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Using agricultural residues for sustainable transportation biofuels in 2050: Case of West Africa

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ABSTRACT

This article focuses on the use of biomass to produce transportation fuels such as synthetic natural gas, bioethanol and electricity under a sustainable scenario in West Africa in 2050. The aim of this work was to evaluate the feasibility of producing such biofuels using agricultural residues as feedstock in the studied area. The potential of biomass from ten agricultural residues was estimated in R environment using FAO data. Options were analyzed in order to generate portfolios of transportation fuels based on energy indicators, biomass availability and scenarios of technological progress. The optimal allocation varied from one country to the other, showing a fair tradeoff between the objective functions.

1. Introduction

The "Economic Community of West African States (ECOWAS)" involves fifteen-member states: Benin, Burkina Faso, Cape Verde, Gambia, Ghana, Guinea, Guinea-Bissau, Ivory Coast, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone, and Togo. Most of them are in the category of Low Human Development according to the Human Development Index (HDI). The HDI simplifies what human development entails, such as average achievement in a long and healthy life, being knowledgeable and having a decent standard of living (UNDP, 2019a). The health dimension is assessed by life expectancy at birth, the education one is measured by means of years of schooling for adults aged no less than 25 years and expected years of schooling for children of school entering age. The standard of living dimension is measured by gross national income per capita. This index does not reflect inequalities, poverty, human security, empowerment, etc. HDI values lower than 0.55 denote the Low Human Development category, whereas HDI ≥ 0.8 represent Very High Human Development (UNDP, 2019b). The HDI of 13 ECOWAS countries were in the range of 0.354 (Niger) to 0.532 (Nigeria) in 2017 (FAO, 2019). Only Ghana (0.592) and Cape Verde (0.654) were in the Medium Human Development Group.

The climate strongly influences the lives of people in this geo-political area limited by the Atlantic sea on the West and South and by the South of the Sahara Desert in the North. The aridity increases with the distance to the Atlantic Ocean and three climatic zones are distinguished: a semi-arid zone (Sahel) in the North suffering from dry climatic conditions, the Sudanian zone characterized by a high variability of precipitation, and a sub-humid Guinean zone located along the Guinea Gulf. Variability in West Africa's Climate is one of the highest in the world considering intra-seasonal and decadal data (Riede et al., 2016; Sylla et al., 2016). Projections indicate a slight increase of total precipitation and a longer rainy season with a drier phase within. Possible warming over West Africa was recorded ranging from 1.5 to 6.5 °C, with the Sahel experiencing the greatest changes. West Africa countries have recorded in recent decades a warming between 0.3 and 1 °C; but some countries located in Gulf of Guinea and west Sahel like Ghana, Cote d'Ivoire, Guinea and Senegal are exposed to a higher warming ranging from 0.2 °C to more than 0.5 °C per decade (World Bank (IBRD), 2009).

The region is substantially vulnerable to these changes since they will threaten agricultural activities, water resources management and ecosystem services (e.g. biomass and related energy production).

The main sources of biomass in West Africa include Guinean savannah, rain and semi deciduous forest, Sudanian savannah and deciduous forest, Sahelian and Saharan steppes. Long term availability of biomass in West Africa countries depends highly on future climate change and land use change. Studies at continental and global scales showed the loss of large proportions of suitable habitats, which in turn

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affects the distribution and richness of a large number of plant species, during this century attributed to climate change (McKeon et al., 2009). These effects of climate change on plant composition, distribution and richness would impact on the long-term availability of biomass in West Africa.

The biomass is a significant source for energy and fodder in Africa, where more than 90% of the harvested wood is consumed to meet the primary energy needs (FAO, 2017) and pastoralism plays a pivotal role. Feeding livestock is another function of biomass in WA. Natural pastures are the main feeding source far before crop residues and agricultural wastes such as spent grains.

WA is expected to almost triplicate its population from 2010 to 2050, reaching the 796.5 million peoples according to the medium scenario of the World Population Prospects 2019 (UNDP, 2019a, b). The increase in human population and the improvement of lifestyle lead to an increase in fodder needs due to the increase of livestock production. The use of biomass has been diversified with higher increase in demands for energy and fodder which are intensified by the lack of access to modern and efficient energy sources and concentrate diets at affordable prices. Studies of land-use and land-cover changes have shown significant reduction of areas of natural vegetation in this area due to their high conversion to croplands to ensure food sufficiency for the growing populations (Sun et al., 2009).

In 2010, about 83% of peoples relied on firewood and charcoal for domestic energy services. Due to the rapid urbanization and according to the energy substitution policy of the ECOWAS Renewable Energy Policy (EREP) conducted by several countries in the Community, this percentage would decrease but still would be at around 60% by 2030 (ECOWAS, 2015). The EREP is mainly based on the promotion of imported Liquefied Petroleum Gas (LPG). In the urgency of declining wooded areas, that policy of substitution seems to be the least bad instrument for environment conservation. However, a renewable biomass would be more environmentally and economically sustainable. The countries of WA face the challenges of energy poverty, energy security and climate change mitigation (UNDESA, 2015; ECOWAS, 2015). Biomass could contribute in a certain extent to cope with these challenges enabling energy security and poverty reduction in a sustainable way. One of the targets set by EREP involves first-generation (1G) biofuels (ECOWAS, 2015). They have set 5% and 15% as share of ethanol blended to gasoline for the 2020 and 2030 political agendas, respectively. For biodiesel as share of diesel consumption, the targets are 5% and 10% for 2020 and 2030, respectively (ECOWAS, 2015). However, for 2020 the targets are far from reaching. Furthermore, only1G biofuels are envisioned, which would anticipate direct and indirect competition with food and animal feed.

The use of agricultural residues to satisfy energy requirements is a potential way to guarantee energy services avoiding such issues. Multi-feedstock plants using agricultural residues to produce bioethanol, synthetic natural gas (SNG) and electricity are potential options for energy procurement. From the knowledge of the authors, that is the first time such perspective is considered for the WA region where all the strategies for solid biomass focus rather on fuelwood, charcoal converted by low efficiency stoves and electricity generation from small-medium scales gasifier power plants. The envisaged more efficient biomass conversion in such a region requires a challenged technology transfer and appropriate logistics systems that are implicitly assumed by the study.

