per capita generation of that particular year and the number of days in the year. The values for the population size and per capita generation of MSW are highlighted in Table 3.

Step Two:

The estimated municipal waste generation was multiplied by the percentage of the organic fraction of municipal solid waste for each year to obtain the theoretical potential of municipal solid waste. The percentage of the OFMSW is shown in Table 3.
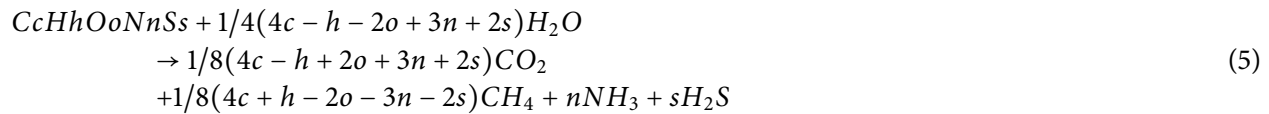
To obtain the total theoretical potential of all the feedstocks, equation four was used by simply summing up the MSW theoretical potential with the crop residue theoretical potential. This was done for each of the respective years.

Total theoretical potential

$$Total\ Theoretical\ potential = MSW + Crop\ residue \tag{4}$$

2.6.2 Theoretical Buswell's Equation

Buswell's equation

$$CcHhOoNnSs + 1/4(4c - h - 2o + 3n + 2s)H_2O$$
$$\rightarrow 1/8(4c - h + 2o + 3n + 2s)CO_2 \tag{5}$$
$$+1/8(4c + h - 2o - 3n - 2s)CH_4 + nNH_3 + sH_2S$$

To calculate the methane and energy yield, the steps below were followed using the proximate and ultimate analysis data from Table A8, which were sourced from various studies on individual feedstocks: rice straw and rice husk [50–52], maize stalk, husk, and cob [53–56], cassava stalks [57,58], groundnut shells and straw [59,60], millet stalks [61,62], oil palm kernel shells and fibers [63–65], sorghum stalks [66], seed cotton stalks [67,68], and the organic fraction of municipal solid waste [69].

Step One: Theoretical biogas composition

This was calculated with the use of Eqs. (5) and (6).

- To get the coefficient of carbon dioxide and methane, the elemental value from the ultimate analysis of a specific feedstock was divided by its corresponding atomic mass.
- The values obtained at this stage were then used in Buswell's equation to get the earlier-mentioned coefficients.
- The methane percentage of the biogas was then determined by dividing the methane coefficient by the sum of the methane and carbon dioxide coefficients, as shown in Eq. (6).
- This value was then subtracted from one hundred to get the carbon dioxide percentage.

Methane percentage

$$CH_4/(CH_4 + CO_2) = \%CH_4 \tag{6}$$

Step Two: Methane yield

- The theoretical potential of each of the chosen feedstocks was converted from tons to kilograms.
- The converted values were used to determine the theoretical potential dry matter and moisture content by multiplying the specified moisture percentage in Table A8 with its respective theoretical potential. The same process was followed for the dry matter content.
- The carbon percentage was calculated by multiplying the elemental value by its corresponding atomic mass from the ultimate analysis. The values for each of the elements were then summed up. The value for carbon was then divided by the summed-up value and multiplied by one hundred to get the carbon percentage.
- Calculate the weight of carbon of the feedstock by multiplying the carbon percentage by the dry matter content of the feedstock's theoretical potential.
- Calculate the weight of carbon converted to biogas first, assuming the percentage of biodegraded carbon is 70%. This percentage is multiplied by the weight of carbon to get the weight of carbon converted to biogas.
- Determine the weight of methane carbon by multiplying the methane percentage of biogas by the weight of carbon converted to biogas.
- According to [27], 1 mol of methane is equal to 16 g of methane.
- To calculate the weight of methane, 16 g of methane is divided by the atomic mass of carbon, which is then multiplied by the weight of carbon to get the weight of methane in kilograms before it is later converted to grams.

- According to [27], 1 mol of gas at standard temperature and pressure (STP) is equal to 22.4 L, and 16 g of methane is equivalent to 22.4 L.
- To calculate the volume of methane in cubic meters, the weight of methane in grams obtained earlier is then divided by 16 to get methane in moles. The methane in mols is then multiplied by 22.4 to get the volume of methane in liters, this value is then converted to cubic meters.
- The weight of methane was then converted to metric tons by dividing the value of methane in kilograms by one thousand.

Step Three: Energy value of methane

- Based on [27], 1 m^3 of methane is equal to 36 MJ (megajoules) and 1 kWh is equivalent to 3.6 MJ and 1 m^3 of methane is equal to 10 kWh.
- The energy value of methane for each of the chosen feedstocks was determined by multiplying the volume of methane in cubic meters by ten to get it in kilowatt hours.
- This was then converted to MWh with the use of Eq. (7).

kWh to MWh conversion equation

$$MWh = kWh * 10^{-3} \tag{7}$$

MWh to MW conversion equation

$$MW = MWh/h \tag{8}$$

2.6.3 Hydrogen Production Potential from Steam Methane Reforming with the Use of Stoichiometry

Steam methane reforming

$$CH_4 + H_2O = CO + 3H_2 \Delta Ho = 206 \ kJ/mol \tag{9}$$

Based on [29,30], 1 mol of methane will give 3 moles of hydrogen gas stoichiometrically. Eqs. (10)–(12) were then used to calculate the hydrogen theoretical potential.

Molar mass of methane

$$Molar \ mass \ of \ methane = 12 + 4 = 16 \ kg/kmol \tag{10}$$

Amount of methane

$$Amount \ of \ methane = m/M = y/16 = x \ \ kmol \tag{11}$$

Amount of hydrogen

$$Amount \ of \ hydrogen = x * 3 = z \ kmol \tag{12}$$

2.6.4 Technical Potential

The technical potential for energy generation and hydrogen production was calculated to determine the achievable production quantity. To do this, the conversion efficiencies for electricity from methane, which is 85%, and the conversion efficiency of hydrogen through steam methane reforming, which ranges from 65% to 75%, were obtained [70,71]. The conversion efficiency percentage of energy was multiplied by the

theoretical energy potential for each corresponding year. The same process was followed to calculate the technical potential for hydrogen, as shown in Eq. (13).

