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Techno-economic analysis of electricity generation from household sewage sludge in different regions of Nigeria

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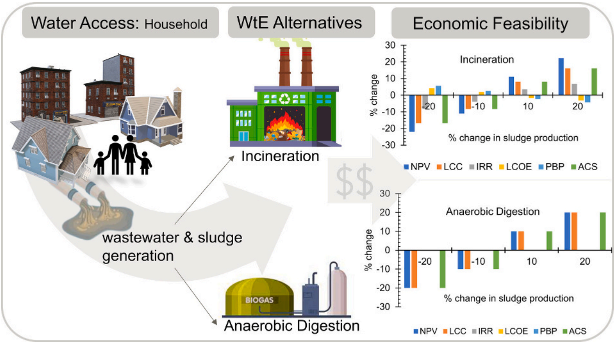
HIGHLIGHTS

- North Central has 11.6 l/c/d of water access and generates 1.9 × 10^7 m^3/yr wastewater.
- AD offers the most viable technology generating 6.8 GWh/yr in the North Central.
- INC has an NPV of 0.31–1.6 million USD and LCOE of 0.046–0.094 USD/kWh.
- NPV is very sensitive to sludge quantity, discount, cost, and electricity tariff.
- Waste-to-energy offers a sustainable solution to address energy deficits.

GRAPHICAL ABSTRACT



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ABSTRACT

Waste management has been a chronic environmental challenge in Nigeria, coupled with declining economic performance due to energy crises. This study was designed to estimate electricity potential of sewage sludge to meet the 2030 Renewable Energy target. However, there was a need to fill the gap in data related to wastewater management in Nigeria. The wastewater and sludge generated from households were evaluated based on data on population, access to water, and coverage of sewer networks. Consequently, the technical and economic

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Abbreviations: ACS, Annualised Cost of System; AD, Anaerobic Digestion; C, Carbon; CHP, Combined Heat and Power; FCT, Federal Capital Territory; H, Hydrogen; HHV, Higher Heating Value; INC, Incineration; IRR, Internal Rate of Return; LCC, Life Cycle Cost; l/c/d, litres/capita/day; LCOE, Levelized Cost of Energy; LFG, Landfill Gas; LFGTE, Landfill-gas-to-Energy; LHV, Lower Heating Value; MSW, Municipal Solid Waste; N, Nitrogen; NC, North Central; NE, North East; NESP, National Environmental Sanitation Policy; NPV, Net Present Value; NW, North West; O, Oxygen; O&M, Operation and Maintenance; OFMSW, Organic Fraction of Municipal Solid Waste; PBP, Payback Period; PI, Profitability Index; REMP, Renewable Energy Master Plan; S, Sulphur; SDG, Sustainable Development Goals; SE, South East; SS, South South; SWS, Sewage Sludge; SW, South West; UAE, United Arab Emirates; USD, United States Dollar; WASHNORM, Water, Sanitation and Hygiene National Routine Mapping; WtE, Waste-to-energy; WW, Wastewater; WW Col., Wastewater collection; WW Gen., Wastewater Generation; WWTP, Wastewater Treatment Plant; WWTPs, Wastewater Treatment Plants.

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Financial feasibility
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Wastewater

feasibility of electricity generation was assessed using Anaerobic Digestion (AD)[1] and Incineration (INC)[2] scenarios. The core results found that North Central had the highest potential for wastewater generation (142.8–403.6 billion litres/yr) and collection (8.3–37.5 billion litres/yr) over 20 years. However, the South East had the highest average sewer collection rate of 9.08 %. The AD technology was the most technically viable, with a maximum generation of 6.8 GWh/yr in the North Central. In comparison, the INC outperformed AD in most of the financial viability indicators considered viz-a-viz: Life Cycle Cost (LCC),[3] Net Present Value (NPV),[4] Pay Back Period (PBP),[5] Internal Rate of Return (IRR),[6] Levelized Cost of Energy (LCOE).[7] The AD had a higher NPV of 16.3–69.58 million USD and a shorter PBP of about 4 years. The INC had a lower LCC of 0.1–0.34 million USD, LCOE of 0.046–0.094 USD/kWh, and a higher IRR of 19.3–25 %. Additionally, the sensitivity of NPV and INC to changes in economic factors would be noteworthy for investors and policymakers. Ultimately, the choice of technology should reflect the fiscal goal and priorities of a project.

1. Introduction

The poor treatment of wastewater (WW)[8] in developing countries has led to the proliferation of diseases. The Sustainable Development Goal (SDG)[9] 6 targets reducing the amount of untreated WW released into the environment. Developing countries often do not meet WW discharge standards, which continues to be a significant environmental concern (World Bank, 2021). Similarly, Nigeria's primary public health concern is poor access to safe potable water and sanitation. In 2019, approximately 80 million people had no access to secure hygiene facilities. Furthermore, 29 % of households in rural areas engage in open defecation. As a result, substantial volumes of WW are released into the environment, untreated or undertreated (World Bank, 2021).

