Optimal sites for agricultural and forest residues energy conversion plant using geographic information system

Ukoba, M. O, Diemuodeke, Ogheneruona, Briggs, Tobinson Alasin, Imran, Muhammad, Ojapah, M. M, Owebor, Kesiena, Nwachukwu, C, Aminu, M. D, Okedu, Kenneth E, Kalam, Akhtar and Colak, Ilhami (2023) Optimal sites for agricultural and forest residues energy conversion plant using geographic information system. Heliyon, 9 (9). ISSN 2405-8440

Heliyon 9 (2023) e19660

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

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ARTICLE INFO

Keywords:
Agrowaste
Bioenergy
Forest waste
GIS
Net-zero
Optimal sites

ABSTRACT

The Federal Government of Nigeria (FGN) has committed to net-zero emission development pathways to respond to the Paris Agreement adopted in 2015. However, the country is in dire need of energy to support its developmental ambitions. Therefore, it is necessary to consider green energy technologies to support both socioeconomic development and to meet the FGN's emission reduction target. In view of this, the current work presents the optimal sites for bioenergy plants in a state in Nigeria using Geographic Information System (GIS). Key findings suggest that 62.03 PJ/yr and 4.12 PJ/yr of energy could be derived from crop residues and forest residues, respectively, to support the state's bioenergy development. The crop residues considered include plantain (stem), oil palm (shell and fibre), maize (stalks) and cassava (peel and stalks). Six criteria were used in selecting the optimal sites, and include biomass residue distribution, settlement, road accessibility, nearness to waterline, slope and aspect. These criteria were incorporated into the ArcGIS platform through the weighted overlay tool. Strategically, the analysis presents seven sites for biomass plants to sustainably meet part of the energy needs. The efforts of the current work which supports not less than three SDGs–SDG 7 (Clean and Affordable Energy), SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), will assist policymakers in Nigeria to make appropriate policies within the climate change space.

1. Introduction

Energy sustainability is a fundamental societal challenge, especially in developing nations, including Nigeria [1,2]. A country's development largely depends on its energy availability. Carbon dioxide and other toxic gases are constantly emitted from burning fossil fuels to meet the increasing energy demand. The lack of fossil fuel resources to meet the continuous rise in energy demand, environmental pollution, climate change, and others have led to the need to source for other forms of energy generation [3,4]. Energy

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https://doi.org/10.1016/j.heliyon.2023.e19660
Received 28 April 2023; Received in revised form 29 August 2023; Accepted 29 August 2023
Available online 9 September 2023
2405-8440/

resources can generally be categorized into; fossil, nuclear and renewable energy - including biomass, solar, wind, geothermal, hydrogen, hydro and ocean energy [1]. The UN Sustainable Development Goals (SDGs) adopted by the UN member states in 2015, Paris Agreement adopted at the UN climate change conference by 196 parties in 2015, and other climate advocating agencies have stressed the need for nations to embrace and support clean energy generation and enact policies to promote its penetration [3,5]. Much effort is currently put in towards replacing fossil fuels with renewable energy sources and promoting the use of modern, efficient energy conversion technologies that promote clean energy generation [6,7]. Since biomass energy supports the reduction of CO_2 gas emission [1], carbon neutrality [8], and, in some cases, negative carbon economy [2], it is, therefore, necessary to utilize biomass for clean energy generation [9]. Annually, Nigeria generates about 15.58 million tonnes of organic waste [10], of which only 20–30% are collected using the right means [11]. The indiscriminate disposal of these biomass wastes is an issue with consequences of environmental mismanagement, health hazard and climate change [12]. However, about 87.5% of these wastes come from crops and forest products, generally referred to as residues [13]. The residues can be gathered and used as a fuel source for a biomass plant to address the problem of environmental mismanagement and sustainable energy generation [2,14].

Nigeria is made up of 36 states and six geopolitical zones distributed within six agroecological zones, namely Mangrove Swamp, Rainforest, Derived savanna, Guinea savanna, Sudan savanna and Sahel savanna zones. Edo state, which is mainly located in Rainforest agroecological zone, is one of Nigeria's states located in the South-South (SS) geopolitical zone, and it's endowed with significant amount of crop and forest resources. It ranks as the highest crop and forest producing state in the South-South (SS) zone [15,16]. The waste produced from this large resource in the state can be used to effectively drive thermal and electricity production by utilizing a Combined Heat and Power (CHP) plant. This system is economical and can produce clean and sustainable energy that can serve as an alternative system for energy generation [2,17], which is appropriate for the state. It is necessary to note that the first step to consider in the development of renewable energy sources for power generation is the critical investigation of the resource potential; next it is the determination of an appropriate site where the power system can be installed [1,18,19].

Several studies have been carried out to select appropriate sites for biomass energy conversion plant [20,21]. Voivontas et al. [22] utilized a GIS tool to map the distribution of biomass resources potentials. They considered the plant capacity and biomass distribution as the key parameters for selecting the biomass plant location and determining the number of biomass plant facility to be sited. Papadopoulos and Katsigiannis [23] used a GIS and a computer program to identify appropriate locations to site biomass energy conversion plant based on the available biomass resources and other parameters, namely accessibility, settlement and terrain. Herrera-Seara et al. [24] used a GIS tool coupled with an analytic hierarchy process (AHP) and consider the resource availability, road network and natural area in the decision-making process. Bojić et al.[25] and Kaundinya et al.[26] developed a mathematical model and a mining algorithm, respectively, for selecting appropriate biomass plant locations and matching the region's energy demand with the available biomass resources.

Recently, Melnikova [27] carried out a multi-criteria assessment based on GIS mapping of renewable energy (RE) potentials to examine the energy status, conditions and available yield of the RE resources, putting into cognizance the land-use and environmental restriction. They assessed the RE resources' theoretical, technical and economic energy potentials utilizing statistical data and Net Primary productivity (NPP), and then, employed a network analysis tool to identify appropriate locations for siting a biomass plant system in QGIS-platform. Davtalab and Alesheikh [1] presented a study on optimum site location of renewable energy conversion plant in Guilan Province, Iran; efforts also presented by Lopez-Rodriguez et al. [28] for Southwest Europe. There are several other studies on the assessment of the viability of biomass resources and potential locations for biomass plant facility, for example, see Refs. [29–39].

Therefore, it is pertinent to first x-ray the biomass residues in Edo state to ascertain the biomass energy potential. The Geographic Information Systems (GIS) software has been widely used for renewable energy potential assessment [40,41]. It can work hand in hand with remotely sensed data for spatial mapping of agricultural products and quantifications [28,42] for estimating the energy potential from biomass residues and performing spatial-temporal and statistical analysis to guide decision-making process [39,43]. The software works with a georeferenced database, handles bulk data, executes arithmetic analysis and produces maps of variables [28]. It is very useful in assessing biomass supply cost [44]. GIS technology is a sophisticated, advanced and still advancing technology that captures data, store it, analyzes and produce maps that show the different data features, giving detailed information for decision-making and planning [37–39]. Going forward, the present work utilizes a weighted overlay analysis method as an MCDM to support the process of identifying the optimal biomass plant locations by considering pertinent criteria like the spatial distribution of the biomass resource, settlement, road accessibility/transportation route distance, nearness to a water line, slope and aspect in determining the optimal location for siting the biomass plant(s) for bioenergy generation in Edo state.

Several studies, such as refs [15,45], have shown that biomass energy is in abundance in different parts of Nigeria. However, no work has considered the optimal siting of biomass power plant, considering that the country is in dire need of sustainable power to meet its socio-economic development. Thus, the novelty of the study is that it establishes the optimal sites for biomass power plants utilizing crop and forest residues in Edo state. This work will serve as a veritable reference in strengthening optimal site selection for biomass power plant in other parts of the country and developing nations to support sustainable energy development.