In this paper, an energy analysis was carried out to evaluate the availability of agricultural residues to meet the energy demand for transport in WA by 2050. The study is based on prospective sustainable scenarios where the vehicles are fueled by E85, SNG and electricity. Given such situations, the opportunity to produce certain amount of each fuel would depend on the efficiency of converting a specific amount of biomass into such fuel. The goal of this work is to evaluate the possibility of meeting the energy demand for passenger cars in WA at long term by using only agricultural residues. The results can provide guidelines to decision makers for paving the way in this African sub-region towards sustainable energy patterns.

2. Methodology

The following phases are involved: evaluation of potential agricultural residues, choice of conversion technologies, elaboration of scenarios on technological progress, and assessment of technological allocation to meet fuel demand for road passenger transportation (RPT) for given strategic goals, and finally sensitivity analyses for selected factors.

2.1. Evaluation of the crop residues availability for transportation fuels

A sustainable scenario has been proposed in this study in order to meet the energy demand for RPT in 2050 in West Africa. At this aim, the availability of residues was estimated based on FAO data (FAOSTAT). First, the agricultural crops available in WA at the reference year (2019) were analyzed using FAO data (FAOSTAT). The products were quantified for each country, and only those with enough potential in at least 8 countries of WA were selected. The data were filtered and analyzed in R environment. The forecasted harvested area and crop yield were then taken for the year 2050 from the Global Perspectives Studies made by FAO (FAO, Global Perspectives Studies).

The FAO database contains projections for 2050 considering three different cases: business as usual (BAU), toward sustainability (TS) and stratified societies. The BAU case shows a perspective where despite the efforts of many countries, several outstanding challenges facing food and agriculture are left unaddressed. The TS case ensures universal and sustainable access to food mostly produced with environmentally sustainable methods. The challenges for both access and utilization, as well as sustainable food stability and availability, are lower than under the BAU case. TS involves a more sustainable use of natural resources and climate change mitigation compared to BAU. Food systems generating low GHG emissions are favored. Adopting conservation agriculture systems, agro-ecological approaches, agroforestry, and other environmentally-friendly techniques allows yields to increase against current levels – albeit more moderately than under BAU – and to converge across countries, while food systems drastically reduce GHG emissions compared with current levels. Since this study focuses on prospective scenarios in 2050 where the situation in WA is carried out by sustainable methods, the TS case of FAO was chosen and evaluated.

Regarding the feedstocks for conversion into biofuels, they were selected with scrutiny in order to avoid any competition with food and animal feed. Since data of Guinea Bissau and Cape Verde were not available, these countries were not considered in the analysis. For each of the thirteen remaining countries (Benin, Burkina Faso, Côte d'Ivoire, Gambia, Ghana, Guinea, Liberia, Mali, Niger, Nigeria, Senegal, Sierra Leone and Togo) the crop-to-residues ratio for each selected crop was taken from different literature sources (Faostat, 2019, Magalhães et al., 2019) in order to quantify the availability of residues in 2050.

The amounts of cellulose, hemicellulose and lignin were evaluated for each country. The mass composition values were calculated from average data collected from literature (Magalhães et al., 2019). For soil conservation and organic nutrients preservation, at least 50% crop residues should be kept on the soil (Gobin et al., 2011). A higher percentage of harvested crop residues would lead to extremely low soil organic carbon fluxes. The sensitivity of the results to the percentage of residues left on the fields was studied as well.

2.2. Multi-feedstock plants for conversion of biomass

Three types of renewable transportation fuels were envisaged to satisfy the demand: E85, SNG and electricity. These transportation biofuels were considered to be produced entirely from the conversion of the selected residues in prospective multi-feedstock plants. Three different multi-feedstock plants were addressed: A lignocellulosic ethanol plant, a gasification and methanation plant and finally a Biomass Integrated Gasification Combined Cycle (BIGCC) for electricity generation. These technologies were chosen for their high readiness level and their potential for transfer to West Africa by 2050.

2.2.1. Lignocellulosic ethanol plant

After several decades of bench scale, pilot and demonstration operations, biochemical conversion of lignocellulosic materials into ethanol started its “first of a kind” commercial stage in the earliest 2010s. Despite several troubles due to economic reasons such as low prices of petroleum oil and high price of feedstock, technical issues like process inefficiencies or failures, lignocellulosic ethanol remains the most commercially mature and promising pathway for producing transportation biofuels. As examples of existing projects, a company in Slovakia is planning to set up a cellulosic ethanol plant that will use agricultural residues as feedstock (Rosales-Calderon and Arantes, 2019). The French pre-industrial plant Futurol is designed as a multi-feedstocks plant capable to use inter alia agricultural and forest residues (Stadler and Chauvet, 2018). However, the existing plants or projects cannot exemplify the prospective technologies in 2050. In this study, the existing technologies were extrapolated in the future based on the 2011 design by the National Renewable Energy laboratory (NREL) and well documented in Humbird et al. (2011). This extrapolation keeps on the high variety of possible designs and the potential technology progress by 2050. However, whatever progress could occur by 2050, it was considered in this study for the evaluation of the potential production of bioethanol form residual biomasses, that both hexoses and pentoses would be converted into bioethanol. From the technology in Humbird et al. (2011), a reference overall yield of 87 gallon/ton of biomass, dry basis) was found that was assumed as the lowest value in 2050. Assuming a full conversion and stoichiometric reactions, a theoretical yield of 105 gallon/ton d.b. was calculated. The highest value of yield was chosen as 95% of the theoretical value. The yields are then expressed in terms of energy ratio (energy value of bioethanol/energy value of feedstock). It is worth noting that the terms “energy ratio” used in this paper only consider the ratio between the energy content of the bioethanol and the one in the biomass feedstock. This ratio that only expresses the ethanol yield per ton of feedstock, does not account for the energy used in the conversion process. That is not an energy efficiency. The yield in Humbird et al. (2011) say 87 gallons/ton d.b or an energy ratio of 0.44 represents 83% of the theoretical yield. The latter corresponds to an energy ratio of 0.53 and the assumed highest value in 2050 to an energy ratio of 0.50. As a comparison with similar assumptions, Sandia National Laboratories (SNL), General Motors' R&D Center (2009) assumed an average yield of 95 Gallon/ton d.b. for the conversion of cellulosic material to ethanol by 2030 or an energy yield of 0.48.