The main problems existing Wastewater Treatment Plants (WWTPs)[10] face in developing countries include irregular power supply and mismanagement of sludge. Likewise, there are limited information on wastewater and faecal sludge production, treatment, and disposal in Nigeria (World Bank Group, 2017). Moreover, sludge has been previously classified as sewer and non-sewer sludge. Sewer sludge is made up of sludges from sewerage and WWTPs. On the contrary, non-sewer sludge is faecal sludge from a septic tank or pit latrine (Englund and Strande, 2019). Faecal sludge disposal techniques in Nigeria include treatment at designated treatment plants, burial in covered or open pits, and discharge into water bodies (FMWR et al., 2022; World Bank Group, 2018). In one case, the sludge is dried on site as feedstock for AD or a medical incinerator (World Bank Group, 2018). The management of sludge at WWTPs could be similar as there is very limited information, in addition to the fact that most plants are not operating optimally. However, an operational facility in Nigeria is equipped with drying beds for the drying of sludge. Most dried sludge accumulates within the facility, some being used as manure (Saidu et al., 2019). Other WWTPs also practice agricultural application and landfilling of sewage sludge (Nikolopoulou et al., 2023). Additionally, a recent study (Ogwueleka et al., 2021) also investigated the disposal of wastewater treatment plant sludge by bio-drying technique to produce a material usable as fuel in steam and power generators (Navaee-Ardeh et al., 2010).

Furthermore, Nigeria's economy depends on energy, but most of the population lacks access to electricity (Ziady, 2021). Oil and gas remain the mainstay of power in Nigeria; however, the high intensity of Nigeria's energy implies an ineffective energy utilisation (Ritchie et al., 2022). The Nigerian government launched a plan to increase the amount of renewable energy in the energy mix from 13 % in 2015 to 36 % by 2030. The Renewable Energy Master Plan (REMP)[11] was intended to promote energy security and regulate the carbon footprint of the country's energy sector (ITA, 2021). The progression of the energy situation has left more to be desired, marked by erratic supply, an outdated grid, and infrastructure.

Waste-to-energy (WtE)[12] technologies have received attention as a means of renewable energy generation. Significant studies have been conducted to quantify and characterise Municipal Solid Waste (MSW)[13] in Nigeria: thus, demonstrating the potential energy recovery options of MSW. Several studies examined the potential of MSW energy recovery in Nigerian cities. Incineration (INC),[14] Anaerobic Digestion (AD),[15] and Landfill-Gas-To-Energy (LFGTE)[16] have been studied for WtE in Lagos and Abuja. The AD had the highest energy generation (Lagos (683 kWh/t) and Abuja (667 kWh/t)) (Nubi et al., 2022). Selected landfills in Adamawa state received 15 Gg/yr of MSW and released 0.31 Gg/yr of LFG[17] with a methane content of 82.95 Mg. A projected 33.78 GWh of heat or 10.14 GWh of electricity can be generated from these landfills (Usman, 2022). In Ibadan, methane production from AD and LFGTE technologies averaged 104.66–212.15 $\times$ 10^6 m^3/yr and 22.65–127.65 $\times$ 10^6 m^3/yr for a 20-year period, respectively. The mean generation of electricity during this period was 321.73–652.15 GWh for AD and 63.25–436.18 GWh for LGTE (Ayodele et al., 2018). The treatment of abattoir waste in Ile-Ife, Southwest Nigeria, by AD, showed the potential to generate 1040 MWh of electricity at a conversion efficiency of 0.25. The waste was digested using a 2-batch reactor for 30 days, producing biogas at a mean rate of 1.03 l/day with a methane content of >63 % (Odekanle et al., 2020). The Organic Fraction of MSW (OFMSW)[18] in selected Nigerian cities generated 491 Gg of methane, which is 3.48 $\times$ 10^9 kWh of electricity from 26,600 Gg of waste in 2015. It is projected to increase to 4.74 $\times$ 10^9 kWh electricity due to 669 Gg of methane from 36,250 Gg of waste in 2030. With an estimated income of USD 365.04 $\times$ 10^6 and USD 473.82 $\times$ 10^6 for 2015 and 2030, respectively (Yusuf et al., 2019). Using a university campus as a model community through the WtE calorific value technique, the energy recovery potential of MSW was approximated to be 2490 kWh/d of electricity (Okeniyi et al., 2012). In addition, the Swedish WtE model was used to simulate the generation of electricity from MSW. The model showed a combustible 14 million tonnes of waste in Nigeria worth about 4.4 TWh of electricity (Akhator et al., 2016). Also, waste generation in 2020 was estimated at 40 million tons based on a population of 158 million and a waste generation rate of 0.5 kg/person/day. The forecast showed that with a calorific value of 9.6 MJ/kg, there is the potential to generate 3000 MW of electricity (Atta et al., 2016). However, the characterisation of the MSW components showed that 73 % was organic with an energy content

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[1] AD - Anaerobic Digestion
[2] INC - Incineration
[3] LCC - Life Cycle Cost
[4] NPV - Net Present Value
[5] PBP - Payback Period
[6] IRR - Internal Rate of Return
[7] LCOE - Levelized Cost of Energy
[8] WW - Wastewater
[9] SDG - Sustainable Development Goals
[10] WWTPs - Wastewater Treatment Plants
[11] REMP - Renewable Energy Master Plan
[12] WtE - Waste-to-energy
[13] MSW - Municipal Solid Waste
[14] INC - Incineration
[15] AD - Anaerobic Digestion
[16] LFGTE - Landfill-gas-to-Energy
[17] LFG – Landfill Gas
[18] OFMSW - Organic Fraction of Municipal Solid Waste

of 13,022 KJ/kg. Methane generation over 10 years was estimated at 27,517 t (Akintayo and Olonisakin, 2014). Other studies evaluated the potential for biogas from OFMSW (Ngumah et al., 2013), energy from biomass sources (Ojolo et al., 2012), fuelling steam generators using MSW (Adeoti et al., 2014), comparative analysis of hybrid WtE systems (Ogunjuyigbe et al., 2017), and electricity generation from LFGTE technology (CPE, 2010).