1.1. Study area

Edo State comprises 18 Local Government Areas. It has a total land area of 19,840 km^2, between 5° 5′N–7° 35′N and 5°E–6° 40′E latitudes and longitudes, respectively, and situated at the Southern inland of Nigeria, bounded by Kogi and Ondo States at the West, Delta and Kogi states at the East and shares a border with Delta state at the South [46]. A greater area of Edo land is low, but its northern part is characterized by hills as high as about 672 m above sea level. It is a tropical state, with a wet/rainy season (late March–October) and dry season (November–March) [46]. Fig. 1 shows the map of Edo state, the Local Government Area (LGA)

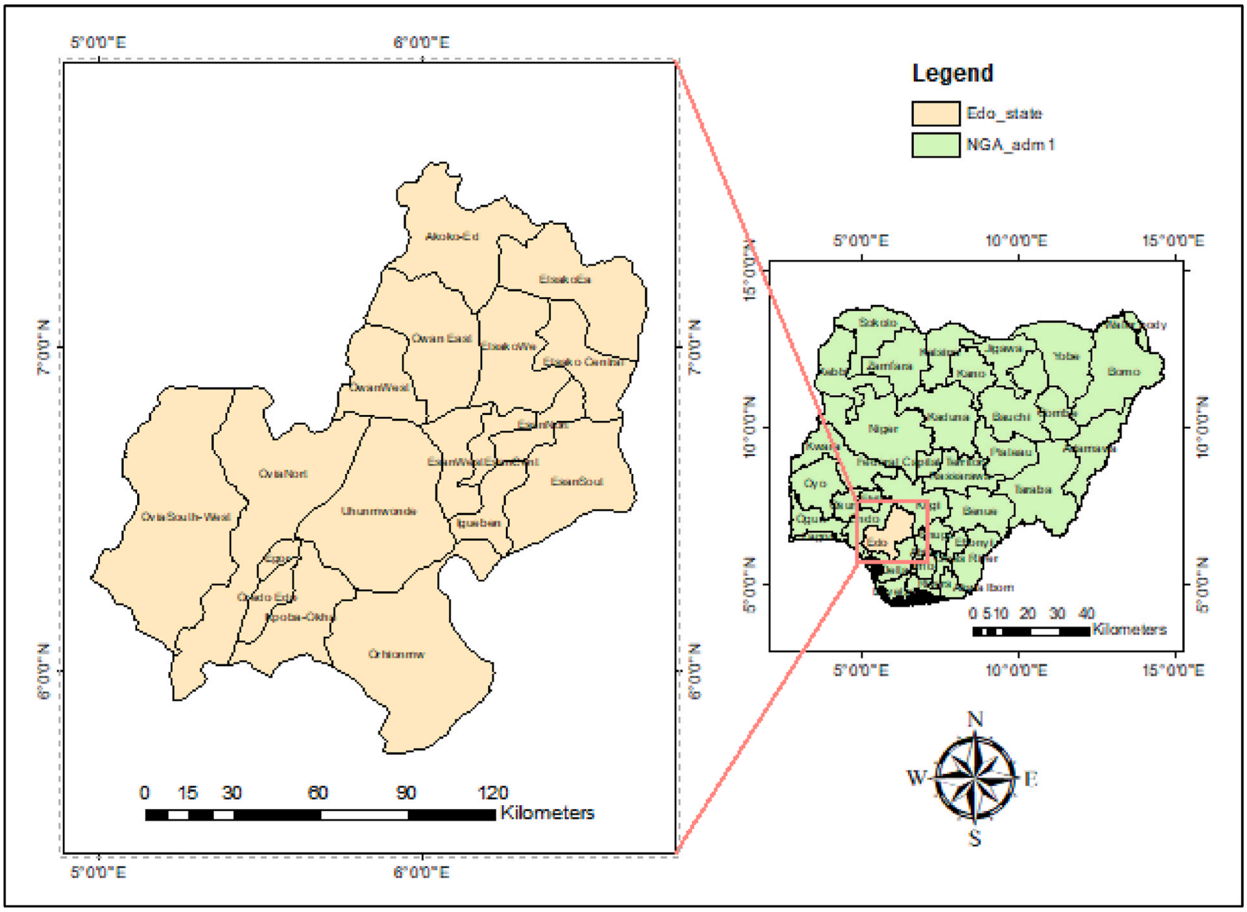

Fig. 1. Map of Edo State with its LGAs.

boundaries and its position in the Map of Nigeria.

Edo state is blessed with many natural resources, including forest [47]. There are over 22 forest reserves in Edo State, typically tropical rainforest, with economically-valuable trees like Afara, Okwen, Opepe, Mahogany, Alstonia, Albizia and others, of close canopy. The forest serve as a source of income for the community, government and even individuals via logging, lumbering and farming operations [48]. Meanwhile, there has been a significant rise in the deforestation rates of forests in Edo state [49]; for instance, thirty-one years of a study revealed the depletion level of Sokponba and Ehor forest reserve areas from 289.1363 to 111.2886 [km^2] in 1987 to 15.7815 and 32.4228 [km^2] in 2018, respectively [48]. Edo state is also blessed with diverse climatic conditions appropriate for growing agricultural produce like cassava, oil palm, plantain, maize, corn, potatoes and others. The vast forest reserve and agricultural produce make the state an agro-waste generation state in the forms of crops residues and forest residues, which could be harnessed for clean energy generation to meet the energy needs of the state [5,12].

2. Materials and methods

Biomass energy data was gathered from reputable literature and international databases including NASA, FAO and other online sources, using keywords that focus on biomass resources and GIS-based resource assessment. Google Scholar, Scopus, Web of Science and ResearchGate, are some of the international databases visited. Remotely Sensed data was also utilized to generate data on biomass resource distribution, including those of poorly assessable or secluded areas, monitor the resource and estimate the biomass production of each Local Government Area (LGA) across Edo state. Data obtained from the various sources were then integrated into the GIS platform, which was utilized to assist the assessment. The ArcGIS (version 10.7.1) was employed to conduct the GIS analysis of the data gathered.

Remotely sensed data including Land Use and Land Cover (LULC), Digital Elevation Models (DEM) and other GPS data, collected in pixel form from USGS- science explorer [16] and other sources were analyzed separately due to their unique structure. GPS data, generally saved in ''. GPX' format, was imported into the GIS domain and converted into shape-file formats. Secondary data with specified location, X, Y coordinates (longitude and latitude) data were also imported from excel into the GIS. All these data were collected and integrated into the ArcGIS domain to form a geodatabase system, which was then queried and analyzed. The research carried-out digitalization of spatial referencing of vital factors influencing biomass potential assessment. It considered factors such as biomass residue distribution, settlement, road accessibility, nearness to water sources, slope and aspect in determining the optimal location for siting a biomass plant using the weighted overlay tool (a Multicriteria Decision Analysis (MCDA) procedure) in the ArcGIS domain. The implication is that, areas were detailed biomass potential data are lacking or unavailable were accounted for [5], and its result reliable as long as the remotely sensed data is appropriately analyzed.

2.1. Crop/Forest residue

2.1.1. Theoretical assessment

This assessment specifies the available biomass residue resources that can be utilized for energy generation [50]. The cultivation area, annual biomass yield, obtainable residues and other parameters that affect the biomass production, including Residue-to-Product Ratio (RPR), Low Heating Value (LHV) are also considered [5,15,51]. The theoretical energy can be estimated with Equ. (1) [52];

$$E_{theoretical} = \sum_{m}^{n} R_{p,i} * LHV; \; i = \{crop, forest\} \tag{1}$$

where; $E_{theoretical}$ is theoretical energy; LHV is low heating value [kJ/kg]; R_p is residue potential [k-tonnes] obtained from Equ. (2);

$$R_{p,crop} = \sum_{m}^{n} P * RPR \tag{2}$$

where $R_{p,crop}$ is crop production [k-tonnes]; RPR is residue-to-product ratio [−]

For the forest residue, the mass of the various forest products having a volume (m^3) value can be obtained from Equ. (3).

$$m_{forest} = \rho \times V \tag{3}$$

where m_{forest}, ρ and V represent the mass, density and volume of the forest product, respectively.

The forest residue is therefore obtained from Equ. (4)

$$R_{p,forest} = m_{forest} \times RPR \tag{4}$$

where $R_{p,forest}$ is forest residue, and RPR is Residue-to-Product ratio (assumed as 0.72 [12]).

The LHV of wood fuel and wood charcoal are assumed to be 19.5 MJ/kg and 28.0 MJ/kg, respectively [14].

2.1.2. Technical assessment

This assessment is a function of the annual theoretical residue gathered. It shows the fraction of theoretical energy potential that can be used for energy generation. A factor termed 'availability factor (*AF*)' which ranges from 0 to 1 is introduced to handle the variation of residue potential from one location to another. The technical energy potential is estimated with Equ. (5) [15,51].

$$E_{technical} = \sum_{m}^{n} E_{theoretical} * AF \tag{5}$$

where E_{tech} is technical potential and AF is availability factor [−].

AF for oil palm, wood and rice residues are assumed as 0.8, 0.5–0.75, and 0.4, respectively [15,51,53] while, that of other crops are assumed to be 0.30 [5,15,54]. Also, $\propto$ for forest residues is assumed to be 0.6 [15].