2.2.2. Synthetic natural gas

The agricultural residues feedstocks are converted into a methane rich gas that is purified to release a substitute to fossil-based natural gas: the Synthetic Natural Gas (SNG). The thermochemical conversion process involves the following phases: pretreatment of the feedstock, gasification, syngas conditioning, methanation, and conditioning of the SNG. First, the solid biomass is grinded and dried. The small particles are then conveyed to a Milena type gasifier. The indirect gasifier operates at a temperature in the range of 700–900 °C and a pressure of 7 bar (Aranda et al., 2014). It generates a raw syngas that is a mixture of CO, CO_2, CH_4, H_2, ethylene, benzene, and contaminants like nitrogen, sulphur compounds, and heavy metals). The conditioning of the raw syngas consists in cooling, cleaning and adjusting the composition (CO_2 content and H_2/CO ratio in order to comply with the requirements of the subsequent phase. At the methanation stage, the cleaned syngas is converted into an SNG through an exothermic reaction. The raw SNG still contains water and CO_2 that need to remove. The gas is then cooled and and its pressure is adjusted to the uses requirements. Bio-SNG is at the stage of pilot and demonstration stages. The efficiency in the case of Milena project was reported to be 70%. In this study, it was considered a minimum efficiency of 54% and a maximum of 74% (Kraussler et al., 2018).

2.2.3. Biomass gasification integrated combined cycle

While the bio-SNG plant issues a substitute natural gas that can be converted into electricity in a Combined Cycle Power Plant (CCPP), it is expected that direct integration of the gasification stage with a combined cycle power generation will improve the whole energy efficiency. Like the development of bio-SNG that learns from Coal-SNG, BIGCC inherits from Coal Integrated Gasification and Combined Cycle (CIGCC). In a BIGCC, the syngas produced after the gasification is directly used to fuel a gas turbine that is equipped with a Heat Recovery Steam Generator (HRSG). Then the generated heat drives a steam turbine. Whereas a combination of bio-SNG and CCPP would give a maximum efficiency of 45%, it was assumed in this study that in 2050, the efficiency of BIGCC would be in the range of 40–50%.

2.3. Elaboration of scenarios of technology progress

Eight scenarios of technological progress were elaborated and evaluated. They were based on the following variables: the yield of conversion of the agricultural residues to bioethanol, the conversion efficiency of biomass to SNG and BIGCC, and the fuel economy for Road Passenger Transportation (RPT) using E85, SNG and electricity generated by BIGCC. For each variable two future states (2050) of Technological progress were envisioned, except for the fuel economy of electric vehicles that is already assumed high. A “low” value describes a state where the technological progress is not significant compared to the present trend. The “high” value is assigned to a state in 2050 beyond the state of the art. Fig. 1 shows the various scenarios. In the reference scenario all the variables were assigned a “low” value. Technical efficiency advantage for e-mobility over the two other biomass pathways was anticipated due to the difference in fuel economy. In the scenario “High Ethanol Technology Progress HETP”, the value “High” was assigned to the yield of biomass residues-to-ethanol and all the other variables were credited with “Low” progress. There are two groups of scenrios according to the state of fuel economy. Scenarios 1 to 4 have a low value of fuel economy (high value of fuel specific consumption); The reference case of this group is scenario 1 with low values of conversion yields. The grouip 2 is composed of scenarios 5 to 8 with high value of fuel economy. Scenario 5 with high values of conversion yields is the reference case of the second group.

2.4. Allocation of the available agricultural residues to the fuels supply chains

In order to meet the energy demand for transport in a given scenario, the percentage of biomass for each type of car fuel was evaluated. In this study, an indicator of energy yield was considered, for the fuel generation part, to evaluate the viability of meeting energy demand for transport. It is based on the ratio between the calorific value of the fuel to the calorific value of the amount of biomass used. The energy content of the available biomass estimated by 2050 was calculated using their low heating values (LHV). The assumed LHVs for cellulose, hemicellulose and lignin are 17 MJ/kg, 16.63 MJ/kg and 21.13 MJ/kg, respectively (Murphey and Masters, 1978).

The first step of this stage consisted in calibrating the model used in the study for the evaluation of the relation between the fuel consumption for passenger road transportation and socio-technical variables. Based on the gasoline consumption in Nigeria, Cote d'Ivoire, Ghana, Senegal, and West Africa forecasted by the International Agency of Energy for 2040b (IEA, 2014, 2019), the following assumptions were made to obtain the same amount of fuel consumption in 2040. It was

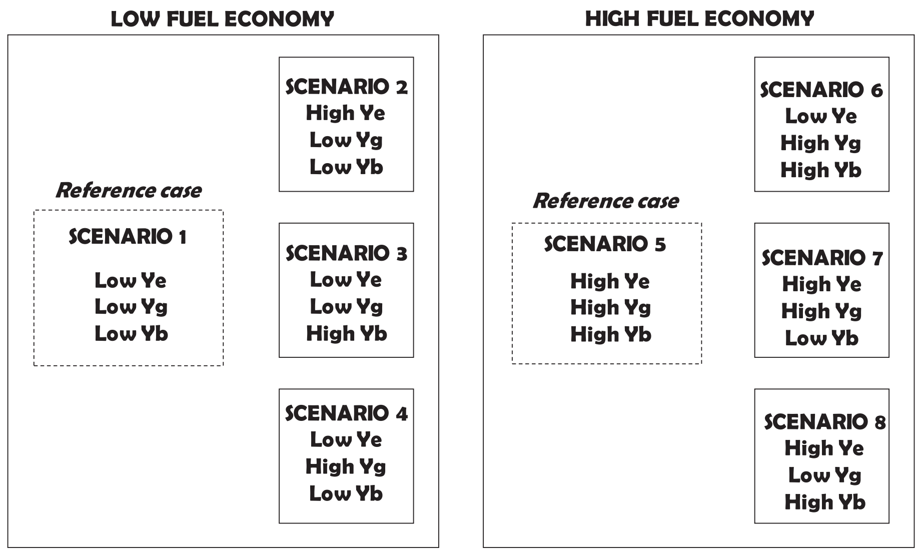

Fig. 1. Definition of scenarios.

assumed that 25% population in each country will use passenger vehicles for meeting an average mobility of 12,000 passenger.km/year per person. An average of 6 persons per vehicle was considered as well assuming large public and private vehicles. The assumed fuel specific consumptions for 100 km were 15 kWh (Tesla, 2019) for electric cars, 6 L gasoline equivalent for SNG (Pawlak, 2003) and 15L E85 for flexible vehicles. The two latter values were decreased for scenarios 5–8.