Furthermore, the low heating value and high moisture content of sewage sludge significantly impact its use in electricity generation through AD and INC. However, biomass material with a calorific value of 6.25 MJ/kg (EPA, 2013) or 6 MJ/kg (World Bank, 1999) can be used for bioenergy. The calorific value of sewage sludge in various studies attests to its suitability as an energy source. In the analysis of sewage sludge as an energy feedstock in Italy, the moisture content ranged from 71.8 to 79 % of total weight with a Higher Heating Value (HHV)[19] of 12.7–15.5 MJ/kg dried basis (Bianchini et al., 2015). In France, the ultimate analysis showed C 58.5 %, H 9 %, N 5 %, O 27.45 %, and S 0.05 % with HHV of 20.43 MJ/kg (at 6.2 % moisture content) while proximate analysis revealed moisture 6.2 %, ash 16 %, volatile matter 58.9 %, and fixed carbon 19 % (Jayaraman and Gökalp, 2015). Moisture, ash, volatile matter, and fixed carbon content in Canada were 73.21, 4.02, 22.52 and 0.26 %, respectively. C, H, N, S and O were obtained as 13.2, 9.8, 1.2, 0.5 and 71 %, respectively, for the wet sludge with HHV of 5.65 MJ/kg and 18.75 MJ/kg after microwave drying (Chen et al., 2014). A comparative analysis of coal, agricultural biomass (wood and oat), and sewage sludge showed an HHV of 23.5, 17.6, 17.2, and 12.8 MJ/kg, respectively. Sewage sludge had an ash content of 33 % and a higher N content (4.1 %) than wood <0.05 %, oat 1.7 %, and coal 2.2 % (Magdziarz and Wilk, 2013). Moreover, due to increased organic and volatile content, the primary sludge has a higher energy content than the secondary. The calorific value of the dry matter of the secondary sludge of different treatment technologies was found to be in the 13.5–18.5 MJ/kg range. The digested sewage sludge had a comparatively lower calorific value of 8.5–10 MJ/kg (dry basis). Ultimately, the calorific value of sewage sludge ranges between 8 and 21 MJ/kg (Singh et al., 2020). At the same time, the quantity of sludge generated during WW treatment varies from 1 to 6 % of WW. The Lower Heating Value (LHV)[20] of sludge is influenced by its dry matter content and the organic content of the dry matter. 4.2 % of the initial dry matter content is obtained after the dewatering and drying of the raw sludge. The LHV of dried sludge ranges from 9 to 12 GJ/ton (at 90 % dry matter content) (Ozcan et al., 2015).

Unlike in Nigeria, several WtE plants worldwide are fuelled by sewage sludge (Ijoma et al., 2022). Predominant technologies for WtE from sewage sludge include AD, INC, pyrolysis, gasification, and fuel cells. Some run solely on sewage sludge; for example, an alternative electricity source in Dubai runs on domestic sewage generating 45,000 MWh/yr electricity and is worth around 89 million USD (Meladi, 2019). Another plant worth 4 million USD in Sofia produces 2.4 MWh/yr electricity (powering plant operations) (Ijoma et al., 2022). A 29.4 million USD plant in Serbia generates 3.8 MWh/yr of electricity for optimal operations and heating (MET Group, 2021). Similarly, two biogas plants in Oregon, USA, generate 6000 MWh/yr and 4324 MWh/yr for electricity and heating purposes (Clackamas County, 2018; Hayward, 2018; Loggan, 2021). In South Africa, a Biogas-Combined Heat and Power (CHP)[21] plant generated 725 GWh of electricity and 1150 GWh of heat per annum from organic solid waste and slaughterhouse WW (Russo and von Blottnitz, 2017). Additionally, an innovative nano-membrane toilet design for a Bill and Melinda Gates Foundation project had a capacity of 4620 kWh per 16.2 kg of human faeces and urine (Anastasopoulou et al., 2018). At a Wastewater Treatment Plant (WWTP)[22] in Gamasa, Egypt, an integrated biogas plant produces about 1396.5 kWh of electricity to supplement the power needs of the WWTP (Awad et al., 2019). Meanwhile, other plants mix sewage sludge with biomass waste. Such as in South Africa (cattle manure & OFMSW) and Finland (WWTP sludge plus OFMSW), with a capacity of 4.4 MWh/yr and 40 GWh/yr, respectively (Bailey, 2021; Ijoma et al., 2022). Several sanitation systems combined with one or more AD, CHP and INC technologies were studied in Uganda. The systems were fuelled by cow dung, food waste, and domestic sewage and had a capacity of 441.3–826 kWh/day of electricity and 740.2–1385.5 kWh/day of heat (Agunyo et al., 2019). Nevertheless, the potential of energy recovery from sewage has not received attention in Nigeria, and little or no information is available.