2.1.3. Economic assessment

The economic assessment is a function of the technical energy potential, which shows the fraction of the technical potential that is economically profitable based on specific criteria [5,55]. The accessibility distance from the residue collection area to the plant site has a significant role in the transportation cost. It forms part of the total cost of energy generation [56,57]. Therefore, 30–100 km is assumed to be the optimal feasible distance range from the collection area to the plant site location. Also, not all the residues available are used for energy generation. The value 24–59% is assumed as the economic radius constant range since not all the obtainable resources can finally get to the biomass plant site and be utilized for useful energy generation [56,58,59]. The economic potential can be estimated from Equ. (6).

$$E_{economic} = \sum_{m}^{n} E_{tec} * \varepsilon_r \tag{6}$$

where E_{eco} is the economic potential and ε_r is the economic radius constant [%] (adopted as 27.66% [5,51]).

2.2. Remote sensing using Normalized Difference Vegetation Index

The Normalized Difference Vegetation Index (NDVI) is used to quantify vegetation by estimating the vegetation which is strongly reflected, near-infrared (NIR), and vegetation that is absorbed (RED). Its value ranges between −1 and +1. Negative values indicate a high possibility of water, while values close to +1 indicate a high possibility of dense green leaves, which are high temperature and tropical rainforest areas. Values from −0.28 to 0.015 indicate areas characterized by water, 0.015 to 0.14 indicate built-up areas, 0.14 to 0.18 mean barren lands, 0.18 to 0.27 indicate shrub and grasslands, 0.27 to 0.36 show areas with sparse vegetation and values equal to and greater than 0.36 imply areas with dense vegetation.

2.2.1. NDVI calculation

NDVI makes use of near-infrared (NIR) and RED channels to estimate the feature of a given area, and it is obtained from Equ. (7) as;

$$NDVI = \frac{NIR - RED}{NIR + RED} \tag{7}$$

2.3. Simulation and optimization software

Weighted overlay analysis method, an example of Multicriteria decision analysis (MCDA) is utilized for evaluating the best location for siting the biomass plant. The optimum site location is obtained by using GIS simulation software–weighted overlay analysis tool, for the analysis based on the stipulated criteria with assigned weighted values based on their level of importance.

2.4. Criteria for site selection of the biomass plant site

The selection of the optimal biomass plant location in Edo state was done using several criteria, including: *Land use land cover (LULC)*: it is the most pertinent criteria that shows the availability of the crop/forest residue feed which will serves as fuel for the running of the biomass plant; *settlement*: the target areas to supply the energy generated is also vital, siting the biomass plant close to the energy supply areas would help reduce energy loss during transmission and the cost of installing and maintaining energy infrastructures; the *distance from road*: accessibility of the site is vital for the supply of feed, transportation of biomass plant facilities and carrying-out the maintenance of the biomass plant by professionals when necessary; *availability of water*: this is needed for the cooling of the plant system and heat exchange, more so, the waterline can also serve as means of transportation of the biomass plant facilities, supply of feeds and other forms of site accessibility; the *slope*: though a minimum gradient is essential for gas to be effectively conveyed via the line, meanwhile a stable or flat landscape is critical for the siting of the biomass plant. Flat landscape will help to reduce the cost of sand-filling the proposed site where the biomass plant would be installed; the *aspect*: sunlight is required to fall on the plant at temperature of about 15 °C, which is vital for the pretreatment of the biomass resource (residue) and drying before it is fed into the biomass plant [1].

2.4.1. Reclassification of criteria

To identify locations of high vegetation (crop and forest) areas, the crop land and forest lands are classified into various categories. The vegetation classification was carried out with an NDVI range difference of 0.02 and 0.065 for cropland and forest areas respectively.

The reclassification helps to place all the parameters in a dimensionless unit. Analysis can thus be easily carried-out on the parameters using the raster calculator or other relevant tools. Table 3 (Reclass column) shows the reclassification of the criteria used for the suitability analysis to determine the best location for siting the biomass in the ArcGIS platform. The classification of was done in different levels depicting region with very-high, high, moderately-high, low and very-low potential. Based on the potential level of the criteria, a reclassification ranges of 1–10 is assigned, to indicate the potential level from the least to the highest.

2.4.2. Weighted overlay analysis

The weighted overlay tool is an analytical tool used to create a liberal model, where the overall score is computed as the sum of the products of the individual weights and the criteria assigned scores. The overall score can be computed using Equ. (8);

$$W_{score} = \sum_{m}^{n} C_i * W_i; \tag{8}$$

$$i = \{LULC_j\ resource, \text{distance from road}, \text{distance from water}, \text{slope}, \text{aspect}, \text{settlement}\};$$

$$LULC_j = \{LULC\ crops, LULC\ forest\}$$

where, W_{score} is overall weighted overlay score; C_i is criteria score of i; W_i is weight value of criteria i; *LULC* is land use land cover.

The weighted overlay analysis is used to display low–high potential regions using a scale of 1–9. The weighted overlay of the crop and forest areas were carried-out base on the reclassified criteria (See Table 3) using the weighted overlay tool in the ArcGIS platform. The reclassified criteria considered for selecting suitable biomass plant site region were upload into the weighted overlay domain in the ArcGIS platform and assigned a weighted percentage summing 100% based on the influence level of each criterion, thereafter, the reclassified values were used to match the scale range value in the weighted overlay domain.

Table 1
Edo State Crop production and obtainable residues from energy producing crops in 2019.

crop	Nigerian 2019 Production (Mtonnes) [5]	% rate of Edo state	Reference	Edo state production	Crop Residue	LHV [kJ/kg] [5]	RPR [5]
Cassava	59.19	1.19	[65]	704405.13	Peels	16,400	0.36–0.91
					Stalks	17,000	0.20–1.00
Rice, paddy	8.44	0.41	[65]	34583.50	Husk	14,000–16,410	0.17–0.35
					Straws	12,440	0.40–3.96
Oil palm fruit	10.03	5.35	[66]	536346.81	Fiber	17,800–18,133	0.11–1.10
					Shells	20,200–21,700	0.05–1.00
					Bunches	15,170	0.2
Cocoa	0.35	6.40	[66,67]	22409.34	Husks	13,000–17,237	1.00–2.00
Maize	11.00	1.98	[65]	217800	Husk	16,370–19,900	0.20–0.30
					Stalks	17,740	0.55–4.33
Coconut	0.23	2.50	[68]	5739.45	Husk	10,000–17,030	0.42–1.60
					Stalks	17,400–18,000	0.12–0.70
Sugar cane	1.46	0.71	[66]	10337.88	Bagasse	7700–8000	0.05–1.16
Coffee	0.001	7.20	[66]	80.42	Husks	16,000	0.12–1.88
Cowpeas	3.58	0.00	[69]	0	Shells	17,900	1.20–1.90
Groundnut	4.45	0.04	[65]	1780.02	husks/shells	13,785–18,130	0.37–1.20
					Cobs	25,330	0.20–1.80
Millet	2.00	0.00	[65]	0	Straws	15,400	0.95–2.00
					empty bunches	16,730	0.23–0.39
Plantain	3.18	7.50	[70]	238715.40	Leaves	15,730–17, 510	0.25–0.50
					Stem	16,130	3.91–5.00
Potato	1.40	1.65	Estimated [65]	23048.72	Peels	16,430–25,770	1.14
Sorghum	6.67	0.00	[65]	0	Straws	15,400	0.85–7.40
Soybean	0.63	0.00	[65]	0	Straws	17,900	0.80–3.94
Wheat	0.06	0.00	[71,72]	0	Straws	16,210	0.70–1.80
Yam	50.05	1.65	[65]	825874.12	Peels	16,433	0.06
Cocoyam	2.86	4.94	[65]	141328.90	Peels	16,433	0.06
Seed Cotton	0.23	0.00	[65]	0	Straw	14,600	2.45
Melonseed	0.61	9.27	[65]	56181.48	Shells	14,000–16,410	0.17–0.35
Sweet potatoes	4.15	1.65	Estimated [65]	68400.56	Peels	16430	1.14
Rubber (natural)	0.15	14.47	[66]	21660.29	tree residue	17,000	0.72

Fiber is the non-consumable part of the oil palm fruit.

2.4.3. Suitability analysis

The weighted overlay result is subjected to further analysis in the Map Analyst" Raster calculator tool in ArcGIS domain to get the most suitable area in siting the plant. The suitability area (SA) calculation of the crop/forest areas based on the available resources is performed by using Equ. (9);

$$SA_i = W_i \times LULC\ ;\ i = (crop, forest) \tag{9}$$

where, SA_i represents suitability area, W_i represent weighted vegetation and $LULC$ represents land use and land cover.