Then under different constraints optimizations were carried out to generate various allocations of the available biomass between the three pathways and the potential contributions of the available biomass to meet the energy demand for passenger road transportation were estimated.

A set of three objective functions was defined with the aim to maximize the ratio between the available agricultural and the use as feedstock for transportation biofuels, to minimize the cost including new infrastructures for fuel logistics, and to maximize the diversity of the fuel mix.

For the first objective, the following function ($Perfbiom_{k,j}$) was defined to characterize the performance of each portfolio k for the strategic share Rstj of road passenger mobility fueled with biofuels.

$$Ebiom_{k,j} = \frac{\frac{Rstj}{100} * Pop * PUV * \frac{mobility}{filling}}{\sum_{i=1}^{n} \frac{R_{k,i,j}}{100} * \frac{Y_i}{C_i} * T_i}$$
$$Perfbiom_{k,j} = \frac{TEbiom}{Ebiom_{k,j}} \tag{1}$$

where I is the type of fuel; natural gas (g), electricity (e), or bioethanol (b), then $n = 3$;j is strategy that aims to meet a certain percentage of mobility demand with biofuels; k is a portfolio that denotes a given combination of share of each fuel; Pop is the population of the country under consideration (person); PUV is the percentage of people using vehicles (%); mobility is the need for mobility (passenger.km/(year.-person); filling is the number of passengers per vehicle (passenger /vehicle); $R_{i,j}$ is the amount of biomass for conversion into i, according to the portfolio j(%); Y_i is the energy conversion yield from biomass to fuel; C_i: is the specific energy consumption per vehicle (GJ/(vehicle.km)); Ti is the energy efficiency of transport and distribution of the fuel I; Rstj is the Strategic goal for the share of mobility demand covered by agricultural residues (%); Ebiomk,j is the agricultural residues required to meet the strategic goal Rstj, for the portfolio k (GJ/year); TEbiom is the total available agricultural residues (GJ/year); Perfbiomk,j is the performance of the portfolio k for the strategic goal Rstj with regard to the requirement of agricultural residues.

A simple estimation of the biomass resource needed to fuel one vehicle.kilometer would show that electric mobility gives the lowest value, followed by SNG and then by bioethanol if the cost of nationalwide infrastructure and fuel is not accounted for.

The second objective function A was defined through $Perfinfr_{k,j}$) that expressed the relative need in infrastructure and other costs for each option and portfolio k, the portfolio with 100% bioethanol being chosen as reference for this function.

$$Perfinfr_{k,j} = \frac{\log(A) * \sum_i c_{i,j} * \frac{R_{k,i,j}}{100} * Ebiom_{k,j} * Y_i * T_i}{c_{b,j} * Ebiom_{k=100\%bioethanol,j} * Y_b * T_b} \tag{2}$$

where $c_{i,j}$ is the unit penalty for nation-wide infrastructure and other costs (for instance $c_{e,j} = 10$, $c_{s,j} = 2$, and $c_{b,j} = 1$), $Ebiom_{k,j}$ is estimated in Eq. (1); A is the area of the country under study.

With the formula (2), it was assumed that the ratio of cost of infrastructures and other costs with the reference case (bioethanol pathway) was propoprtional to the logarithm of the country area.

Given the higher efficiency of electric vehicles supply chain, the best option based on objective function (1) would be to allocate the whole amount of biomass to electric mobility supply chain. However, the development of this technology in 30 years ahead and the requirement of charging infrastructures challenge the possibility of drastically change to electric mobility especially in developing countries like those in West Africa. SNG would be also made expensive by the need of distribution and gas filling infrastructures. However fossil-based natural gas is available in the region and it was envisaged that it could justify the progressive building of the same infrastructure needed for SNG. Even though further techno-economic and environmental analyses should be performed, the qualitative assessment presented in this study was a preliminary consideration of this aspect. However, the result would be sensitive to the relative penalty chosen in the Eq. (2).

The third objective function maximizes the diversity of the portfolio.

$$Perfdiversity_{k,j} = S * (1 - (1.5 * \sum_{i=1}^{3} \left(\frac{R_{k,i,j}}{100}\right)^2 - 0.5)) \tag{3}$$

where S is a scale factor ($S \geq 1$)); the value of the function is in the interval [0, S]; it is zero in a case where only one technology (BIGCC, SNG, or Bioethanol) receives the whole biomass resource; it is S if the biomass resource is equally distributed between the three technologies. The indicator was built from the well known Herfindahl-Hirschman Indiex (HHI).

The method developed to solve this multiobjective optimization is as follows:

1) Each fuction was transformed using an affine scaling and each portfolio k was scored between zero associated to the lowest performance and ten that was the score of the highest performance. The lowest and highest performances were estimated over the values for the thirteen countries. So each portfolio was assigned three scores.
2) The aggregate score was the weighted average of the three scores. For each strategic goal Rstj, the optimal portfolio is the one with the highest aggregate score.

The weights characterize the preferences of the decision makers between the objectives that may be contradictory. Since it is difficult for the decisionmakers to be aware of the implications of the weightings, in this study, they were determined by using the reference scenario of the group 1 (scenario 1) and finding the weighting system that maximizes Shannon Entropy defined as follows.

$$E = -(Log(3))^{-1} * \sum_{p=1}^{3} w_p * Log(w_p) \quad (4)$$

where w_p is the relative wieighted score of the objective p, that is the ratio of the weighted score for the performance p (p = 1,2,3) and the sum of the weighted scores.

The weights obtained for scenario 1 for each country were used to evaluate the optimal portfolio for the scenarios 2–8.

3. Results and discussion

3.1. Availability of agricultural residues

The availability of agricultural residues for use to partly satisfy by 2050 the fuels demand for transportation biofuels was estimated based on projections of FAO. The crops available in at least eight of the WA countries were selected, as they would produce enough potential biomass to feed the fuel generation plants. The selected crops are bananas, cassava, maize, oil palm fruit, paddy rice, raw cotton, sorghum, soybeans and sugar cane.