In addition, data on the volume and distribution of WW in Nigeria seem to be a mirage. However, some attempts have been made to estimate the volume of WW generated, collected, and treated in Nigeria. In most conventional databases, such as AQUASTAT (FAO, 2021), data on WW metrics in Nigeria are absent. On the one hand, limited data until 2020 is available from the Joint Monitoring Programme (JMP)[23] (WHO and UNICEF, 2021) database and a UN (UN-Habitat and WHO, 2021) report. The available JMP data is non-volumetric, population-based, and at the national level, although segregated into rural and urban residence types. The JMP data is also segregated according to facility type, service type, service level, and management element. However, the UN data is volumetric but only national level estimates. On the other hand, a study (Jones et al., 2021) used a data-driven model to aggregate, assess, and homogenise country-level WW data from electronic databases while using regression to predict unattainable data. Another study (Ijoma et al., 2022) estimated the generation of sludge from domestic WW using data on domestic freshwater withdrawal at the country level from the World Bank repository. Nevertheless, these studies arguably applied top-to-bottom approaches based on national-level data. The peculiarities and variations in different micro-locations (e.g., cities in the country), such as sanitation type, water accessibility per capita, and population, were not considered simultaneously.

Therefore, the objectives of the study are: (i) to estimate the volume of household WW generation and collection through sewer networks for different geo-political regions in Nigeria, (ii) to estimate the generation of Sewage Sludge (SWS)[24] for the regions, and (iii) to provide a holistic assessment of the technical and economic potential of two different WtE technologies (i.e., INC and AD) for electricity generation in the regions.

2. Methodology

2.1. Area under study and data collection

In this study, the energy generation potential of the produced SWS is determined using the most recent population statistics of the National Bureau of Statistics (NBS, 2023) and projected for 2022–2042 based on a growth rate and per capita access to water in the 36 states and the Federal Capital Territory (FCT)[25] of Nigeria. The growth rate per state and FCT is published by (NBS, 2023), while water accessibility (l/c/d) was obtained from the WASHNORM report (FMWR et al., 2022).

In theory, domestic WW contains WW from households and selected services (UN-Habitat and WHO, 2021). Like the UN report (UN-Habitat and WHO, 2021), the information and estimates in the present study cover only WW generated by households. Therefore, subsequent parts of this paper may mention household WW instead of domestic WW and vice versa. The WW generation was estimated as a percentage of the per capita water accessible at each location. The portion of WW collection

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[19] HHV - Higher Heating Value
[20] LHV - Lower Heating Value
[21] CHP - Combined Heat and Power
[22] WWTP - Wastewater Treatment Plant
[23] JMP - Joint Monitoring Programme
[24] SWS - Sewage Sludge
[25] FCT - Federal Capital Territory

was adapted as the percentage of coverage of the sewer network or households connected to a central sewer network at each location (FMWR et al., 2022). The model to estimate the amount of sewage sludge processed from AD and INC was adopted from previous studies (Nubi et al., 2022; Ogunjuyigbe et al., 2017). Nigeria comprises 36 states and the FCT, subdivided into six geo-political zones, as shown

in Fig. 1.

The North East (NE)[26] zone comprises Adamawa, Bauchi, Borno, Gombe, Taraba, and Yobe states. The North Central (NC)[27] zone contains Benue, Kogi, Kwara, Nasarawa, Niger, Plateau states, and FCT Abuja. The North West (NW)[28] zone includes Jigawa, Kaduna, Kano, Katsina, Kebbi, Sokoto, and Zamfara states. The South East (SE)[29] zone comprises Abia, Anambra, Ebonyi, Enugu, and Imo states. South South (SS)[30] includes Akwa Ibom, Bayelsa, Cross River, Delta, Edo, and Rivers states. Finally, the South West (SW)[31] zone comprises Ekiti, Lagos, Ogun, Ondo, Osun, and Oyo states.

2.1.1. Estimation of sewage sludge for potential energy generation

The WW generation is estimated to be 90 % of the water available to a person per day (V_{WA}) (Ijoma et al., 2022). V_{WA} in each state is obtained from the WASHNORM report (FMWR et al., 2022). The WW generation (litres) per capita per day can be calculated as:

$$V_{WG} = 0.9 \times V_{WA} \tag{1}$$

The total volume of WW (litres) generated per year is given as:

$$V_{WGT} = P \times V_{WG} \times 365 \tag{2}$$

$$P = P_0(1+r)^t \tag{3}$$

where P is the projected population of each location based on a growth rate, r; 365 = the number of days per year; P_0 denotes the 2006 census population, which serves as the base; t = the extrapolated time of interest.

The annual WW collection in litres is given as:

$$V_{WCT} = P \times V_{WG} \times WW_{CR} \times 365 \tag{4}$$

where WW_{CR} = wastewater collection rate, adapted from the percentage of households connected to a central sewer network (FMWR et al., 2022).