2.4.4. Proposed/optimum siting points of biomass plants across Edo state

The best point for siting the biomass plant was determined by extracting very high and high biomass potential sites of the suitable areas from the raster data using the reclassification tool and converting it into point data (vector data). Identical points of the crop suitability points and forest suitable points were merged, thereafter, the crop and forest suitable points were combined to obtain the best point to locate the biomass plant, where both the crop and forest residue resources can be used as feed for the plant.

2.4.5. Estimation of the economic distance for Edo state

The economic distance can be obtained from Equ. (10), as the minimum route distance of the plants to the minimum route distance;

$$E_d = X_{j,min} - X_{j,max} \tag{10}$$

where, E_d is economic distance; $X_{j,max}$ and $X_{j,min}$ are the maximum and minimum route distances of plants respectively, obtained from Equ. (11) and Equ. (12), respectively;

$$X_{j,max} = max\{X_{ij,min}\}; i,j = (1, 2, 3\ .\ .\ .) \tag{11}$$

$$X_{j,min} = max\{X_{ij,min}\} \tag{12}$$

Table 2
Edo State crop and forest residues energy potentials.

Crop Resource	Crop Residue	RPR [−]	Residue potential [k tonnes]	LHV [kJ/kg]	$E_{theoretical}$ [GJ/year]	AF [−]	$E_{technical}$ [GJ/year]	$E_{economical}$ [GJ/year]
Cassava	Peels	0.635	447.30	16400	7335674.97	0.3	2200702.49	608714.31
	Stalks	0.600	422.64	17000	7184932.28	0.3	2155479.68	596205.68
Rice, paddy	Husk	0.260	9.00	15205	136718.95	0.4	54687.58	15126.59
	Straws	2.180	75.39	12440	937876.85	0.4	375150.74	103766.7
Oil palm fruit	Fiber	0.605	324.49	17966.5	5829946.34	0.8	4663957.07	1290050.53
	Shells	0.525	281.58	20950	5899144.47	0.8	4719315.57	1305362.69
	Bunches	0.200	107.27	15170	1627276.22	0.8	1301820.98	360083.68
Cocoa	Husks	1.500	33.61	15118.5	508193.50	0.3	152458.05	42169.9
Maize	Husk	0.250	54.45	18135	987450.75	0.3	296235.23	81938.66
	Stalks	2.440	531.43	17740	9427603.68	0.3	2828281.1	782302.55
Coconut	Husk	1.010	5.80	13515	78344.35	0.3	23503.31	6501.01
	Stalks	0.410	2.35	17700	41651.19	0.3	12495.36	3456.22
Sugar cane	Bagasse	0.605	6.25	7850	49097.16	0.3	14729.15	4074.08
Coffee	Husks	1.000	0.08	16000	1286.78	0.3	386.04	106.78
Cowpeas	Shells	1.550	0	17900	0	0.3	0	0
Groundnut	husks/ shells	0.785	1.40	15957.5	22297.67	0.3	6689.3	1850.26
	Cobs	1.000	1.78	25330	45087.91	0.3	13526.37	3741.39
Millet	Straws	1.475	0	15400	0	0.3	0	0
	empty bunches	0.310	0	16730	0	0.3	0	0
Plantain	Leaves	0.375	89.52	16620	1487793.73	0.3	446338.12	123457.12
	Stem	4.455	1063.48	16130	17153885.74	0.3	5146165.72	1423429.44
Potato	Peels	1.140	26.28	21100	554413.86	0.3	166324.16	46005.26
Sorghum	Straws	4.125	0	15400	0	0.3	0	0
Soybean	Straws	2.370	0	17900	0	0.3	0	0
Wheat	Straws	1.250	0	16210	0	0.3	0	0
Yam	Peels	0.060	49.55	16433	814295.37	0.3	244288.61	67570.23
Cocoyam	Peels	0.060	8.48	16433	139347.47	0.3	41804.24	11563.05
Seed Cotton	Straw	2.450	0	14600	0	0.3	0	0
Melonseed	Shells	0.260	14.61	15205	222102.26	0.3	66630.68	18430.05
Sweet potatoes	Peels	1.140	77.98	16430	1281156.02	0.3	384346.81	106310.33
Rubber (natural)	tree residue	0.720	15.60	17000	265121.92	0.625	165701.2	45832.95
Forest Resources	**Density (Kg/m^3)**	**Volume [m^3]**	**Mass [tonnes]**	**Forest Residue [*1000 tonnes]**	**LHV [kJ/kg]**	**E_Theoritical (GJ/year)**	**AF [−]**	**E_technical [GJ/yr]**
Wood fuel, non-coniferous	521	399666.64	208226.32	149.92	19500	2923497.55	0.6	1754098.53
Sawlogs and veneer logs, non-coniferous	675	45648.25	30812.57	22.19	19500	432608.45	0.6	259565.07
Pulpwood, round and split, non-coniferous (production)	550	132.14	72.68	0.05	19500	1020.38	0.6	612.23
Other industrial roundwood, non-coniferous (production)	449	14415.24	6472.44	4.66	19500	90873.07	0.6	54523.84
Wood charcoal		0	28063.34	20.21	28000	565756.85	0.6	339454.11
Sawnwood, coniferous	415	12.01	4.99	0	19500	69.99	0.6	42
Sawnwood, non-coniferous all	560	12012.7	6727.11	4.84	19500	94448.63	0.6	56669.18
Veneer sheets	451	9.01	4.06	0	19500	57.05	0.6	34.23
Plywood	595	336.36	200.13	0.14	19500	2809.85	0.6	1685.91
Particle board	661	240.25	158.81	0.11	19500	2229.66	0.6	1337.8
Mechanical and semi-chemical wood pulp	–	–	54.06	0.04	19500	758.96	0.6	455.38
Chemical wood pulp	–	–	84.09	0.06	19500	1180.61	0.6	708.37

(*continued on next page*)

Table 2 (*continued*)

Crop Resource	Crop Residue	RPR [−]	Residue potential [k tonnes]	LHV [kJ/kg]	$E_{theoretical}$ [GJ/year]	AF [−]	$E_{technical}$ [GJ/year]	$E_{economical}$ [GJ/year]
Chemical wood pulp, sulphate, unbleached	–	–	84.09	0.06	19500	1180.61	0.6	708.37
Recovered paper	–	–	120.13	0.09	19500	1686.58	0.6	1011.95
Printing and writing papers	–	–	6.01	0	19500	84.33	0.6	50.6
Other paper and paperboard	–	–	108.11	0.08	19500	1517.92	0.6	910.76

Table 3
Criteria assigned weights, influence, sub-criteria and ranks in weighted overlay domain.

S/N	Criteria	Assigned Weight	Influence [%]	Sub-Criteria	Reclass	Rank
1	Crop land/Forest land					
	Crop land	0.30	30%	Others	0	1
				0.27–0.29	2	2
				0.29–0.31	4	4
				0.31–0.33	6	6
				0.33–0.35	8	8
				0.35–0.36	10	9
	Forest land	0.30	30%	Others	0	1
				0.36–0.39	2	2
				0.39–0.42	4	4
				0.42–0.45	6	6
				0.45–0.48	8	8
				0.48–0.50	10	9
2	Settlement	0.25	25%	0.015–0.06	1	7
				0.06–0.105	2	8
				0.015–0.06	3	9
3	Distance from Road [km]	0.20	20%	0–5	10	9
				5–10	8	8
				10–15	6	6
				15–20	4	4
				20–25	2	2
				25–30	1	1
4	Distance from River [km]	0.10	10%	0–5	10	9
				5–10	7	7
				10–20	4	4
				20–30	1	1
5	Slope	0.8	8%	0–3	10	9
				3–10	8	8
				10–20	6	6
				20–30	4	4
				>30	2	2
6	Aspect	0.7	7%	−1–0 (Flat)	10	9
				0–22.5 (N)	1	1
				22.5–67.5 (NE)	3	3
				67.5–112.5 (E)	5	5
				112.5–157.5 (SE)	9	8
				157.5–202.5 (S)	9	8
				202.5–247.5 (SW)	10	9
				247.5–292.5 (W)	5	5
				292.5–337.5 (NW)	3	3
				337.5–360.0 (N)	1	1

where, $X_{ij,min}$ is the minimum route distances for plant(j);

3. Result and discussion

3.1. Resource assessment

The top energy producing crops in Nigeria were basically selected and analyzed in this section following the results presented in Ref. [5], which include the thermo-gravimetric composition of the crop residues and forest wood. The crop production ratio of Edo