Technical potential

$$Technical\ potential = Theoretical\ potential * Conversion\ efficency\ percentage \qquad (13)$$

3 Results and Discussion

3.1 Theoretical Crop Residue Potential

Shown below in Fig. 2 is the total theoretical crop residue potential for each of the respective years. The years 2017 and 2019 had the highest theoretical crop residue potential due to the high production yield, as compared to 2018, which had a lower potential due to flooding that occurred during July and August in The Gambia. Although the theoretical crop residue potential for the years 2020 (303,660.0 t/annum) and 2021 (297,639.2 t/annum) was much better than that of 2018 (231,094.8 t/annum). However, compared to the year 2019, which had a potential of 416,284.7 t/annum, it was significantly lower; this reduction in yield could be attributed to the COVID-19 pandemic, which had a severe impact on the country's agricultural activities. Assuming the absence of natural disasters and pandemics, the estimation for the year 2038 was conducted with the aid of data in Table 2, which helped to prove that when exposed to the required growth conditions, the country's theoretical crop residue potential would increase steadily.
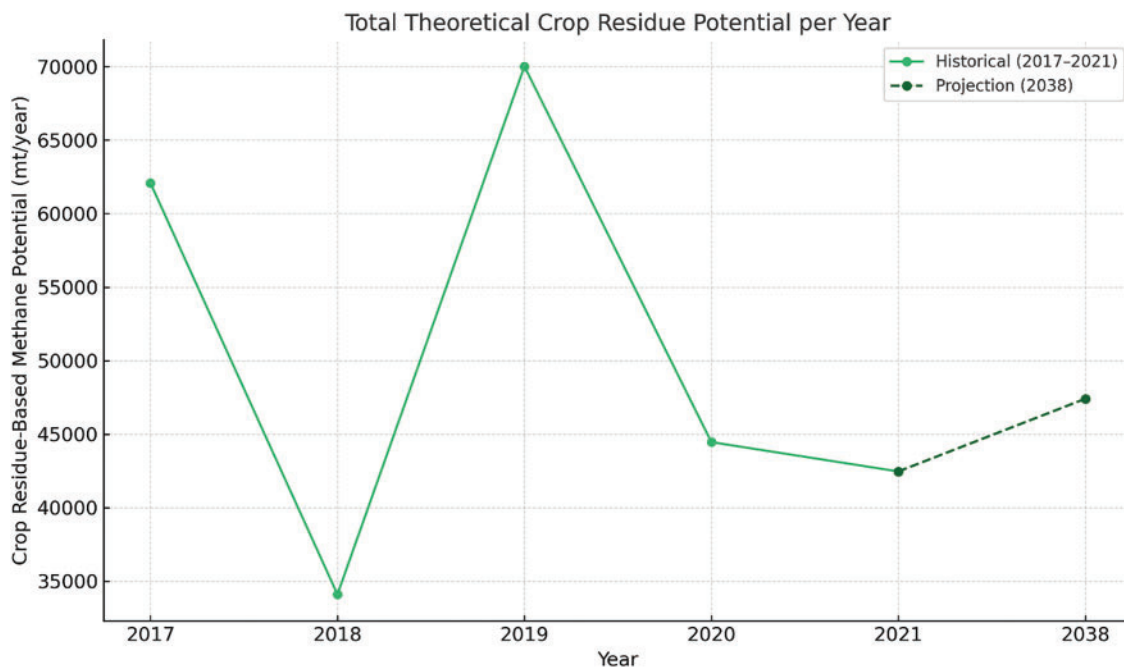

Figure 2: The total theoretical crop residue potential per year

3.2 Municipal Solid Waste Theoretical Potential

Unlike the theoretical crop potential shown above in Fig. 2, the municipal solid waste theoretical potential represented in Fig. 3 shows a steady yearly increase in municipal solid waste theoretical potential. This trend is due to the increase in population size and the per capita generation of the country. Based

on this trend, in addition to that of the crop residue potential, when the theoretical potential for crop residue and MSW is combined, it shows that the country has an estimated total theoretical potential of 329,889.7 t/annum.
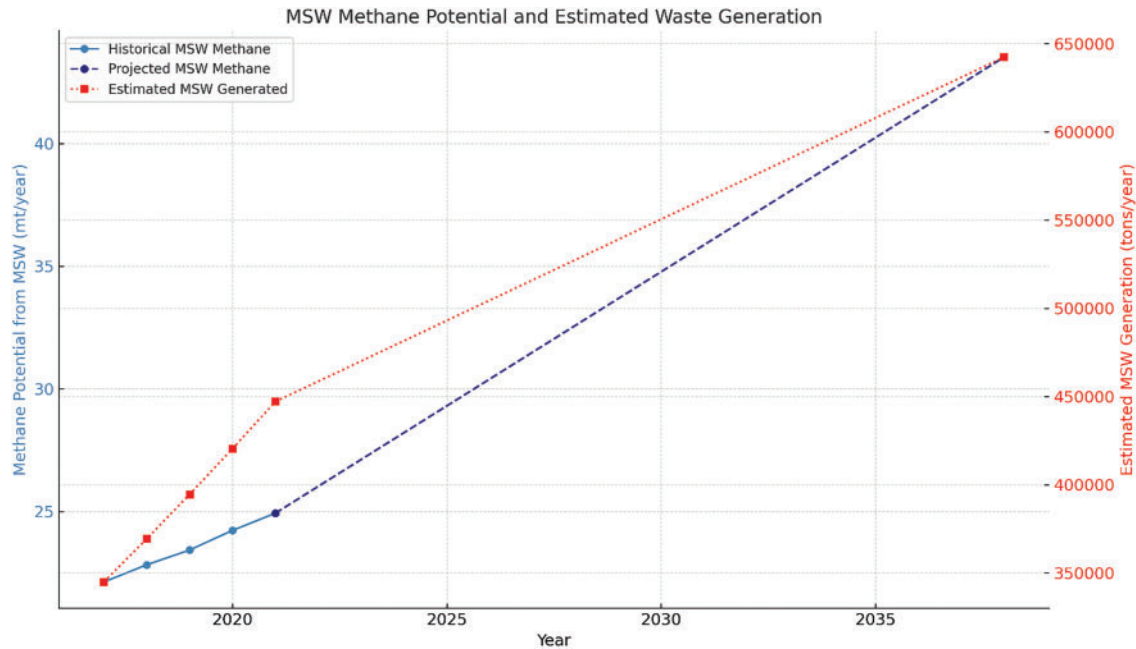

Figure 3: The total theoretical potential of municipal solid waste

3.3 Theoretical Methane Potential

The findings presented in Fig. 4 illustrate that the residues derived from cash crops, specifically groundnuts, millet, sorghum, and maize, exhibit significantly higher methane production potentials in comparison to subsistence crops. Conversely, the organic fraction of municipal solid waste (OFMSW) demonstrates the lowest theoretical methane production potential.