2.2. Energy recovery techniques for scenarios based on technology

2.2.1. Anaerobic digestion technology for energy recovery from sewage sludge

The theoretical potential volume (m^3/t) of biogas production from the AD of organic matter is determined using the Buswell equation (Amoo and Fagbenle, 2013; Ogunjuyigbe et al., 2017):

$$C_nH_aO_bN_c + (n - 0.25a - 0.5b + 0.75c)H_2O \rightarrow (0.5n - 0.125a + 0.25b + 0.375c)CO_2 + (0.5n + 0.125a - 0.25b - 0.375c)CH_4 + cNH_3 \tag{5}$$

The values of the variables n, a, b, and c are determined by normalised mole ratio (Ogunjuyigbe et al., 2017) given as:

$$Mole\ Ratio = \frac{K[C,H,O,N]}{M[C,H,O,N]} \tag{6}$$

where K is the elemental composition (C, H, O, N) derived from the ultimate analysis of sewage sludge (Singh et al., 2020); M = molar mass of the elements, C = 12.01 g, H = 1.01 g, O = 16 g, and N = 14.01 g (Nubi et al., 2022).

The mass of methane (t) produced from AD is given by:

$$M_{CH_4} = \frac{16 \times A}{(M_C \times n) + (M_H \times a) + (M_O \times b) + M_N} \times 1,000 \tag{7}$$

$$A = 0.5n + 0.125a - 0.25b - 0.375c \tag{8}$$

$$\text{The volume of methane } \left(\text{m}^3/\text{t}\right), V_{CH_4} = \frac{M_{CH_4}}{\rho_{CH_4}} \tag{9}$$

where ρ_{CH_4} = density of methane, taken as 0.717 kg/m^3 (Ogunjuyigbe et al., 2017).

The actual volume of methane produced during the AD process is less than the theoretical volume and is expressed as 85 % of the theoretical volume of methane. The actual volume of methane is taken as (Ogunjuyigbe et al., 2017):

$$V_{CH_4(Actual)} = \frac{V_{CH_4} \times 85}{100} \tag{10}$$

The electrical energy (kWh) from AD is given by:

$$E_{AD} = \frac{MSWS_{AD} \times V_{CH_4(Actual)} \times LHV_{CH_4} \times 0.85 \times \eta_{AD}}{3.6} \tag{11}$$

where $MSWS_{AD}$ is the mass of sewage sludge (in tonnes) for the AD process; LHV_{CH_4}= lower heating value of methane, 37.2 MJ/m^3 (Nubi et al., 2022); 0.85 is the capacity factor (Nubi et al., 2022); η_{AD} is the efficiency of the AD technology, 0.30 (Singh et al., 2020); 3.6 is the conversion factor from MJ to kWh.

$$MSWS_{AD} = \frac{V_{WCT} \times SWS_{CR} \times \rho_{SWS}}{1,000} \tag{12}$$

where SWS_{CR} = wastewater to sewage sludge conversion rate, 1 % (Ijoma et al., 2022); ρ_{SWS} = density of sewage sludge (wet basis), 1 kg/l (Ozcan et al., 2015); 1000 = conversion factor from kilogram to tonne.

The size of the generator based on the estimated electrical energy from AD is determined using:

$$P_{S(AD)} = \frac{E_{AD}}{8,760 \times CF}$$

where $P_{S(AD)}$ is the capacity (kW) of the plant; 8760 is the number of hours of plant operation per annum; CF is the capacity factor, 0.85 (Ogunjuyigbe et al., 2017).

2.2.2. Incineration technology for energy recovery from sewage sludge

The total energy (MJ) is calculated using Eq. (13):

$$TE_{INC} = LHV_{DSWS} \times MSWS_{INC} \tag{13}$$

where LHV_{DSWS} is the lower heating value of dried sewage sludge, 1100 MJ/t (Ozcan et al., 2015).

The total mass of dried sewage sludge (in tonnes) processed for INC is calculated as:

$$MSWS_{INC} = \frac{V_{WCT} \times SWS_{CR} \times DSWS_{CR} \times \rho_{SWS}}{1,000} \tag{14}$$

where $DSWS_{CR}$ = dried sewage sludge conversion rate, 4.2 % (Ozcan et al., 2015).

Electrical energy (kWh) from the INC technology is calculated as:

$$E_{INC} = \frac{TE_{INC} \times \eta_{INC}}{3.6} \tag{15}$$

where η_{INC} = electrical efficiency of the INC technology, taken as 20 %

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[26] North East
[27] North Central
[28] North West
[29] South East
[30] South South
[31] South West