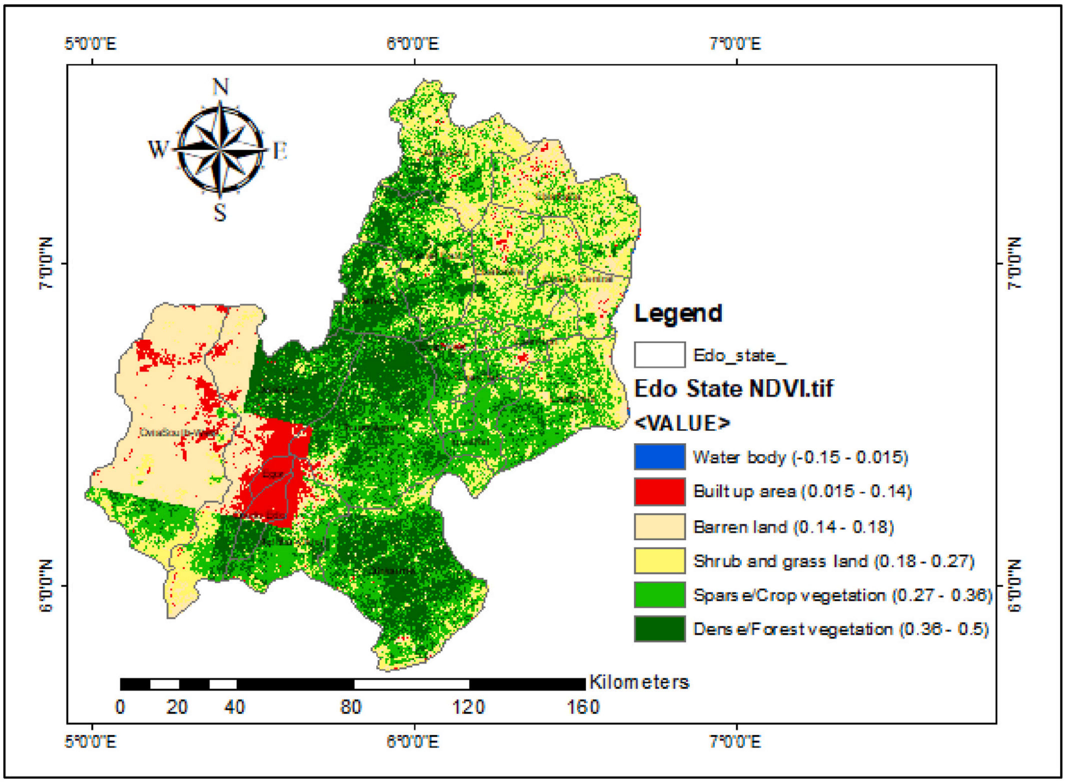

Fig. 2. LULC and biomass distribution map of Edo State.

state was obtained from different sources and analyzed with the crop production quantity of Nigeria [5].

Table 1 presents Edo state crop production and obtainable residues from producing crops in 2019. The estimated crop residue theoretical, technical and economic energy potential of Edo state are 60.03 [PJ/year], 25.48[PJ/year] and 7.05 [PJ/year], respectively, as presented in Table 2. The crop residue with the highest economic potential in Edo state is plantain (stem), followed by oil palm (shell and fibre, respectively), maize (stalks), and cassava (peel and stalks, respectively) as displayed in Table 2. Also, Edo state forest residue potentials for the year 2020 are presented in Table 2. The estimated theoretical, technical and economic energy potentials for the state stood at 4.12, 2.47 and 0.68 [PJ/year], respectively. The estimated densities utilized for the forest resources followed that of Ukoba et al. [5], which they obtained from Refs. [60–64].

3.2. Land use and land cover (LULC) classification and analysis

Based on the described methodology in section 2, Edo state NDVI classification range for six land cover derived from 2021 Landsat-8 OLI data [16]. The NDVI classification range for Edo state strongly corresponds to Akbar et al. [73] NDVI classification, except for the initial classification (water body: 0.15–0.015) and final classification (dense vegetation: 0.36–0.50) range, whose variation is due to the geographical location. Akbar et al. [73] NDVI classification is given as follows; water: 0.28–0.015, built-up area: 0.015–0.14, barren land: 0.14–0.18, shrub and grassland: 0.18–0.27, sparse vegetation: 0.27–0.36, and dense vegetation: 0.36–0.74. The implementation of the NDVI ranges gave rise to the Edo state land cover map presented in Fig. 2.

3.2.1. Forest and cropland classification

The cropland and forest lands were further classified into various categories to identify locations of high vegetation areas from that of low vegetation area. The vegetation classification was carried out with an NDVI range difference of 0.02 and 0.03 for cropland and forest areas.

From the Landsat-8 data obtained from USGS, the crop and forest area counts were captured [16], and analyzed with the total crop production of Nigeria in 2019 and forest production of Nigeria in 2020 [74] to get the crop and forest production in Edo State. Edo State crop and forest production was further analyzed based on the Local Government Area (LGA) counts to get the estimated crop and forest product across the LGAs in Edo State as presented in Fig. 3.

From the findings, Orhionmwon LGA has the highest energy production crops, followed by Uhunmwonde, Owan-East and Ovia-North, with generation capacity of 958296.64, 843098.04, 445708.43, and 431463.15 [tonnes/year], respectively. For forest production, Ovia-North featured the highest production followed by Uhunmwonde, Orhionmwon and Owan-West, with the production value of 81220.20, 57149.30, 56565.00 and 35176.39 [tonnes/year] in that order. Egor LGA seems to have no value (Zero value) for

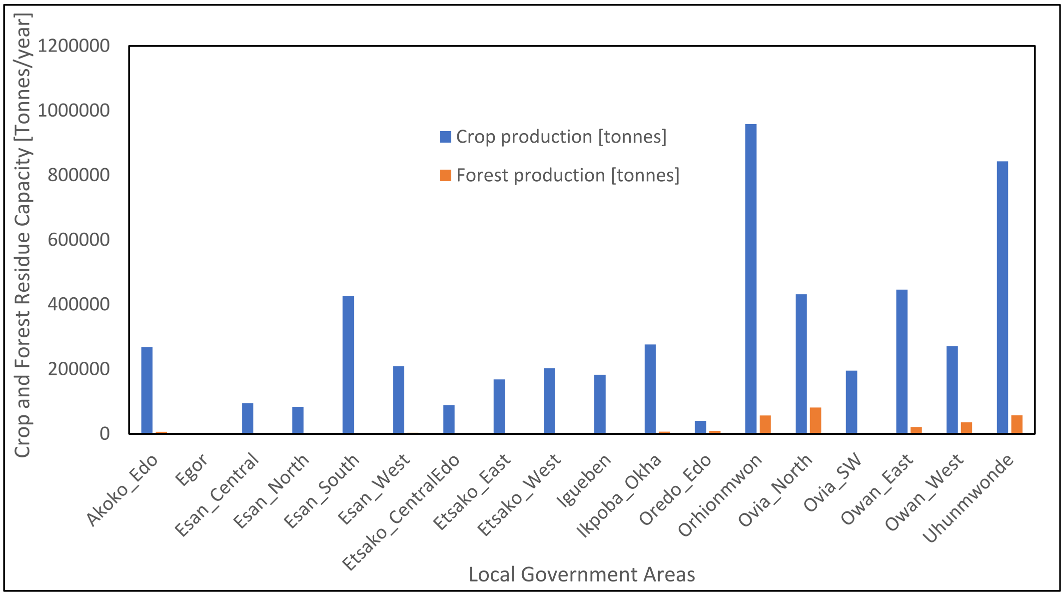

Fig. 3. Energy Crop and Forest production by LGAs in Edo State.

both crop and forest production (See, Fig. 3).

3.3. DEM analysis

The Digital Elevation Models (DEM), also called digital terrain model (DTM) or digital surface model (DSM) provides a 3-dimensional view of the earth surface. The DEM data downloaded helped to provide information about the interface between the lithosphere and the atmosphere [75]. The DEM data was used to obtain the slope, elevation, aspect, contour, and hill-shade of a geographical area. Meanwhile, the slope and aspect were extracted to serve as part of the criteria for determining optimal site locations for biomass plants in Edo state, Nigeria. The slope data help create room to obtain a minimum gradient between the biomass plant and storage/consumption facility for the gas produced to be effectively transported via pipeline. The aspect data identifies the regions of high, moderate, or low sunlight. Sunlight is required to fall on the plant at a temperature of about 15 °C, which is vital for gas generation. Fig. 4 shows the Edo state aspect, slope and hilltop analyzed from DEM data.