The data spanning the years 2017 through 2021 indicate that groundnut residues, which possess the highest methane production potential, yielded the following annual methane generation figures: 30,836 mt/annum in 2017, 11,696.6 mt/annum in 2018, 30,836.6 mt/annum in 2019, 19,139.9 mt/annum in 2020, and 18,608.3 mt/annum in 2021. Moreover, the projected methane production for groundnuts in the year 2038 is estimated to be 20,203.3 mt/annum.

In stark contrast, the methane production levels derived from OFMSW further corroborate its relatively low potential when juxtaposed against crop residues. The respective methane production metrics for the years 2017, 2018, 2019, 2020, 2021, and the projection for 2038 are as follows: 22.1, 22.8, 23.4, 24.2, 24.9 and 43.5 mt/annum.

While crop residues alone demonstrate considerable potential for methane production, an optimal outcome would involve the synergistic integration of OFMSW with crop residues. The comprehensive total combined feedstock outputs for the years 2017, 2018, 2019, 2020, and 2021, and the projection for 2038 were recorded at: 62,102.7, 34,129.4, 70,039.9, 44,485.7, 42,492.7, and 47,455 mt/annum, respectively.
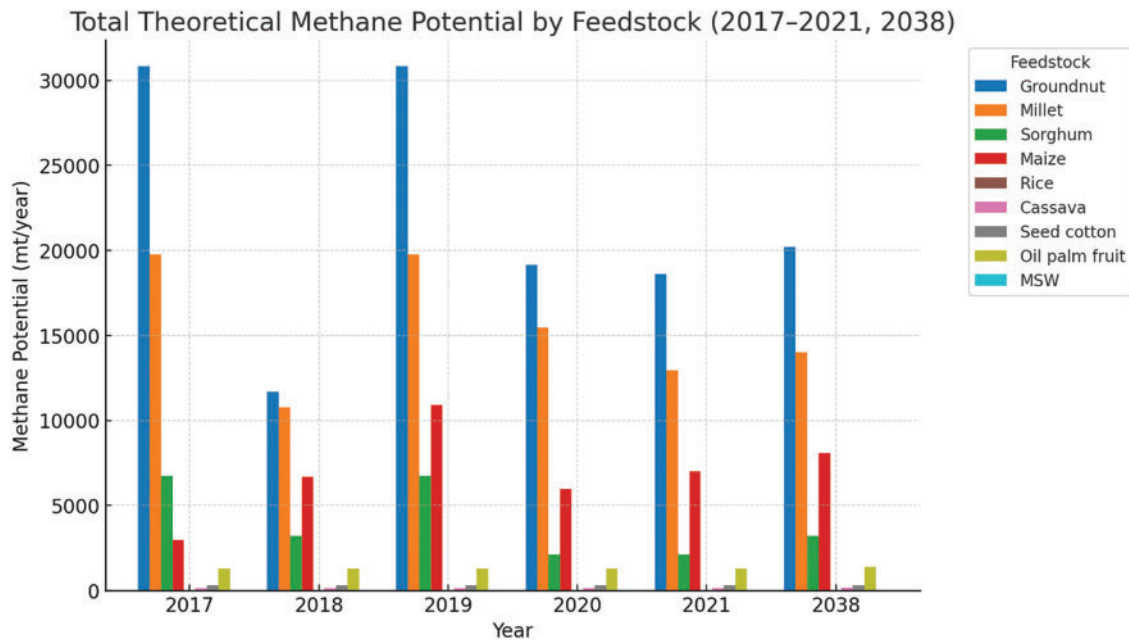
Figure 4: Total theoretical methane potential

3.4 Theoretical and Technical Energy Potential

Similarly, to that of the methane potential, the results indicate that the residues from cash crops, specifically groundnuts, millet, sorghum, and maize, exhibit significantly higher energy production potentials from methane compared to those derived from subsistence crops. Furthermore, the analysis demonstrates that the organic fraction of municipal solid waste possesses the lowest theoretical energy potential among the evaluated materials. Data for energy production from groundnut residues, which were identified as having the highest potential among the studied residues, for the years 2017, 2018, 2019, 2020, 2021, and 2038 are reported as follows: 431,711.8, 163,752.8, 431,711.8, 267,959.1, 260,515.8, and 282,845.7 MWh, respectively. In contrast, energy generation from OFMSW consistently yields the lowest potential when compared to crop residues, with the following production levels recorded for the respective years: 309.8, 319.6, 328, 339.2, 349.4, and 609.4 MWh. While individual crop residues demonstrate a commendable potential for energy production, an optimal strategy would involve the synergistic combination of OFMSW and crop residues to enhance overall energy yield. The resulting totals for the combined feedstock for the years 2017, 2018, 2019, 2020, 2021, and 2038 were: 869,437.6, 477,811.1, 980,558.1, 622,799.2, 594,898.1, and 664,367.3 MWh, respectively.
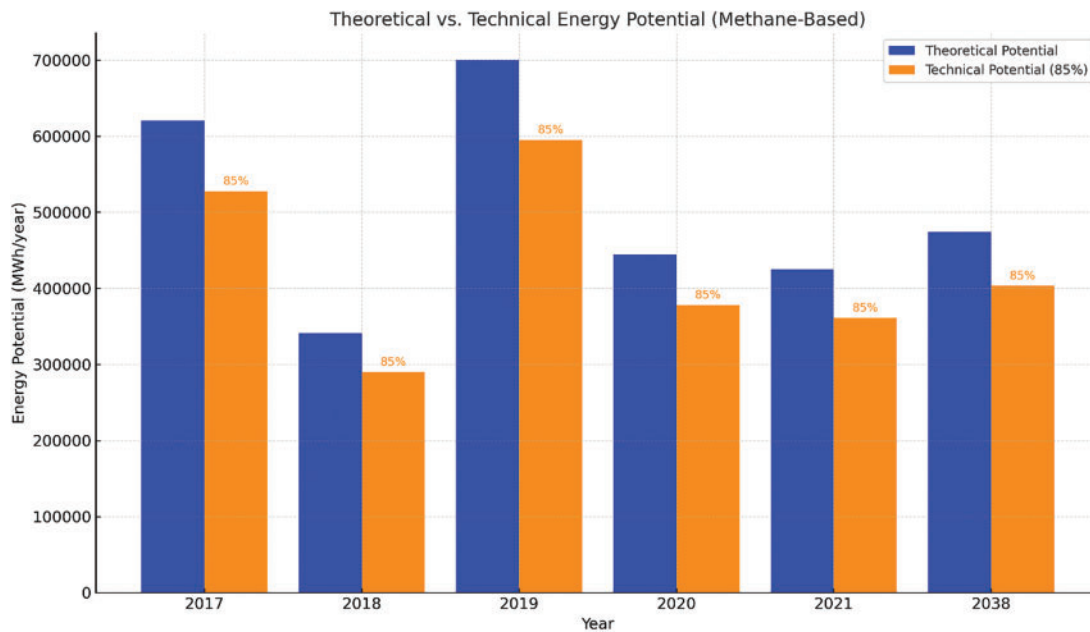
Figure 5: Total theoretical and technical potential