Using predicted data for harvesting area and crop yield, and the crop-to-residues ratio, the amount of residues per country, crop and type of residue were calculated for 2050 for the FAO TS case. Table 1 shows the total amount of all types of residues for each country and crop. The total residues estimated by 2050 in the considered WA area are 314 million tons.

In order to meet a significant share of the energy demand for transportation in the maximum number of countries, 50% agricultural residues were assumed available for conversion into biofuels the other half being left in the field for soil regenaration. Based on the mass composition (Magalhães et al., 2019) and the LHV of the components of the feedstocks, Table 2 shows the energy content of the biomass available for conversion into transportation biofuels estimated for each country. Data required for such estimation is available in Supplementary Data (Tables S1 and S2). After calculating the ratio to the population and the ratio between the maximum final energy the available biomass can meet and the final energy required by the mobility demand assuming a full electric mobility, it was found that Burkina Faso had the highest ratios among the thirteen countries. Since the climate of Burkina Faso is Sahelian with low agricultural productivity, the data used for this country must be considered with caution. The cases of Côte d'Ivoire (Ivory Coast) and Mali are also abnormal. The data were adjusted by considering the average value of the other countries of the same climatic zone. For Burkina Faso and Mali, the average value per capita of Senegal and Niger was adopted. For Côte d'Ivoire, the mean of amounts of residues per capita of Ghana, Benin, and Togo was used. Based on the adjusted data, the maximum ratios were found for Benin followed by Ghana, Ivory Coast, Togo, Nigeria, and Guinea. The required residues for full fueling by electric mobility were found less than the available feedstock in Burkina Faso, Gambia, Liberia, Mali, Niger, Senegal and Sierra Leone.

3.2. Optimal portfolios

The car specific energy consumptions were assumed as: 0.54, 1.62 and 2.72 MJ/km for C_e, C_g and C_b respectively. All possible portfolios (combinations among R_g, R_e and R_b) were comparatively assessed for each country. Fig. 2 shows the three performances calculated for all possible portfolios in the case of Benin. As expected, higher values for Perfbiom and Perfinfr (in yellow) are appearing in those portfolios containing higher shares of Re due to the low specific energy consumption associated to electric cars. As mentioned before, Perfdiverity increases with the equality of shares in the portfolio. Then the results would be sensitive to the weightings. The optimal portfolios associated to the optimal weights of the reference scenario were found for each country. The results with the FAO data for Côte d'Ivoire, Burkina and Mali can be found in the Supplementary Data (Tables S3).

Using the adjusted data, the optimal weighting found for each country and the associated optimal portfolio are presented in Tables 3 and 4 for the eight scenarios. For the scenario 1 (group 1 reference scenario), the value of the maximum entropy was found higher than 85% except for Mali where it was 79%. The maximum entropy values (≥99%) were found for the cases of Togo, Benin, Sierra Leone and Liberia. The structures of the optimal portfolios were characterized by a higher share of the required biomass allocated to the electricity pathway (≥40%) far above the SNG and bioethanol ones. The share of

Table 1
Total amount of residues for each crop and country in 2050.

Country	Residues in 2050 (tons/year)								
	Banana	Cassava	Maize	Oil palm fruit	Rice	Cotton	Sorghum	Soybeans	Sugarcane
Benin	9′234	819′256	7′685′674	3′077′327	1′065′856	1′472′230	989′713	59′640	30′021
Burkina Faso	–	973	8′918′250	–	1′674′142	2′827′218	14′391′713	93′638	374′608
Côte d'Ivoire	129′339	501′689	3′715′272	10′684′203	902′837	1′387′922	366′398	3′412	1′620′026
Gambia	–	2′419	166′548	242′021	35′543	2′949	207′549	–	–
Ghana	33′892	3′119′461	11′614′328	11′937′521	348′962	74′947	2′208′393	–	121′572
Guinea	93′332	249′527	3′771′572	4′045′498	119′5235	228′402	284′269	–	115′888
Liberia	56′800	117′975	–	1′102′467	167′959	–	–	11′262	119′738
Mali	104′809	10′079	9′656′257	–	1′874′119	2′628′206	9′565′583	13′228	295′313
Niger	–	30′143	60′527	–	11′585	48′853	9′418′996	–	106′378
Nigeria	–	9′918′856	65′349′629	30′153′631	3′061′685	1′631′367	45′238′144	2′448′622	1′544′025
Senegal	15′077	35′143	1′304′100	971′578	452′933	186′605	880′192	–	879′523
Sierra Leone	–	810′805	272′168	1′347′265	747′960	–	266′739	–	37′117
Togo	10′652	212′098	4′425′680	584′178	72′804	493′664	2′186′686	14′621	–
TOTAL	453′135	15′828′423	116′940′006	64′145′689	11′611′622	10′982′362	86′004′374	2′644′424	5′244′209

Table 2
Amount of cellulose, hemicellulose and lignin available in the selected WA area by 2050 considering that 50%residues were left on the field. Energy content in the selected biomass. Values in brackets represent adjusted data.

Country	Cellulose (tons/year)	Hemicellulose (tons/year)	Lignin (tons/year)	Total Energy content (GJ/year)	$E_{bioRatio}$ (GJ/hab.)	$E_{finalRatio}$
Benin	2′435′313	1′463′603	1′341′186	93′989′852	3.87	1.86
Burkina Faso	4′602′408	2′882′498	2′164′508	172′284′720 (38′070′923) [2]	3.97 (0.88)[2]	1.90 (0.42)[2]
Côte d'Ivoire	3′259′012	1′997′339	1′904′670	126′688′100 (181′533′693) [1]	2.47 (3.54)[1]	1.19 (1.70)[1]
Gambia	106′951	67′504	54′160	4′000′678	0.82	0.39
Ghana	4′899′719	3′009′908	2′692′610	190′514′168	3.66	1.76
Guinea	1′484′255	911′400	828′349	60′235′161	2.32	1.11
Liberia	260′013	160′925	153′594	1′0195′012	1.09	0.52
Mali	3′593′196	2′223′739	1′742′045	135′486′934 (38′205′352)[2]	3.11 (0.88)[2]	1.49 (0.42)[2]
Niger	1′671′345	1′104′608	660′506	60′474′290	0.92	0.44
Nigeria	25′635′444	1′603′5878	12′817′400	981′005′286	2.44	1.17
Senegal	731′502	469′398	384′690	27′583′543	0.83	0.40
Sierra Leone	480′114	290′291	274′929	19′140′877	1.48	0.71
Togo	1′262′812	781′084	629′165	47′632′777	3.09	1.48

[1] Values obtained from average $E_{bioRatio}$ of Benin, Ghana and Togo.
[2] Values obtained from average $E_{bioRatio}$ of Senegal and Niger.