3.4. Accessibility to the proposed biomass plant site

The biomass plant site needs to be accessed via roads and water. The accessibility of the site is vital for the supply of feed, transportation of biomass plant facilities, and carrying-out of maintenance of the biomass plant by professionals when required. Water availability also allows cooling the biomass plant system and heat exchange during operation. Multiple-Ring-Buffer of 5–50 km was taken for the road-network and water-lines across the state to identify areas that are close to the road and water lines in Edo state. Raster buffer was done, and then the road and water-line were masked out to capture only areas within the state. Fig. 5 present the Multiple-Ring-Buffer (c), Raster-Buffer (b), and Mask (a) of Edo state road network and the Multiple-Ring-Buffer (c), Raster-Buffer (b), and Mask (a) of Edo state water lines. From the legend in Fig. 5, features with the value '5' displays the closest areas to the road and water-lines, and as the value moves above 5, it shows areas that are far away from the road and water-lines in Edo state.

3.5. Suitability analysis using weighted overlay in ArcGIS

The reclassification of all the criteria used to determine the best location for siting the biomass CHP plant are presented below.

3.5.1. Reclassification of criteria

The reclassification tool is embedded in the Arc-toolbox. The various criteria, including crop/forest area, road network, waterline, slope and aspect, were reclassified to make them dimensionless for easy analysis.

The reclassification of the criteria used was performed for the suitability analysis in the ArcGIS platform. The classification was done in five (5) levels; very-high, high, moderate, low, and very-low potential levels of the various criteria. Based on the potential level of the criteria, reclassification range of 1–10 was assigned to indicate the potential level from the least to the highest.

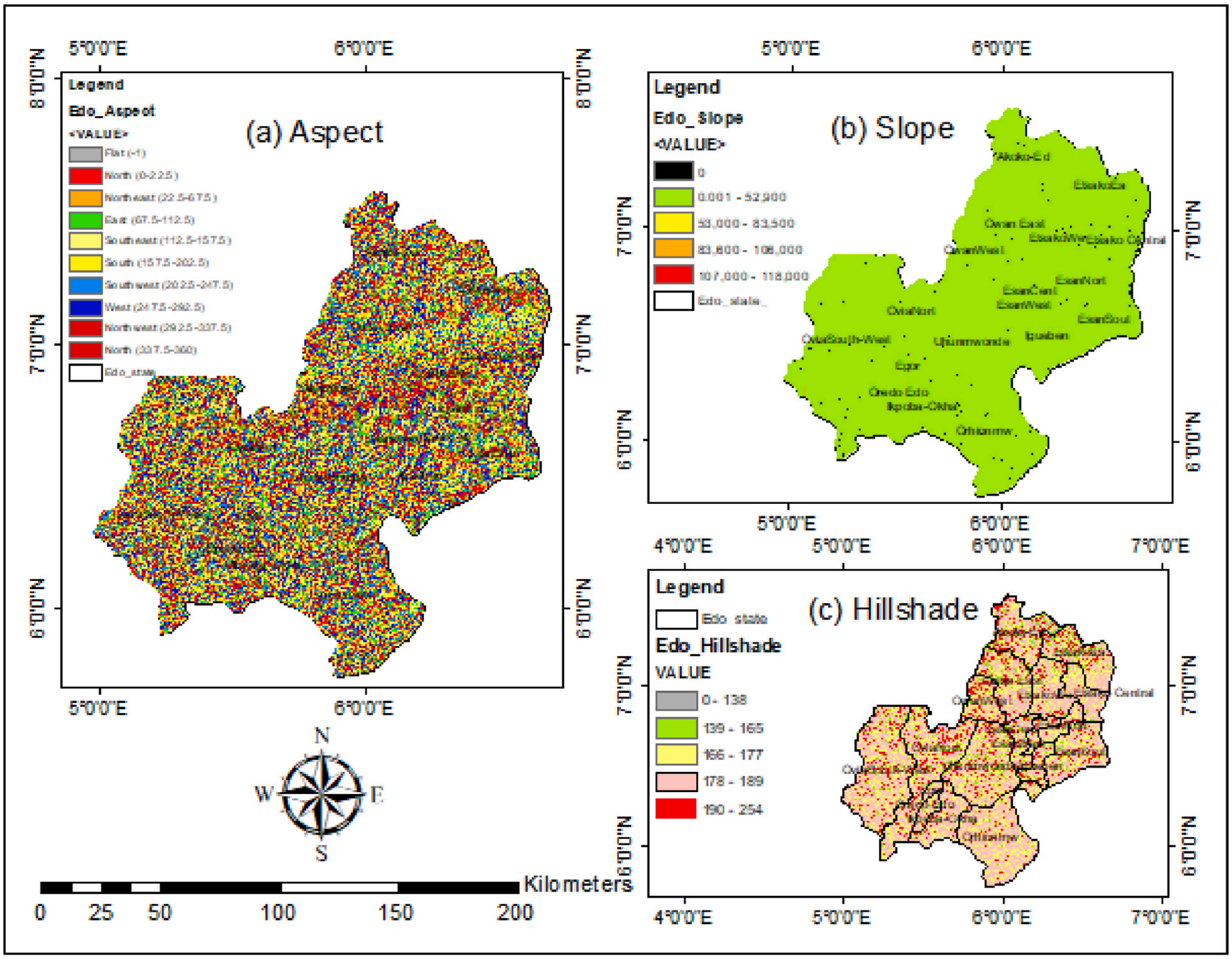

Fig. 4. Edo State's (a) Aspect, (b) Slope and (c) Hilltop analyzed from DEM data.

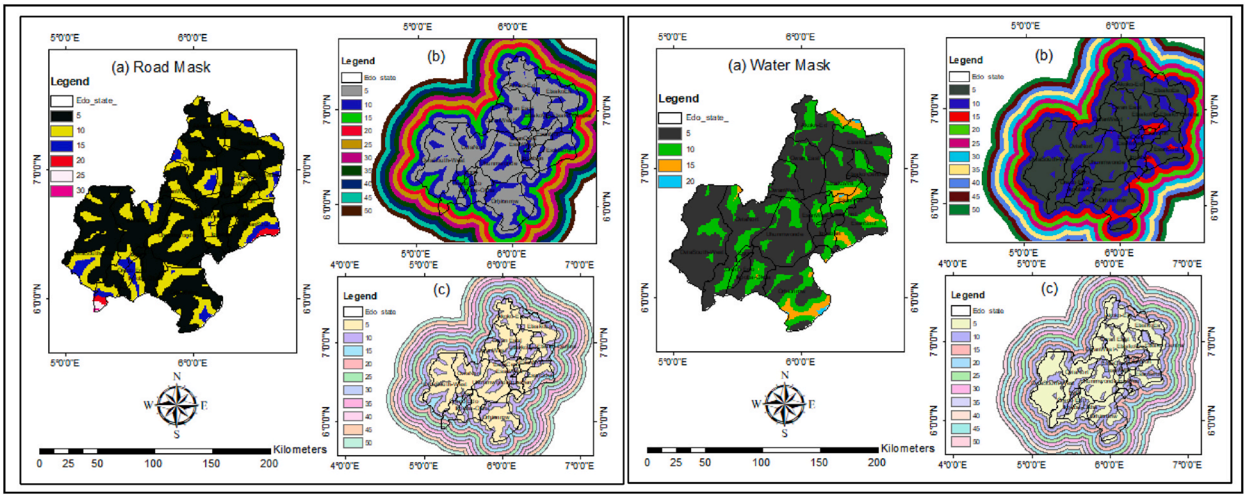

Fig. 5. Edo state's (a) Road and water Mask, (b) Raster-Buffer and (c) Road Multiple-Ring-Buffer.