As shown above in Fig. 5, the technical potential represented in orange proves that when all the feedstocks are summed up the actual achievable capacity for the country to produce electricity from the feedstocks for the years 2017, 2018, 2019, 2020, 2021, and 2038 were: 739,022, 406,139.5, 833,474.4, 529,379.3, 505,663.4, and 564,712.2 MWh.

Based on the feedstocks analyzed for this research, the country could potentially implement a waste-to-energy plant with an actual achievable capacity of 64.5 MW for electricity generation.

3.5 Theoretical and Technical Hydrogen Production Potential

As seen in the results for methane and energy production potentials, the residues from the cash crops, namely groundnuts, millet, sorghum, and maize, have higher hydrogen production potentials as compared to the subsistence crops. It also shows that the organic fraction of municipal solid waste has the lowest theoretical hydrogen potential.

In the years 2017, 2018, 2019, 2020, 2021, and 2038, the results for hydrogen production from groundnut residues, which had the highest potential, were: 5,781,855.1, 2,193,117.4, 5,781,855.1, 3,588,737.6, 3,489,050.5, and 3,788,111.9 kmol.

In contrast, hydrogen produced from the OFMSW results showed that it has the lowest potential when compared to crop residue. Its results for years 2017, 2018, 2019, 2020, 2021, and 2038 were 4148.9, 4280.3, 4393, 4543.1, 4674.6, and 8161.1 kmol, respectively.

Although crop residues on their own have a good potential for energy production, a more desirable output would be combining the OFMSW and crop residues for production. The results of the total combined feedstock for the years 2017, 2018, 2019, 2020, 2021, and 2038 were 11,644,254, 6,399,256.1, 13,132,474.2, 841,060.2, 7,967,385.5, and 8,897,776.7 kmol, respectively.
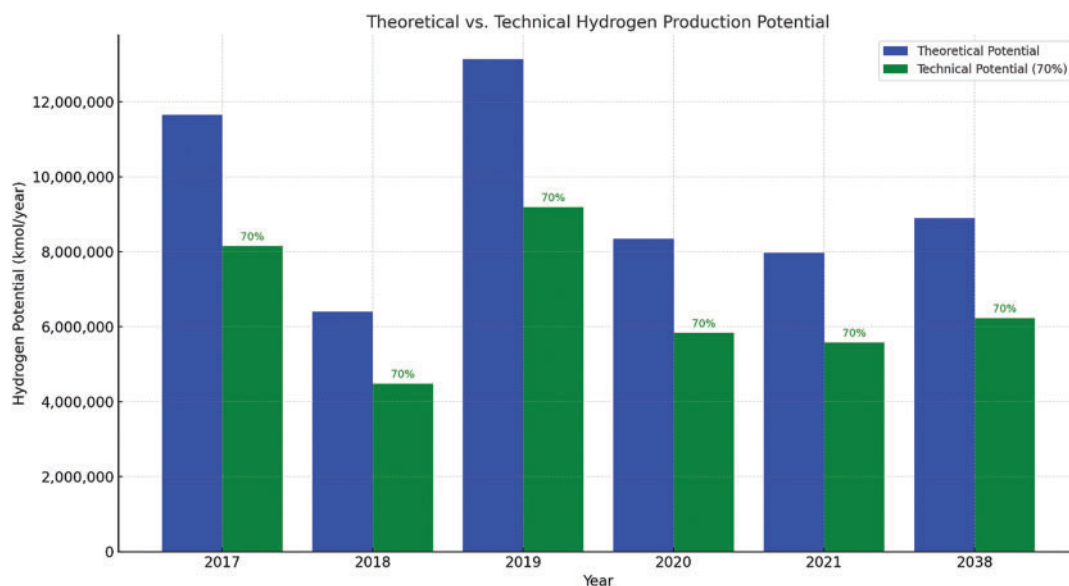
Figure 6: Total theoretical hydrogen production potential compared to technical potential

Fig. 6 compares the results for the theoretical potential to those of the technical potential for hydrogen. Although the theoretical potential is more than the technical potential for each of the years, the country still has a good hydrogen production capacity based on the chosen feedstock for this research.

The technical hydrogen potential for the years 2017, 2018, 2019, 2020, 2021, and 2038 was 8,150,977.8, 4,479,479.3, 9,192,731.9, 5,838,742.2, 5,577,169.9, and 6,228,443.7 kmol, respectively.

3.6 *Pilot Waste-to-Energy Plant Based on Technical Energy and Hydrogen Potential Results*

Based on the results obtained from Figs. 5 and 6 clearly show that The Gambia has the potential to produce both electricity of 64.5 MW and hydrogen of 6,228,443.7 kmol from the organic fraction of municipal solid waste although based on the method of calculation used a potential pilot plant can choose to produce only electricity and later produce hydrogen based on the market demand and what the country needs at the time but not the two products at the time. Moreover, this will aid the country in achieving its 2050 long-term development goal of achieving 100% electrification. However, to fully utilize the country's potential waste from livestock and aquatic life, the country should be investigated.

Considering the results and the above-mentioned factors, the country has a strong potential to produce methane, electricity, hydrogen, and other products if a pilot plant is implemented. This will aid the country in achieving its development goals by increasing the GDP and standard of living, and reducing migration, as it will open job opportunities both in rural and urban centers. Due to the country's strategic location next to the Atlantic Ocean on its western borders, the export of other products, such as catalysts, to other countries can be easily achieved.

To select an ideal location for the pilot plant, the following factors were considered:

- The district that generates the highest amount of MSW is shown in Fig. 7: MSW potential across the eight districts for the year 2013 and potential location for the pilot plant.
- Former mining sites that are no longer operational, namely Kartong and Kachuma, shown in Fig. 8, could be used as a location to build the mining site. Mining sites were considered to avoid competition with fertile land that can be used for agriculture and urbanization as the country is still developing, mining sites in the country are also close to water bodies and are far from residential areas and factories making it an ideal location to avoid fire incidents and to increase methods of transportation of waste and products either by land or sea.
- The country's Sandika market and the largest slaughterhouse in the country are also located in Brikama. This is also ideal as waste from the market and slaughterhouse can be easily transported to the potential site.
- Brikama has easy access to the River Gambia and the Banjul port. This could facilitate the trade of products between the two countries.