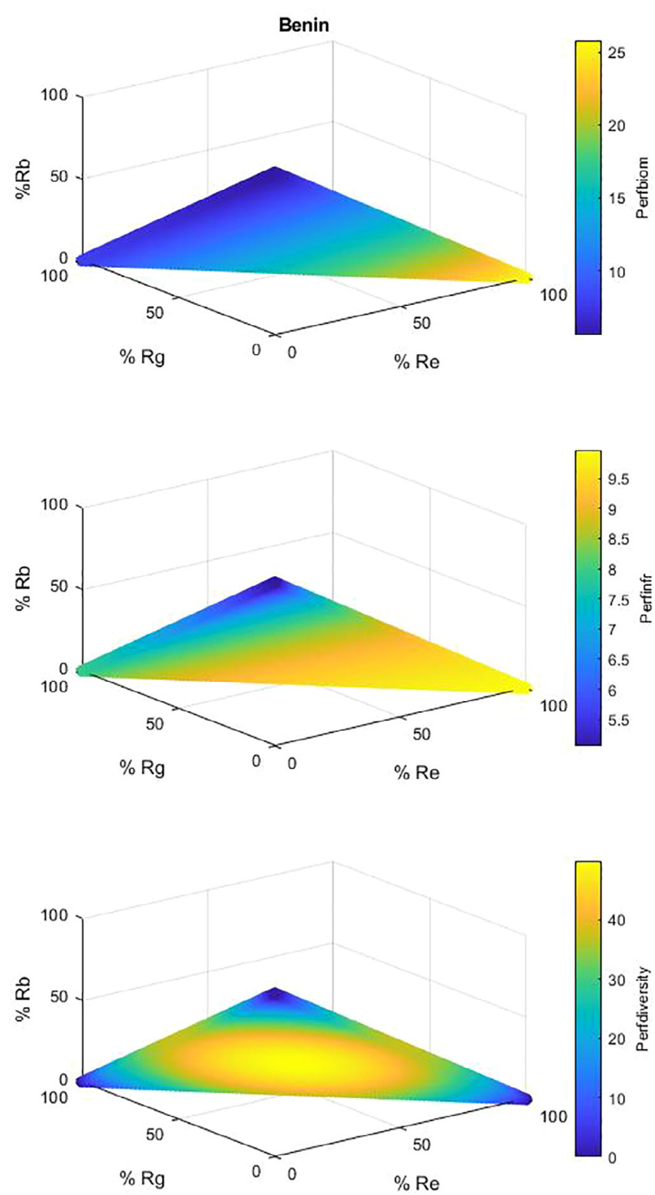

Fig. 2. Illustration of the three performances studied in this work for the reference strategy in Benin.

these latter two was more balanced each other. The share of biomass to electricity for Gambia is the highest (54%). The relative weighted grade is useful to better understand the results. For instance, in the case of Gambia, the relative weighted score attributed to the completion of the first, second and third objectives are 32%, 26% and 42% respectively showing that the results are more led by the completion of the objective of diversity while the influence of the completion of the other objectives is not marginal. This balanced relative weighted score is also illustrated by the high Shanon Entropy (0.98). It may be concluded that the high share of electricity pathway in the case of Gambia does not stemm from any biases but is the result of the advantage of this country for being small in area, which also explains the lowest relative score attributed in the optimum portfolio to the second objective. Liberia shows the second highest share of feedstock allocated to the electric mobility with 51%. However, the direct comparison of the portfolios is not relevant since they apply to different required amounts of feedstock. The strategy to fuel 20% of the road passenger mobility by agricultural residues is feasible in the scenario 1 since the maximum ratio between the required feedstock and the available residues is 30% (case of Senegal). Lower values of this ratio, less than 10%, are given by the cases of Benin, Ghana, Côte d'ivoire, and Togo.

The only difference between the scenarios 2 and 1 is that the energy efficiency of BIGCC is considered as high (50%) instead of low (40%) in scenario 1. In a mono-objective optimization, the improvement of the energy efficiency of one technology would make it more attractive and one could anticipate that the share of electric mobility pathway would increase from scenario 1 to 2. That is the case for most of the countries except Côte d'Ivoire where the share of electric mobility pathway drops to zero. This result can be explained by the higher relative weighted score of objective 2, 57% in the case of this country compared for instance to 11%, 23%, 42% in the cases of Nigeria,Ghana, and Mali respectively. When this value is high, an improvement of the energy efficiency of BIGCC penalizes the compliance of the objective 2, which gives comparative advantages to portfolios whithout electricity. For all the countries but Ivory Coast, the percentage of required feedstock decreases as a result of increase of the share of electricity.

Scenario 2 compares to scenario 1 except the increase of the energy yield of bioethanol. As a result, for all the countries but Ivoiy Coast, the share of E85 in the optimal portfolios increases. For Ivory Coast the optimal portfolio does not change from scenario 2 to 3 but the required residues decreases as a consequence of the improvement of the energy yield of the conversion to ethanol. This value increases in the cases of other countries since the increase of the share of bioethanol is detrimental to the percentage of electricity pathway, the most efficient one. In the case of Nigeria, the share of electricity pathway decreases from 44% in scenario1 to 0% in scenario 3 whereas bioethanol pathway

Table 3
Allocation of biomass to produce E, SNG and Bioethanol for scenarios of Low Fuel Economy.