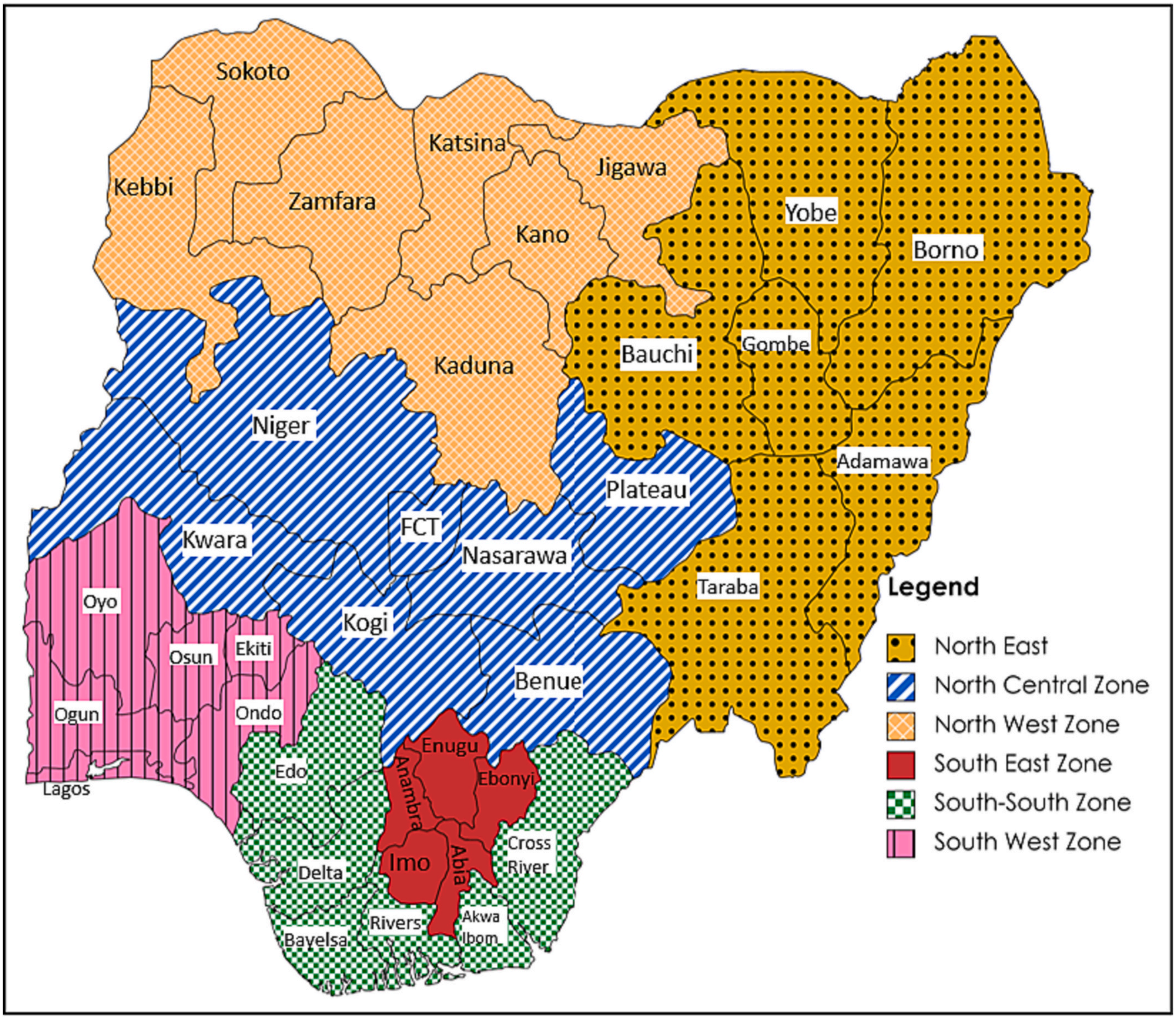

Fig. 1. The map of Nigeria showing the different zones and states under them.

Table 1
Indices used in the economic analysis of energy recovery technologies.

Indices	Project lifespan (N)	Inflation rate (e)	Nominal discount rate (d_n)	Sale price of electricity in Nigeria (F_d)
Value	20 years (Ogunjuyigbe et al., 2017)	21.34 % (CBN, 2022)	10 % (Ogunjuyigbe et al., 2017)	USD 0.1868/kWh (Ogunjuyigbe et al., 2017)

(Nubi et al., 2022); 3.6 is the conversion factor from MJ to kWh.

The size of the INC plant based on the estimated electrical energy from INC is determined using:

$$P_{S(INC)} = \frac{E_{INC}}{8,760 \times CF} \tag{16}$$

where $P_{S(INC)}$ is the capacity (kW) of the INC plant; 8760 is the number of hours of plant operation per annum; CF is the capacity factor, 0.85 (Ogunjuyigbe et al., 2017).

2.3. Economic analysis of energy recovery technologies

Understanding the economic viability of a project is crucial to make the best investment decision in any WtE initiative. Life cycle and economic parameters were used to evaluate and compare the economic viability and sustainability of the energy recovery options. The parameters applied in this study include Life Cycle Cost (LCC),[32] Net Present Value (NPV),[33] Levelized Cost of Energy (LCOE),[34] Pay Back Period (PBP),[35] Annualised Cost of System (ACS),[36] and Internal Rate of Return (IRR).[37] The metrics utilised in the economic assessment of the WtE technologies are shown in Table 1.

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[32] LCC - Life Cycle Cost
[33] NPV - Net Present Value
[34] LCOE - Levelized Cost of Energy
[35] PBP - Payback Period
[36] ACS - Annualised Cost of System
[37] IRR - Internal Rate of Return

2.3.1. Life Cycle Cost (LCC)

The LCC (in USD) is a crucial financial life cycle metric for an investment project. It is the sum of all expenses incurred throughout the ownership and operation of a project. According to the equation below, LCC is the total investment, Operation and Maintenance (O&M)[38] costs (Ogunjuyigbe et al., 2017).

$$LCC = C_{inv(i)} + \sum_{n=1}^{N} \frac{C_{O\&M(i)}}{(1+d_n)^n} \tag{17}$$

where $C_{inv(i)}$ is the initial cost of the investment (in USD); $C_{O\&M(i)}$ is the cost of O&M (in USD); d_n is the nominal discount rate (%); N is the project's lifespan in years.