Fig. 7 represents The Gambia's eight districts, with the darkest color representing the area with the highest MSW generation. It also highlights the suggested location for a pilot plant.
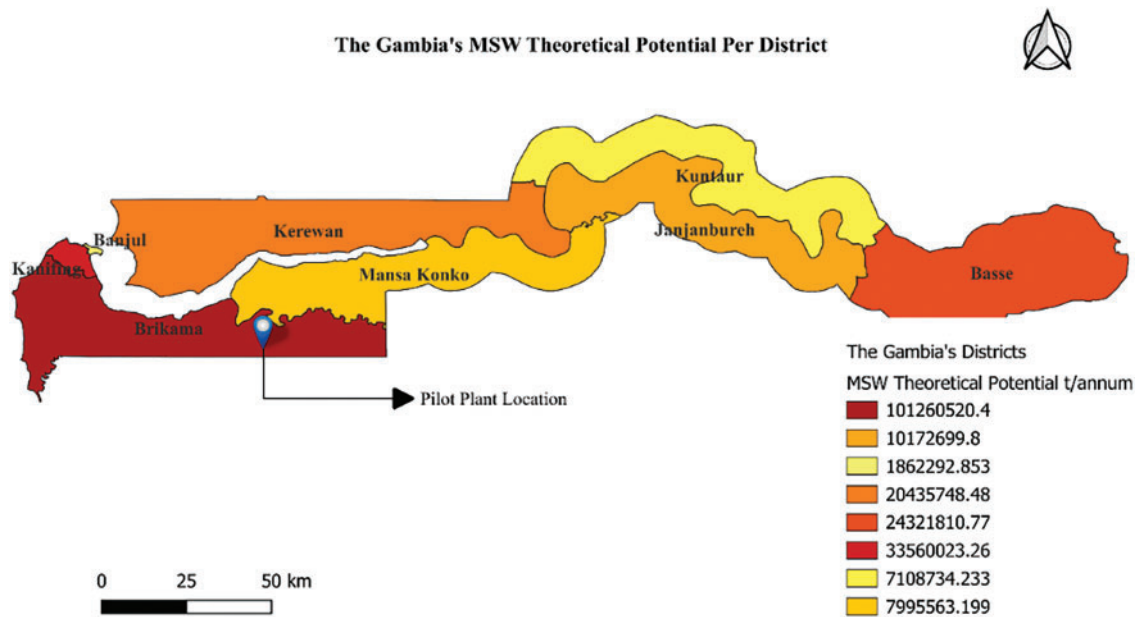

Figure 7: MSW potential across the eight districts for the year 2013 and potential location for the pilot plant (Reused with permission and modified after National Environment Agency 2014)
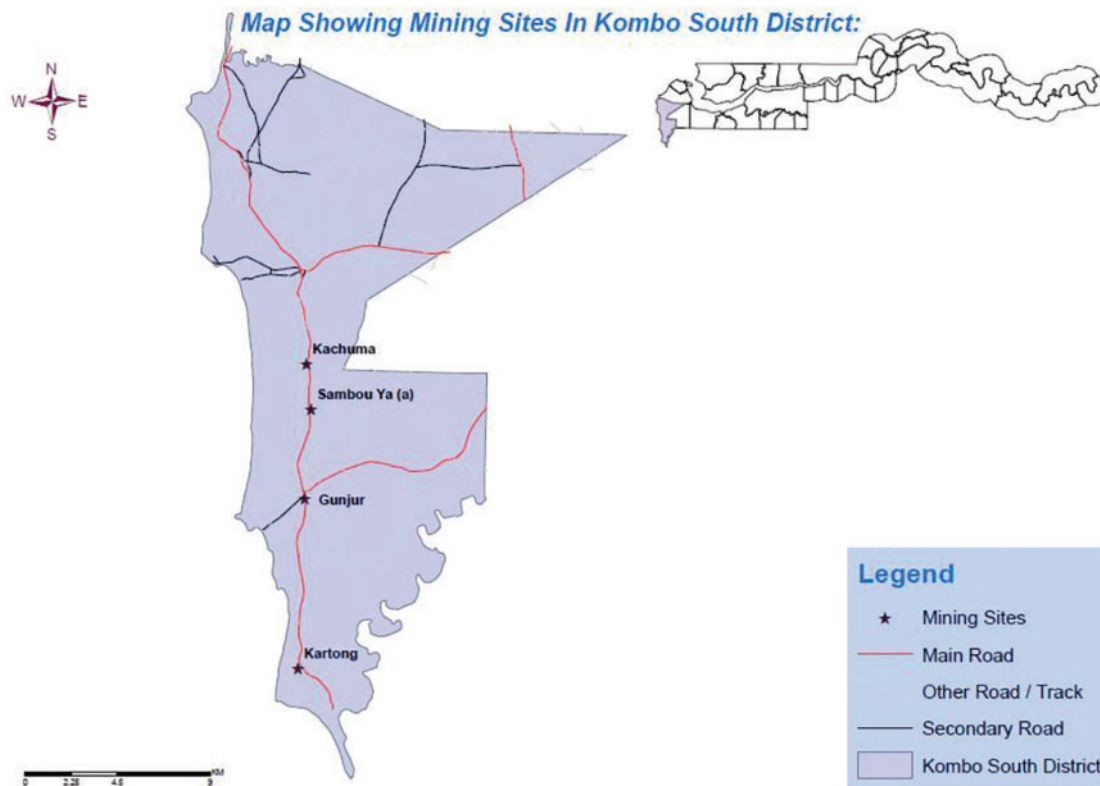
Figure 8: Mining sites in the Brikama district

MSW potential across the eight districts for the year 2013 and potential location for the pilot plant are explained in Table A9. The calculations shown in this table were unable to be conducted for the other years as demographic sensors for the districts haven't been conducted since 2013.