Country	w1	w2	w3	Scenario 1				Scenario 2				Scenario 3				Scenario 4			
				Re	Rg	Rb	$Biom_{Req./Total}$ (%)	Re	Rg	Rb	$Biom_{Req./Total}$ (%)	Re	Rg	Rb	$Biom_{Req./Total}$ (%)	Re	Rg	Rb	$Biom_{Req./Total}$ (%)
Benin	5	7	3	47	25	28	6.36	52	23	25	4.99	45	24	31	6.44	43	33	24	6.10
Burkina Faso	7	2	1	47	25	28	28.08	52	23	25	22.04	44	25	31	28.75	43	33	24	26.94
Cote Ivoire	3	4	2	40	28	32	7.60	0	38	62	16.65	0	38	62	15.52	37	34	29	7.17
Gambia	7	1	1	54	24	22	27.60	57	22	21	22.13	54	23	23	27.36	51	30	19	26.52
Ghana	3	4	2	42	27	31	7.16	47	25	28	5.63	40	26	34	7.24	39	34	27	6.75
Guinea	7	6	3	42	27	31	11.30	47	25	28	8.90	39	27	34	11.57	38	34	28	10.81
Liberia	6	2	1	51	24	25	21.48	55	22	23	17.04	49	23	28	21.76	46	32	22	20.94
Mali	6	1	1	49	26	25	27.34	52	24	24	22.01	48	25	27	27.37	47	31	22	25.87
Niger	7	2	1	46	25	29	27.05	52	23	25	20.95	44	24	32	27.37	42	33	25	25.94
Nigeria	5	4	2	44	26	30	10.46	50	24	26	8.11	0	37	63	22.54	40	34	26	9.99
Senegal	7	2	1	45	26	29	30.35	50	24	26	23.84	43	25	32	30.71	41	33	26	29.13
Sierra Leone	4	2	1	48	25	27	16.44	52	23	25	13.06	45	25	30	16.83	44	32	24	15.84
Togo	6	7	3	47	25	28	7.97	52	23	25	6.25	44	25	31	8.16	42	33	25	7.74

doubles from 30% to 63%, doubling also the percentage of required feedstock. For scenario 4 as it can be expted, the share of SNG increases detrimental to electricity and E85 in comparison with scenario1, the percentage of required feedstock slightly decreases as a result of the high increase in the efficiency of SNG. The sensitivities of the results of the scenario 1 to the ceteris paribus changes represented by scenarios 2, 3, and 4 make sense for all countries.

In the scenario 5, all the energy yields increase, and the fuel economy of SNG and E85 increase. In relative terms the technological progress is therefore more favourable to SNG and to Bioethanol. Compared to scenario 1, the share of electricity pathway decreases for all the countries and the share of SNG significantly increases. The share of bioethanol varies between a stability- such as in the cases of Burkina Faso, Senegal, Sierra Leone, Togo – and high increases such as in the cases of Benin, Ivory Coast, Niger and Nigeria. Scenario 6 shows a lower value in the energy efficiency of electricity generation, which should contribute to a decrease of the share of electricity. That is the trend for most of the countries, except for Benin, Ghana, Guinea, where the share of electricity increases, which can be caused by the effect of increase in diversity rather than the one of dresease in energy efficiency of electricity generation. In scenario 7 the energy yield of bioethanol is lower than in scenario 5, resulting in slighty lower share of bioethanol for all countries. Finally, the scenario 8 characterized by a low energy efficiency of SNG generation, shows for all countries except for the cases of Burkina Faso and Senegal, a reduction of the share of SNG. In comparison with scenario 5. The two exceptions can be explained by a significant discrepancy between the weights that are particularly suboptimum for these countries in scenario 8. The Shannon entropy is 69% and 66% for Burkina Faso and Senegal respectively, compared to 85% for instance in the case of Ghana.

3.3. Sensitivity analysis

The assessment of scenarios 2 to 8 can be considered as part of sensitivity analyses. But several other investigations can be discussed. For example, how the strategic percentage of the mobility fueled by biofuels can impact the results? Since Rstj is a multiplying factor in the formula (1), there is no impact on the optimal weights and the optimal portfolios; however, the required amount of feedstock is proportional to the value of Rstj (Fig. 3). Another issue is the sensitivity to the penalty for electricity quantity. If the penalty of electricity significantly increases, the share of electric mobility will be reduced. For testing this statement, a new optimization of scenario 1 was carried out by increasing ce from 10 to 15. Table 5 shows that the optimal portfolios were relatively stable in all the countries but in the case of Ghana where the share of electricity drops from 54% to 0%.

3.4. Policy implications

In Africa, energy policy should aim at increasing the supply of affordable energy, assuring energy supply (Karekezi et al., 2009) and improving energy sector governance while decreasing energy restrictions to economic development (Aboua and Touré, 2018). However, the confluence of energy problems with other global issues as climate change is less addressed in energy laws in African countries. Karekezi and Kimani (2002) highlights the need of policy making for the energy sector role in climate change mitigation while prioritizing to meet at short to long-term energy demand.

Table 4
Allocation of biomass to produce E, SNG and Bioethanol for scenarios with High Fuel Economy.

Country	w1	w2	w3	Scenario 5				Scenario 6				Scenario 7				Scenario 8			
				Re	Rg	Rb	$Biom_{Req./Total}$ (%)	Re	Rg	Rb	$Biom_{Req./Total}$ (%)	Re	Rg	Rb	$Biom_{Req./Total}$ (%)	Re	Rg	Rb	$Biom_{Req./Total}$ (%)
Benin	5	7	3	0	45	55	9.66	26	41	33	6.73	0	46	54	10.07	0	40	60	12.17
Burkina Faso	7	2	1	36	36	28	23.61	29	40	31	28.76	38	37	25	23.19	0	41	59	53.63
Cote Ivoire	3	4	2	0	45	55	10.56	0	46	54	10.50	0	46	54	11.01	0	41	59	13.28
Gambia	7	1	1	50	30	20	21.68	47	33	20	25.94	51	30	19	21.60	54	24	22	22.17
Ghana	3	4	2	0	45	55	10.21	23	41	36	7.38	0	46	54	10.64	0	41	59	12.84
Guinea	7	6	3	0	45	55	16.13	23	41	36	11.66	0	46	54	16.80	0	41	59	20.27
Liberia	6	2	1	42	34	24	17.67	35	38	27	21.72	43	35	22	17.57	47	26	27	18.08
Mali	6	1	1	44	32	24	21.61	40	35	25	25.90	45	33	22	21.49	48	26	26	22.24
Niger	7	2	1	0	45	55	40.57	0	46	54	40.32	0	46	54	42.27	0	40	60	51.12
Nigeria	5	4	2	0	44	56	15.40	0	46	54	15.21	0	46	54	15.94	0	40	60	19.28
Senegal	7	2	1	35	36	29	25.23	28	40	32	30.70	37	37	26	24.79	0	41	59	56.56
Sierra Leone	4	2	1	38	35	27	13.68	33	38	29	16.40	40	36	24	13.44	43	27	30	14.05
Togo	6	7	3	35	36	29	6.79	28	40	32	8.26	38	37	25	6.58	0	41	59	15.21