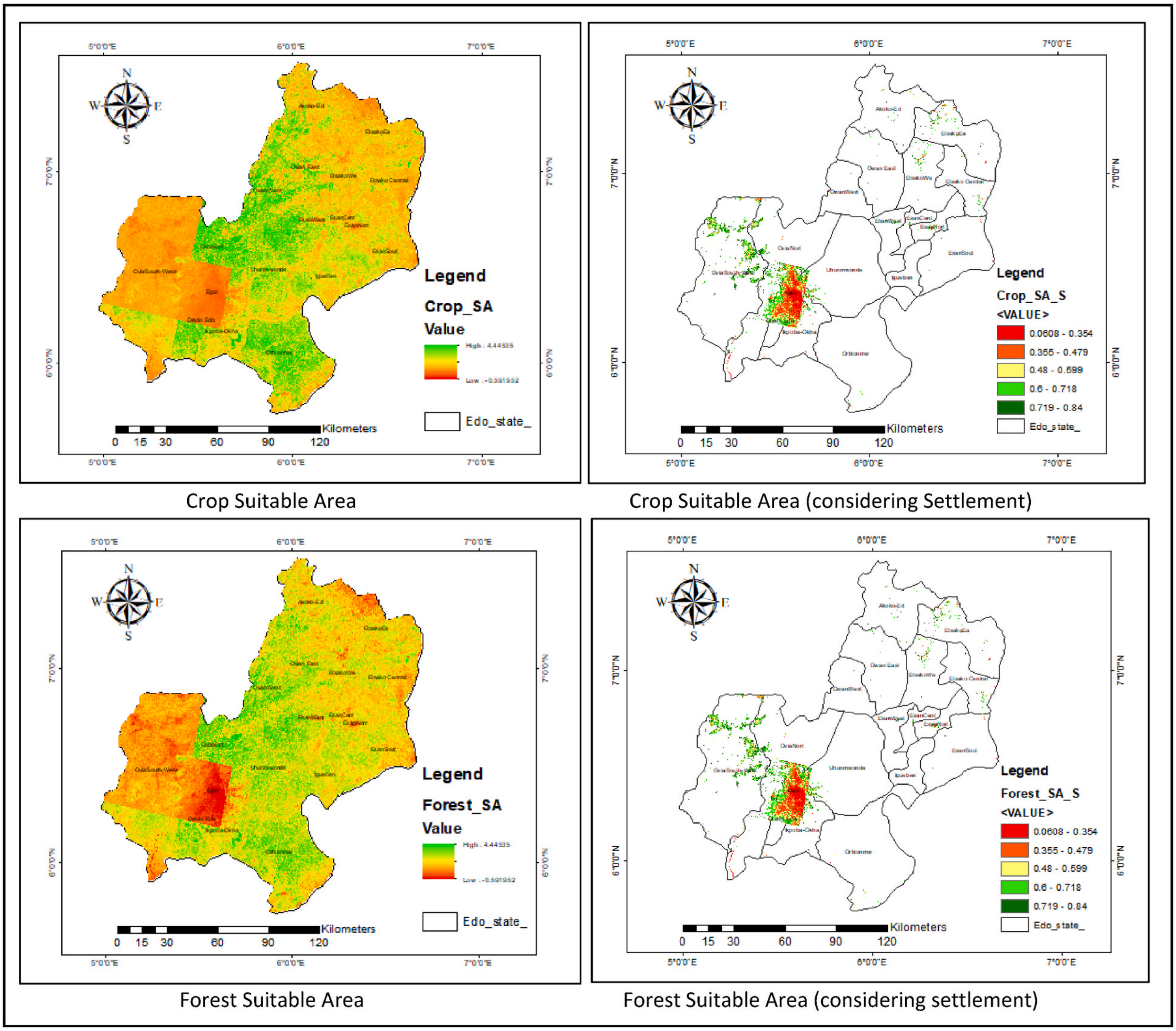

Fig. 6. Edo state crop and forest suitable area.

3.5.2. Weighted overlay analysis

The weighted overlay tool in the ArcGIS platform was employed for the suitability analysis to identify suitable locations for siting biomass plants in Edo state based on specified criteria: crop/forest area, road network, waterline, slope, and aspect. Table 3 shows criteria weights, influences (%), sub-criteria, and rank in the weighted overlay domain. The value range of 1–9 was assigned to the reclass criteria (1–10).

Frist, the weighted analysis was done for the crop area analysis to identify the site suitable for siting a biomass plant without considering the settlement. The reclassified crop area, road network, waterline, slope, and aspect were integrated with the weighted overlay domain and assigned the weighted per cent of 50, 20, 15, 8, and 7, respectively. Next, the reclassified criteria were integrated with the weighted overlay domain alongside Edo state settlement. The settlement which is embedded in the LULC data as a built-up area was reclassified into 1, 2, and 3, which stands for low, intermediate, and high area and thus represent low, intermediate, and high energy demand area, respectively. The weighted overlay percentage was then readjusted for the various criteria; crop area, settlement, road network, waterline, slope, and aspect and assigned the weighted per cent of 30, 25, 20, 10, 8, and 7, respectively. Whereas the weighted rank of 7, 8, and 9 were assigned to the settlement reclassified data of 1, 2, and 3, respectively, the weighted rank of the other criteria remained the same. For the forest area weighted overlay analysis, a similar process to that of the crop-weighted overlay analysis was followed.

3.5.3. Suitability analysis

The weighted overlay of the crop and forest region was subjected to further analysis by using Raster calculator tool embedded in the Map Analyst domain and Arc toolbox in ArcGIS software to get the suitable areas to site biomass plants.

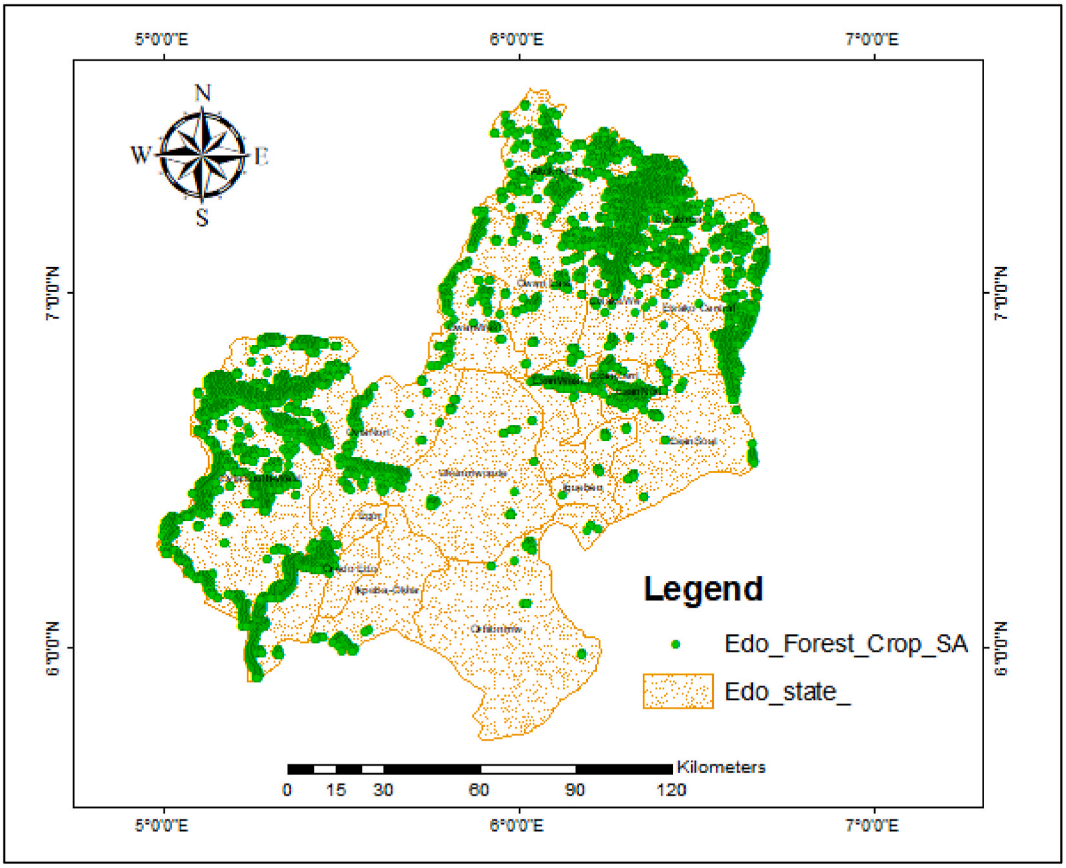

Fig. 7. Biomass power plant sites based on forest and crop residues.

Fig. 6 shows Edo state crop and forest suitable area maps for siting biomass plants; without considering the settlement features and when settlement is integrated into the catchment area.

3.5.4. Proposed optima sites for biomass plants across Edo state

The settlement (urban and rural settlement) data, which features houses, hospitals, schools, offices, industrial areas and others, captured in the LULC data as built-up areas was extracted using reclassification tool and converted into point data using the 'convert from raster to point data tool' embedded in the Arc toolbox, in the GIS domain.

The suitable area raster data was reclassified, extracting only the high crop and forest suitable areas with values ≥ 0.6 and then converted to point data as shown in Fig. 7.

The suitable biomass power plant locations were obtained by deleting identical points of the crop and forest point data (suitable area), then, the crop and forest data points were joined into one file using the joint tool in the ArcGIS domain in other to have a central location where the proposed biomass plant (which will be fed by the crop and forest residues) can be appropriately sited.