3.7 Comparative Analysis of Hybrid Waste-to-Energy Systems in Africa

This study provides valuable insights into the potential of incorporating hybrid WTE technologies, including biohydrogen production, in The Gambia's energy mix. When compared to similar studies in other African countries, such as Ghana, where WTE technologies have been assessed in the context of organic waste and biogas potential, the results of our study highlight the promising scalability of biohydrogen and bioenergy from waste. For instance, in Ghana, the estimated hydrogen yield from organic waste MSW through AD and steam methane reforming (SMR) processes can reach up to 40,000 GWh per year, with significant GHG emissions reductions (14,601 kt CO_2e) [72]. In contrast, our findings suggest that The Gambia's technical potential for hydrogen production is still in its early stages, yet comparable methodologies for hydrogen yield calculations show that waste-to-energy systems could offset a significant portion of fossil fuel use, providing substantial environmental benefits.

Technically, the potential of hybrid W2E systems in The Gambia aligns closely with national energy needs. The energy generation capacity from biogas and hydrogen in The Gambia has the potential to meet

a significant portion of the country's energy demand, as outlined in previous studies on waste-to-energy integration in other regions [73]. The assessment of WTE systems in Ghana demonstrated the feasibility of generating electricity and reducing GHG emissions while simultaneously promoting waste management and energy recovery [72]. This is crucial for countries like The Gambia, where energy access remains a challenge, and renewable energy systems, including bioenergy from waste, can provide both economic and environmental advantages. The results also show that the combination of solar power and waste-to-energy technologies can significantly boost the overall energy capacity, which is crucial for national energy security.

When compared to solar-only strategies, the feasibility of hybrid systems emerges as more promising for countries with high waste generation, like The Gambia and Ghana. The integration of W2E systems, especially those that combine anaerobic digestion with biohydrogen production, offers a more reliable and sustainable alternative than solar power alone. While solar energy plays an important role in reducing carbon emissions, its intermittent nature limits its ability to meet continuous energy demand. In contrast, waste-to-energy systems can provide both base-load power and the ability to generate clean fuels like hydrogen, which can be stored and transported. This hybrid approach is therefore not only technically feasible but also offers greater resilience and reliability in the face of fluctuating solar availability [72].

3.8 Gaps and Recommendations

During this research, the following gaps were identified:

- Data on types and quantity of crops produced yearly and seasonally.
- Use of crop residue and disposal of unwanted residue.
- Geographic information system (GIS) location of gardens and land area planted on.
- Number of dumpsites and the quantity of municipal solid waste generated yearly.
- Composition of The Gambia's municipal solid waste.
- Ultimate and proximate analysis of crops produced and municipal solid waste in The Gambia.
- The residue-to-crop ratio of crops produced in The Gambia.

These gaps were further categorized into three main gaps, which are as follows:

- No proper management and monitoring of crop residue and MSW.
- Lack of awareness of waste management and its energy value.
- Lack of systems and proper infrastructure for the conversion of waste to valuable goods and resources.

The primary objective of this research is to assess whether The Gambia has the potential to produce hydrogen and bioenergy sources from municipal solid waste and crop residues. The theoretical potential of the organic fraction of municipal solid waste and crop residues is calculated based on data from the years 2017 to 2021, as well as projections for 2038. These results are then utilized to estimate the production potential of biomethane and electricity using Buswell's equation, from which, through stoichiometry, the potential for hydrogen production is determined via steam methane reforming. The technical potential for electricity and hydrogen is subsequently calculated using their respective conversion efficiencies.

To help the country achieve its 2050 energy development goals, the following recommendations should be implemented, beginning with the data collection strategy illustrated in Fig. 9. The proposed data collection strategy is designed for implementation within a timeframe of one to two years, contingent upon adherence to the following considerations:

Data collection Strategy

Figure 9: Automated data collection strategy illustration

Acquisition of Tools and Resources:

- Development and procurement of automated data collection software.

- The acquisition of necessary laboratory equipment and reagents to facilitate analysis.

- Recruitment of field personnel, laboratory technicians, data managers, and software developers. Engaging local-stakeholders, such as farmers and waste collectors, will enhance data accuracy and foster community acceptance.

- Procurement of tablets and computers to streamline data collection and management processes.

Training Protocols:

- Comprehensive training programs for staff on the effective use of data collection tools and software.

- Targeted training for field personnel on conducting surveys in local languages to ensure cultural and contextual relevance.

Field Survey Implementation:

- Systematic data collection regarding the monthly harvest of various crops, including quantitative assessments of yield.

- Collection of representative samples for laboratory analysis.

Data Upload and Representation:

- Results from laboratory analyses will be systematically uploaded to a designated software platform.

- The uploaded data will then undergo analysis and interpretation, employing statistical methods and visual representations, including tables and graphs.

Publication of Findings:

- The analyzed data will be disseminated through the official website to ensure transparency and accessibility.

- Annual publications will be produced to document the research findings and analyses, contributing to the scientific community and informing stakeholders.

To effectively implement the data collection strategy, it is crucial to develop an awareness strategy that highlights the importance of adopting a waste-to-energy framework. This framework presents various benefits, such as reducing greenhouse gas emissions, strengthening the nation's economic resilience, and

enhancing energy security. By raising awareness and engaging relevant stakeholders, we can increase social acceptance of waste-to-energy initiatives, which will help facilitate their implementation across the country. The potential steps for the awareness strategy are outlined in Fig. 10.

Figure 10: Awareness strategy illustration

The waste-to-energy strategy will be implemented in three distinct phases, each designed to enhance waste management and energy production as seen in Fig. 11.
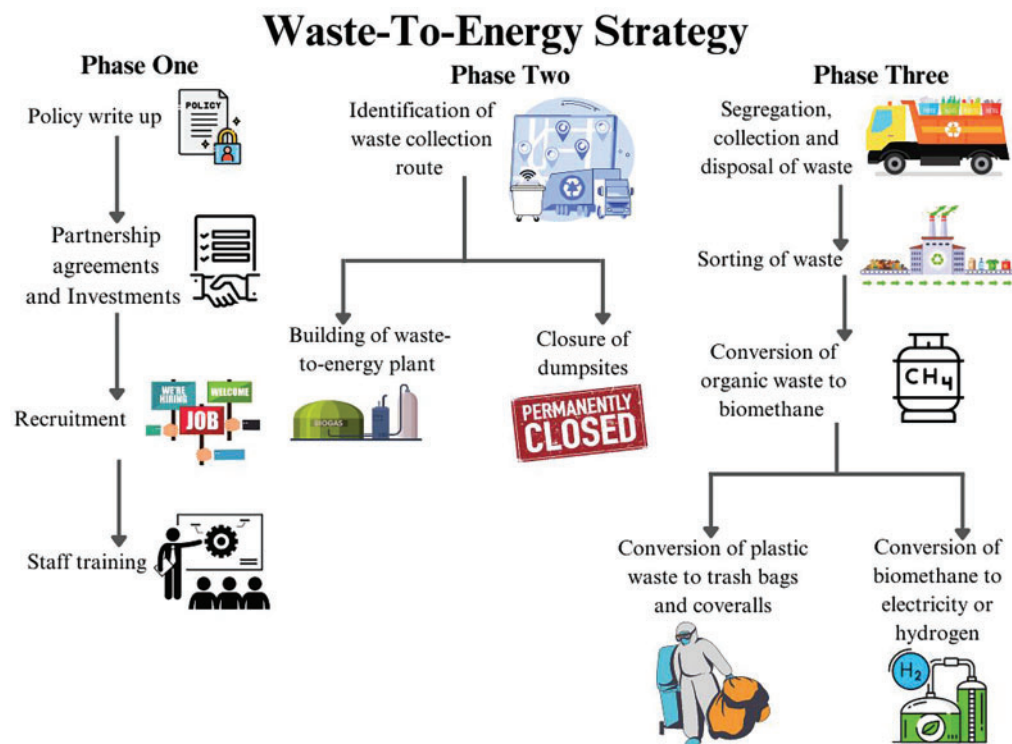