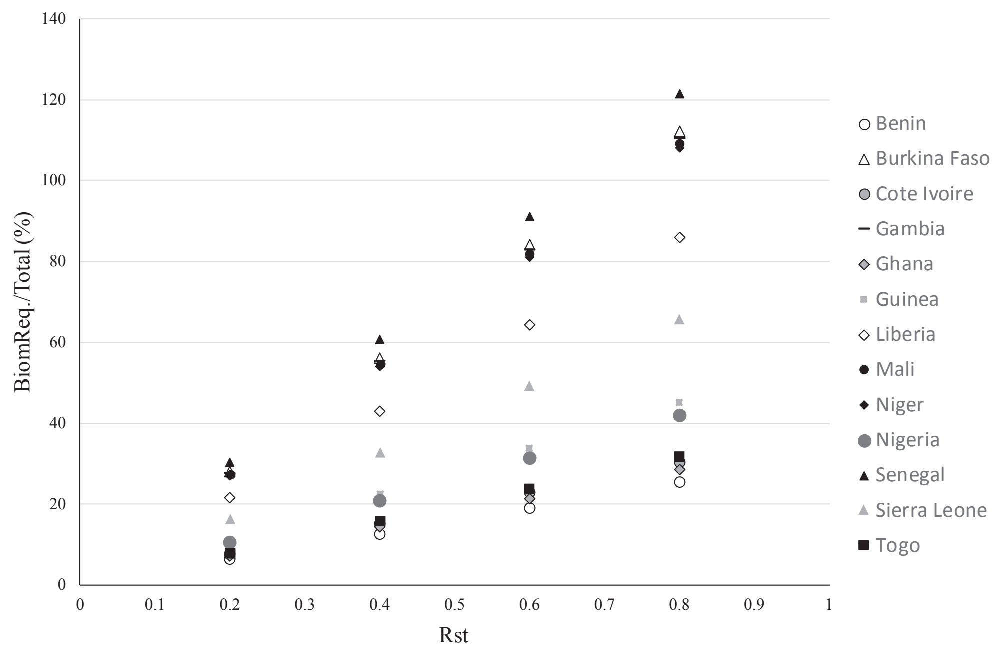

Fig. 3. Sensitivity analysis for the required biomass in each analyzed country by varying Rst.

Table 5
Allocation of biomass to produce E, SNG and Bioethanol in the reference strategy with ce = 15.

Country	w1	w2	w3	Scenario 1			
				Re	Rg	Rb	$Biom_{Req./Total}$ (%)
Benin	7	7	4	47	29	24	6.32
Burkina Faso	6	1	1	47	28	25	27.95
Cote Ivoire	7	6	4	45	30	25	7.08
Gambia	7	1	1	52	26	22	28.19
Ghana	3	6	3	0	44	56	15.75
Guinea	5	3	2	42	31	27	11.23
Liberia	7	2	1	50	28	22	21.62
Mali	6	1	1	45	29	26	28.64
Niger	6	1	1	46	29	25	26.88
Nigeria	7	4	3	42	31	27	10.65
Senegal	7	1	1	50	27	23	28.43
Sierra Leone	5	2	1	49	28	23	16.16
Togo	7	6	3	49	28	23	7.73

The Renewable Energy Policy adopted by ECOWAS, aims at ensuring increased use of renewable energy sources such as solar, wind, small-scale hydro and bioenergy for grid electricity supply and for the provision of access to energy services in rural areas (ECOWAS, 2015). This policy also intends to help the ECOWAS member States to progress in regulatory frameworks for the penetration of renewable energy technologies and services in the region.

Regarding the biomass-energy needs, appropriate policy should be designed for biofuels at long term. After addressing the difficulties of biomass availability that West Africa will have to face to meet the biomass demand for cooking and fodder, short - medium term strategies must be tackled regarding transportation biofuels. These strategies must take care of the overexploitation of the biomass resources. The strategy that was studied in this work would only meet about 5% of the final energy for roal passenger mobility. This percentage can quadruple in few countries especially if electric mobility is developed.

For the cooking end use, biomass briquettes are potential candidates providing that appropriate regulations are set up in order to remove barriers to competition with fuelwood and charcoal. If these regulatory conditions are fulfilled, part of the crop residues would be used in this sector limiting the available resources for transportation biofuels. Besides the need of complementary economic and environmental feasibility, it is worth noting that the scenarios developed in this study are quite futuristic considering the present state of West Africa and the role that oil economy is playing and will play in the future. The region is rich in petroleum resources with Nigeria as the first oil producer of Sub-Saharan Africa and a new discovery of oil fields in Niger. Such geopolitical issue makes dubious the scenarios developed in this paper if they are understood as predictions. The paper only shows that if there is a political willingness to orient the energy system towards a bio-economy, agricultural residues are potentially available in West Africa according to the statistics of FAO. It also shows that biomass conversion to biofuels will be also mature by 2050. However, if the world enters into a sustainable strategy to cope with the objective of climate neutral from 2050, the price of oil will not be high due to the projected reduced world oil demand. Then it is plausible that one of the regions that will suffer the most from climate change, remains dependent on oil since it will be a domestic energy resource even depreciated on the world market.

4. Conclusions

Biomass is a local and potentially renewable resource that should be managed in a sustainable way instead of relying in the medium term on imported fossil fuels such as LPG and gasoline.

This paper analyzes the potential of agricultural residues to satisfy energy demand for biofuels under long-term climate change and variability in West Africa and a perspective of an energy policy towards bio-economy. The multi-feedstock plants producing bioethanol, SNG and electricity are capable to generate the energy required for transportation biofuels of thirteen countries in West Africa using residues from nine selected crops within the considered scenario.

CRediT authorship contribution statement

Edgard Gnansounou: Conceptualization, Methodology, Software, Formal analysis, Writing - original draft, Writing - review & editing, Validation. **Elia Ruiz Pachón:** Software, Data curation, Writing - original draft, Visualization, Writing - review & editing. **Brice Sinsin:** Formal analysis. **Oscar Teka:** Formal analysis. **Euloge Togbé:** Formal analysis. **Ali Mahamane:** Formal analysis.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biortech.2020.123080.

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