2.3.2. Net Present Value (NPV)

The NPV (in USD) is the total present value of all the system's lifetime expenses minus the total current value of all its lifetime revenues. For economic viability, it must have a positive value. NPV is calculated as (Ogunjuyigbe et al., 2017):

$$NPV = \sum_{n=0}^{N} \frac{F_n}{(1+d_r)^n} = F_0 + \frac{F_1}{(1+d_r)^1} + \frac{F_2}{(1+d_r)^2} + \dots\dots\dots + \frac{F_N}{(1+d_r)^N} \tag{18}$$

where F_n is the net cash flow rate (USD); d_r is the annual real discount rate.

The yearly net cashflow for any energy recovery system is the difference between its cash inflow and cash outflow for each year, given by Eq. (19):

$$F_n = R_{(i)} - C_{inv(i)} - C_{O\&M(i)} \tag{19}$$

$$R_{(i)} = E_{(i)} \times F_d \tag{20}$$

$$d_r = \left(\frac{1+d_n}{1+e}\right) - 1 \tag{21}$$

where $R_{(i)}$ is the revenue accrued from the energy recovery project (in USD); $E_{(i)}$ stands for Total Electrical Energy from each technology (kWh); F_d is the sale price of electricity in Nigeria; *i* is the technology of interest, i.e., INC or AD; *e* is the inflation rate as defined by the Central Bank of Nigeria.

2.3.2.1. Anaerobic digestion technology.

The cost model (Hadidi and Omer, 2017) for $C_{inv(AD)}$ and $C_{O\&M(AD)}$ is presented as:

$$C_{inv(AD)} = C_{P_{(AD)}} \times P_{s_{AD}} \tag{22}$$

$$C_{O\&M(AD)} = 0.03C_{inv(AD)} + 0.005E_{AD} \tag{23}$$

where $C_{P_{(AD)}}$ is the value of the plant-specific cost for AD plants, taken as USD 4339/kW; the O&M cost is expressed as 3 % of the investment cost.

2.3.2.2. Incineration technology.

The cost model (Nubi et al., 2022) for $C_{inv(INC)}$ and $C_{O\&M(INC)}$ is given as:

$$C_{inv(INC)} = USD16,587 \times \left(P_{S(INC)}\right)^{0.82} \tag{24}$$

$$C_{O\&M(INC)} = 0.04 \times C_{inv(INC)} \tag{25}$$

2.3.3. Levelized Cost of Energy (LCOE)

The LCOE is the lowest cost at which a system may generate electricity and break even. It can be used to benchmark the economic viability of various technologies. The lowest selling price of the produced electricity is calculated from the LCOE in USD/kWh. Eq. (26) can be used to determine the LCOE for each technology (Ogunjuyigbe et al., 2017):

$$LCOE_{(i)} = \frac{LCC_{(i)}}{E_{p(i)}} \times CRF_{(i)} \tag{26}$$

$$CRF = \frac{d_n(1+d_n)^N}{(1+d_n)^N - 1} \tag{27}$$

where CRF is the capital recovery factor.

2.3.4. Annualised Cost of System (ACS)

The annualised cost of a project is the cost that results in the exact net present cost as the actual cash flow sequence associated with that project if it occurred evenly in every year of the project's existence. Expressed in USD/yr and calculated as (Heaps, 2022):

$$ACS = (CRF \times C_{inv}) + C_{O\&M} \tag{28}$$

2.3.5. Pay Back Period (PBP)

One of the criteria to take into account before starting a project is the PBP. It is the period (years) during which the costs of a project are recovered or when operating costs are equivalent to investment costs. It is calculated using (Nubi et al., 2022):

$$PBP_{(i)} = \frac{C_{inv(i)}(USD)}{Annual\ energy\ savings_{(i)}\ (USD/year)} \tag{29}$$

$$Annual\ energy\ savings_{(i)} = R_{(i)} - C_{O\&M_{(i)}} \tag{30}$$

2.3.6. Internal Rate of Return (IRR)

The discount rate that brings the NPV to zero is the IRR. It is approximately the maximum discount rate at which the project breaks even. The technology will be considered economically desirable only when the NPV exceeds zero and the IRR is at its highest possible level (Nubi et al., 2022).

$$\text{IRR } (\%) = \text{the value of } \mathrm{d_r} \text{ such that } NPV = \sum_{n=0}^{N} \frac{F_n}{(1+d_r)^n} \tag{31}$$

2.3.7. Sensitivity analysis

Sewage sludge generation: It is vital to analyse the effect of changes in the quantity of sludge on the economic indicators of energy recovery technologies. Therefore, the consequence of a percentage variation (±10 % and ±20 %) in sewage sludge processed by each technology is analysed. In essence, this analysis also indicates the effect of changes in WW generation and collection, since they are interconnected.

Nominal discount rate: Sensitivity analysis is required to determine the effect of variation in discount rates (±10 % and ±20 %) on cost indicators to accommodate different categories of investors.

Capital and O&M costs: This study examined the impact of a percentage shift (±10 % and ±20 %) in the capital and O&M costs on the overall economics of the technologies.

Electricity selling price: Therefore, an evaluation of the impact of a percentage shift (±10 % and ±20 %) in electricity prices on the LCC results was performed.