Figure 11: Three-phase waste-to-energy strategy illustration

Phase One will focus on establishing foundational partnerships and training initiatives. This includes forming partnerships through memoranda of understanding with private waste collection companies and governmental entities to streamline efforts. Farmers will receive training on effectively separating and storing crop residues, which will be used for energy generation and composting. Waste collectors will also undergo training to familiarize themselves with Geographic Information System (GIS) tools and equipment, improving the efficiency of waste transportation. Additionally, feasibility studies will be conducted for the proposed waste-to-energy plant, setting the stage for Phase Two.

Phase Two will utilize GIS technology to optimize waste collection routes, thereby enhancing operational efficiency. This phase will also concentrate on connecting the proposed plant to the electrical grid, ensuring that the generated energy is integrated into the larger system. Furthermore, strategies will be developed for distributing products generated from the waste-to-energy process. Essential resources, such as sweepers, waste collection trucks, and color-coded community bins for educational purposes, will be acquired to support effective waste management.

Phase Three will culminate in the generation of electricity that will be fed into the grid, marking a significant achievement in sustainable energy production. This phase will also explore innovative ways to handle plastic waste, converting it into valuable products like trash bags and gloves. The commercial viability of these products will be assessed to promote domestic sales, contributing to economic development and environmental sustainability.

Through these phases, the waste-to-energy strategy aims to promote a comprehensive approach to waste management, enhance energy production, and encourage community involvement in sustainability initiatives.

4 Conclusion

This study offers a comprehensive assessment of the potential for integrating alternative sustainable energy sources, specifically bioenergy and green hydrogen, into The Gambia's energy mix. The investigation uniquely synthesizes the evaluation of agricultural crop residues and municipal solid waste for bioenergy production, providing novel insights into the utilization of these underexploited feedstocks to address the nation's increasing energy demands.

In contrast to previous research, this study effectively bridges the gap between theoretical potential and practical implementation. It presents a detailed analysis of hydrogen yield and its implications for enhancing national energy security. The findings indicate that The Gambia harbors substantial untapped resources in the form of agricultural residues and waste materials, which can be converted into clean energy, including biohydrogen, thereby offering significant environmental benefits.

Furthermore, this research systematically compares the efficacy of a hybrid waste-to-energy approach with solar-exclusive strategies, highlighting the enhanced feasibility and resilience of hybrid systems in ensuring a reliable and continuous energy supply for the nation. By addressing the dual challenges of waste management and renewable energy generation, this study lays the groundwork for future policy initiatives and investments in waste-to-energy technologies.

Ultimately, the novelty of this research lies in its integrative approach to bioenergy, waste management, and green hydrogen production within the context of a low-income country. This work presents a scalable model for sustainable energy development that can be applied to similar regions worldwide.

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Availability of Data and Materials: The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Ethics Approval: Not applicable, this study did not involve any human or animal subjects.

Conflicts of Interest: The authors declare no conflicts of interest to report regarding the present study.

Abbreviations

MSW	Municipal solid waste
OFMSW	Organic fraction of municipal solid waste
AD	Anaerobic digestion
RPR	Residue-to-product ratio
WTE	Waste-to-Energy
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IPP	Independent Power Producers
NAMA	Nationally Appropriate Mitigation Action
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
$GgCO_2e$	Gigagrams of Carbon dioxide equivalent
STP	Standard Temperature and Pressure

Appendix A

Table A1: Theoretical crop residue potential for 2017

2017 Theoretical crop residue potential					
Crop type	**Production/annum in tons**	**Reference**	**Residue type**	**RPR**	**Residue/tons**
Rice	30,000	[34]	Straw	1.66	49,800
			Husks	0.26	7800
			Stalks	1.59	49,290
Maize (Corn)	31,000	[34]	Husks	0.2	6200

(Continued)

Table A1 (continued)

	2017 Theoretical crop residue potential				
Crop type	Production/annum in tons	Reference	Residue type	RPR	Residue/tons
			Cobs	0.29	8990
Cassava	11,941.4	[34]	Stalks	0.06	716.484
Groundnuts	58,000	[34]	Shells	0.37	21,460
			Straw	2.15	124,700
Millet	55,000	[34]	Stalks	1.83	100,650
Oil palm fruit	35,076.1	[34]	Kernel shells	0.07	2455.327
			Fiber	0.14	4910.654
Sorghum	19,000	[34]	Stalks	1.99	37,810
Seed cotton	545.28	[34]	Stalks	2.755	1502.2464
Total	**240,562.78**				**416,284.7114**

Table A2: Theoretical crop residue potential for 2018

	2018 Theoretical crop residue potential				
Crop type	Production/annum in tons	Reference	Residue type	RCR	Residue/tons
Rice	28,000	[34]	Straw	1.66	46,480
			Husks	0.26	7280
Maize (Corn)	19,000	[34]	Stalks	1.59	30,210
			Husks	0.2	3800
			Cobs	0.29	5510
Cassava	11,767.34	[34]	Stalks	0.06	706.0404
Groundnuts	22,000	[34]	Shells	0.37	8140
			Straw	2.15	47,300
Millet	30,000	[34]	Stalks	1.83	54,900
Oil palm fruit	35,075.14	[34]	Kernel shells	0.07	2455.2598
			Fiber	0.14	4910.5196
Sorghum	9000	[34]	Stalks	1.99	17,910
Seed cotton	541.93	[34]	Stalks	2.755	1493.01715
Total	**74,617.07**				**231,094.837**