3.5.5. Economic distance for Edo state biomass plant location

The minimum radius for siting a biomass plant is assumed to be 30 km [51]. Hence, from each proposed point data, a radius of 30 km was mapped out from the suitable area points affected by an already proposed biomass plant. This is to enable the biomass plant to be situated strategically away from each other to avoid competition in biomass energy distribution and residue resource collection from the nearby area to serve as fuel for the proposed biomass (CHP) plant system. Since the minimum radius is considered to be 30 km [51], it implies that one biomass plant can be installed within an area of 2827.43 km^2, thus, a total of seven (7) biomass plants installation is possible in Edo state, which has a total land area of 19800 km^2. Fig. 8 shows the proposed optima sites appropriate to the site of the proposed biomass plant systems in Edo State, Nigeria.

Table 4 displays the biomass plant site location/coordinates, the number of joint crop and forest suitable area point data concerned and the affected LGAs from where resources can be collected. It also shows the proposed biomass plant routes $(X_{ij} - X_{ji})$, the distance from each plant and the estimated economic distance for siting the biomass plant in Edo state, Nigeria.

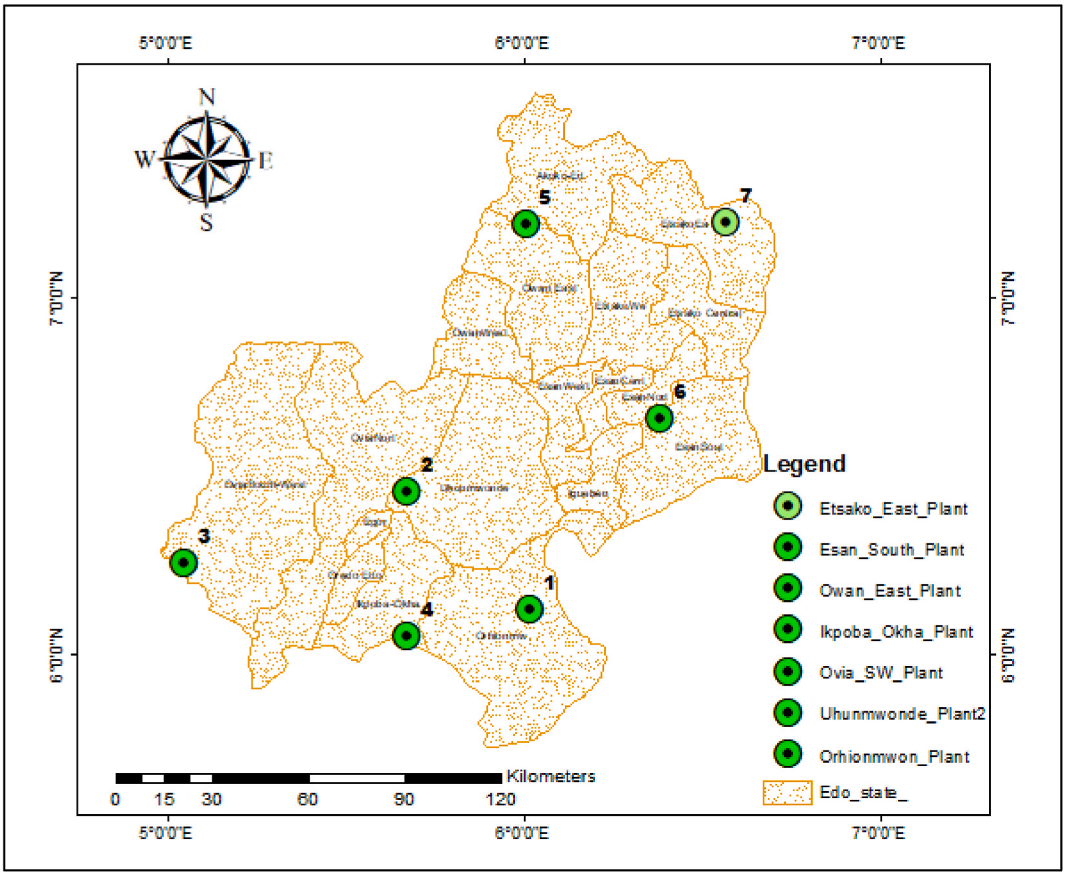

Fig. 8. Proposed optima location for biomass power plants in Edo state.

4. Conclusions

This study suggests that Edo state has energy potentials of 62.03 and 4.12 PJ/yr for crops and forest residues, respectively, to support bioenergy development. The crop residues include plantain (stem), oil palm (shell and fibre), maize (stalks), and cassava (peel and stalks). Six criteria including; biomass residue distribution, settlement, road accessibility, nearness to waterline, slope and aspect were considered in selecting the optimal sites. Orhionmwon local government featured the highest energy crop-producing LGA, followed by Uhunmwonde, Owan-East and Ovia-North with a yearly generation capacity of 958296.64, 843098.04, 445708.43, and 431463.15 tonnes, respectively. For forest production, Ovia-North featured as the highest energy-producing LGA followed by Uhunmwonde, Orhionmwon, and Owan-West, with a yearly production value of 81220.20, 57149.30, 56565.00, and 35176.39 tonnes, respectively.

Going forward, favorable policies are vital to drive the implementation of bioenergy plants in Edo state and by extension, Nigeria. Possible directions to focus the bioenergy policy in the country will be; (i) to develop a socio-technical policy that guarantees the availability of the residues at a near-zero cost, (ii) to develop and implement policies that allow organizations to generate, transmit and distribute power, (iii) to adopt decentralized energy-generation policy system, and (iv) to stipulate a minimum threshold of bioenergy utilization in the mini-grids within the state.

Contribution statement

MOU–Performed experiments, analyzed and interpreted the data, wrote the paper; EOD–Conceived and designed the experiments, analyzed and interpreted the data and wrote the paper; TAB–Conceived and designed the experiments, Contributed reagents, materials, analysis tools or data and wrote the paper; MI–Contributed reagents, materials, analysis tools or data and wrote the paper; KO–analyzed and interpreted the data and wrote the paper; MMO–Contributed reagents, materials, analysis tools or data and wrote the paper; CN–analyzed and interpreted the data and wrote the paper; MDA–Contributed reagents, materials, analysis tools or data and wrote the paper; KEO–analyzed and interpreted the data and wrote the paper; KA–Contributed reagents, materials, analysis tools or data and wrote the paper; IC–Contributed reagents, materials, analysis tools or data and wrote the paper.

Table 4
Proposed Biomass Plants, Location, number of suitable points covered, and the LGAs to supply energy.

S/N	Proposed Biomass Plants	Longitude	Latitude	No of point	LGAs Covered
1	Orhionmwon Plant	6.01388	6.12676	155	Orhionmwon, Uhunmwonde (part)
2	Uhunmwonde Plant	5.67007	6.45358	2059	Uhunmwonde (part), Ovia North-East (part)
3	Ovia SW Plant	5.04475	6.25546	3925	Ovia SW
4	Ikpoba-Okha Plant	5.66800	6.04900	119	Ikpoba Okha, Oredo-Edo, Ovia North-East (part)
5	Owan East Plant	6.00148	7.20332	5976	Owan-Eas, Akoko-Edo, Etsako West (part), Owan West (part)
6	Esan South Plant	6.37817	6.65890	6158	Esan South-East, Esan North-East, Esan Central, Esan West, Etsako West, Etsako Central, Igueben
7	Etsako East Plant	6.56397	7.21030	10845	Etsako East, Etsako Central, Etsako West, Akoko_Edo

–	**Proposed Biomass Plants**	**Plant** (j)	**Closest plants** X_i	**Distances** X_{ij} **[km]**	**Min. distance** X_j **[km]**	$X_{j,min}$ **[km]**	$X_{j,max}$ **[km]**	**Economic Distance** E_d **[km]**
	Orhionmwon Plant	1	(1–2), (1–4), (1–6)	53, 39, 72	39	39	73	39–73
	Uhunmwonde Plant	2	(2–1), (2–3), (2–4)	53, 73, 50	50			
	Ovia SW Plant	3	(3–1), (3–2), (3–4)	108, 73, 73	73			
	Ikpoba-Okha Plant	4	(4–1), (4–2), (4–3)	39, 50, 73	39			
	Owan East Plant	5	(5–2), (5–6), (5–7)	90, 73, 63	63			
	Esan South Plant	6	(6–1), (6–5), (6–7)	71, 73, 65	65			
	Etsako East Plant	7	(7–2), (7–5), (7–6)	130, 63, 65	63			

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.

Acknowledgement

The second and fourth authors acknowledge the funding support through GCRFNGR5\1207 grant by the UK Government. Neither the findings nor the views expressed, however, necessarily reflect the policies of the UK Government.

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