Table A3: Theoretical crop residue potential for 2019

	2019 Theoretical crop residue potential				
Crop type	Production/annum in tons	References	Residue type	RCR	Residue/tons
Rice	30,000	[34]	Straw	1.66	49,800
			Husks	0.26	7800
			Stalks	1.59	49,290
Maize (Corn)	31,000	[34]	Husks	0.2	6200
			Cobs	0.29	8990
Cassava	11,941.4	[34]	Stalks	0.06	716.484
Groundnuts	58,000	[34]	Shells	0.37	21,460
			Straw	2.15	124,700
Millet	55,000	[34]	Stalks	1.83	100,650
Oil palm fruit	35,076.1	[34]	Kernel shells	0.07	2455.327
			Fiber	0.14	4910.654
	19,000	[34]	Stalks	1.99	37,810
Seed cotton	545.28	[34]	Stalks	2.755	1502.2464
Total	**240,562.78**				**416,284.7114**

Table A4: Theoretical crop residue potential for 2020

	2020 Theoretical crop residue potential				
Crop type	Production/annum in tons	References	Residue type	RCR	Residue/tons
Rice	40,300	[34]	Straw	1.66	66,898
			Husks	0.26	10,478
			Stalks	1.59	27,030
Maize (Corn)	17,000	[34]	Husks	0.2	3400
			Cobs	0.29	4930
Cassava	11,855.76	[34]	Stalks	0.06	711.3456
Groundnuts	36,000	[34]	Shells	0.37	13,320
			Straw	2.15	77,400
Millet	43,000	[34]	Stalks	1.83	78,690
Oil palm fruit	35,069.48	[34]	Kernel shells	0.07	2454.8636
			Fiber	0.14	4909.7272
Sorghum	6000	[34]	Stalks	1.99	11,940
Seed cotton	543.77	[34]	Stalks	2.755	1498.08635
Total	**189,769.01**				**303,660.0228**

Table A5: Theoretical crop residue potential for 2021

2021 Theoretical crop residue potential					
Crop type	Production/annum in tons	References	Residue type	RCR	Residue/tons
Rice	41,900	[34]	Straw	1.66	69,554
			Husks	0.26	10,894
			Stalks	1.59	31,800
Maize (Corn)	20,000	[34]	Husks	0.2	4000
			Cobs	0.29	5800
Cassava	11,827.21	[34]	Stalks	0.06	709.6326
Groundnuts	35,000	[34]	Shells	0.37	12,950
			Straw	2.15	75,250
Millet	36,000	[34]	Stalks	1.83	65,880
Oil palm fruit	35,070.62	[34]	Kernel shells	0.07	2454.9434
			Fiber	0.14	4909.8868
Sorghum	6000	[34]	Stalks	1.99	11,940
Seed cotton	543.27	[34]	Stalks	2.755	1496.70885
Total	**186,341.1**				**297,639.1717**

Table A6: Theoretical crop residue potential for 2038

2038 Theoretical crop residue potential				
Crop type	Production/annum in tons	Residue type	RCR	Residue/tons
Rice	44,900	Straw	1.66	74,534
		Husks	0.26	11,674
Maize (Corn)	23,000	Stalks	1.59	36,570
		Husks	0.2	4600
		Cobs	0.29	6670
Cassava	14,827.27	Stalks	0.06	889.6362
Groundnuts	38,000	Shells	0.37	14,060
		Straw	2.15	81,700
Millet	39,000	Stalks	1.83	71,370
Oil palm fruit	38,070.62	Kernel shells	0.07	2664.9434
		Fiber	0.14	5329.8868
Sorghum	9000	Stalks	1.99	17,910
Seed cotton	543.27	Stalks	2.755	1496.70885
Total	**207,341.16**		**13.365**	**329,469.1753**

Table A7: Ultimate and proximate analysis of selected feedstock

Feedstock	Ultimate analysis					Moisture content	Dry matter	Reference
	C	**H**	**O**	**N**	**S**			
Rice straw	39.65	5.2	37.22	0.92	0.12	11.69%	–	[50,51]
Rice husk	45.2	5.8	47.6	1.02	0.21	10.89%	–	[51,52]
Maize stalks	45.33	6.18	46.99	0.52	0.98	6.40%	–	[53]
Maize husk	38.08	5.44	55.89	0.59	0	8.50%	–	[54]
Maize cob	46.2	5.42	47.22	0.92	0.24	9.27%	–	[55,56]
Cassava stalks	51.12	6.87	41.34	0.67	<0.1	15.54%	–	[57,58]
Groundnut shells	50.9	5.15	42.1	0.58	0	9.5%	–	[21]
Groundnut straw	41.42	5.51	35.21	1.27	0.1	–	93.99%	[59,60]
Millet stalks	44.4	6	43.8	0.3	0.15	4.9%	–	[61,62]
Oil palm fruit kernel shells	48.06	6.38	34.1	1.27	0.09	10.23%	–	[63,64]
Oil palm fruit fiber	42.65	5.48	50.78	1.09	0	11.10%	–	[64,65]
Sorghum stalks	46.47	5.69	46.75	1.09	0	6.63%	–	[66]
Seed cotton stalks	47.05	5.35	40.77	0.65	0.21	–	92.28%	[67,68]
OFMSW	47.03	6.75	32.7	2.58	0.52	60%	40%	[69]

Table A8: MSW generation potential per district (2013)

2013 MSW generation per district						
Districts	Population	Per capita generation of MSW	Number of days in the year	MSW tons/ annum	OFMSW	MSW Theoretical Potential t/annum
Banjul	31,054	0.53	365	6.01×10^6	0.31	1.86×10^6
Kanifing	377,134	0.53	365	7.30×10^7	0.46	3.36×10^7
Brikama	688,744	0.53	365	1.33×10^8	0.76	1.01×10^8
Mansakonko	81,042	0.53	365	1.57×10^7	0.51	8.00×10^6
Kerewan	220,080	0.53	365	4.26×10^7	0.48	2.04×10^7
Kuntaur	96,703	0.53	365	1.87×10^7	0.38	7.11×10^6
Janjanbureh	125,204	0.53	365	2.42×10^7	0.42	1.02×10^7
Basse	237,220	0.53	365	4.59×10^7	0.53	2.43×10^7
Total	**1,857,181**			$\mathbf{3.59 \times 10^8}$		$\mathbf{2.07 \times 10^8}$

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