3. Results and discussion

3.1. Wastewater management, sludge generation and electrical energy potential

3.1.1. Water access, projected wastewater generation, and collection

All the zones fall under the basic access service level based on Table 2. According to the WHO, the level of water service is grouped into no, basic, intermediate and optimal access. The average quantity of

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[38] O&M - Operation and Maintenance

water for the levels ranges from <5, 20, 50, to 100 l/c/d,[39] respectively. At no access level, water for consumption is not guaranteed, and that for hygiene might be unlikely, resulting in a very high health concern.

Basic access covers water for consumption, handwashing, and primary food hygiene with high health concerns. In addition to the coverage of basic access, intermediate access covers laundry and bathing with low health concerns. The optimal level meets all consumption and hygiene needs with very low health concerns (Howard and Bartram, 2003). The Federal Capital Territory (FCT) has the highest water access of 15 l/c/d, followed by Yobe, Rivers, Ogun, Kaduna, and Jigawa with 14 l/c/d. At the same time, the least was found in Ebonyi, Ekiti, Kano, and Kebbi with 5 l/c/d (FMWR et al., 2022). Generally, the NC and SW zones have the highest (11.57 l/c/d) and least (8 l/c/d) water access, respectively, across the country.

The total volume of WW generation projected for a 20-year period across Nigeria is shown in Fig. 2. The results indicate that FCT has the highest WW generation, followed by Lagos and Kaduna states. This is attributed to these states being big states with high population and WW generation potential. These states have superior urbanisation and higher standards of living (Ogunjuyigbe et al., 2017). The indices signify that urban areas are critical contributors to WW generation in Nigeria.

In contrast, the lowest WW generation was found in Ebonyi, Ekiti and Cross River states, respectively. The disparity between the states with the highest and lowest WW generation potential is noteworthy. Moreover, a regional pattern indicated that Northern states such as Kaduna, Kano, and Jigawa have relatively higher WW generation potential than Southeastern states such as Abia, Enugu, and Ebonyi.

Like the scene in the states, the volume of zonal WW generation is estimated to grow with the projected population growth rate and per capita WW generation. At the zonal level (Fig. 3), NC is projected to have the highest WW generation with the potential of 142.8–403.6 billion litres/yr from 2022 to 2042, followed by NW (172.4–317.1 billion litres/yr). The SE and NE zones have the least potential for WW generation, with 80.5–145.1 and 98.9–190.4 billion litres/yr, respectively. In contrast, NW has the least WW collection potential ranging from 3.3 to 5.9 billion litres/yr from 2022 to 2042. Like the WW generation, NC has the highest WW collection potential with 8.3–37.5 billion litres/yr.

Although NW has higher WW generation, its WW collection is the least due to the poor coverage of the sewer network in the zone, which translates to a WW collection rate of 1.31 %, which implies approximately 0.15 l/c/d, as shown in Table 2 (FMWR et al., 2022). In fact, the states with the least collection of 0 % were Akwa-Ibom, Delta, Gombe, Kebbi, Ogun, and Zamfara. The maximum was 26.7 % in Rivers and 15.6 % each in FCT Abuja, Enugu and Imo (FMWR et al., 2022). On the other hand, the WW collection rate is highest in SE, then SS. Also, while WW generation potential peaks in the North and drops southward, WW collection climaxes down South compared to the Northern zones. Lastly, as with MSW, the projected WW generation is predicted to increase across zones due to economic and demographic growth (Nubi et al., 2022; Ogunjuyigbe et al., 2017). The estimations are based on the expectations that WW generation in NC, NE, NW, SE, SS, and SW will rise by 77.8, 47.5, 45.1, 45.4, 48.7, and 47.2 %, respectively, from 2022 to 2042.

3.1.2. Sludge generation and electrical energy potential

The quantity of sludge processed for energy generation for each technology is presented in Fig. 4. The potential energy generated from each technology is also shown in the different zones. Fig. 4 shows that NC and SS have a higher potential for electricity while NW has the least potential. This is also directly proportional to the quantity of sludge processed at these zones. Therefore, NC and SS have the most sludge processed for energy generation, while NW has the least.

The AD is the most technically feasible alternative across zones for electricity generation and is highest in NC, SS, and SE, with a potential of 6.8, 6.3, and 4.1 GWh/yr, respectively. The zones in the South demonstrated more electricity potential for AD technology compared to the northern part. Similarly, NC, SS, and SE showed higher potential for the INC scenario, while the lowest is observed in NW. The INC technology presents the lowest potential for energy generation in all zones in Nigeria. Ultimately, the electricity potential in the Southern region generally outweighs that from the Northern part for both AD and INC.

At the country level in the present study, the 20-year average WW generation is about 1,047,970,749.67 m^3/year, while 55,130,851.19 m^3/year is collected, resulting in a sludge generation of approximately 677,808.52 t/year wet basis. The resulting average electrical energy potential is 24.26 and 0.73 GWh/year for AD and INC technologies, respectively. However, the county-level estimates from Jones et al. (2021) showed WW generation (industrial and domestic) of 2289 million m^3/year, collection of 242.63 million m^3/year, and treatment of 77.71 million m^3/year. Similarly, the UN report (UN-Habitat and WHO, 2021) estimated about 2962.368 million m^3 as the total household WW generated in 2020. Approximately 648.76 million m^3 (21.9 %) of the total generation was attributed to the sewers, and 324.38 million m^3 (50%) of this volume was treated safely. In comparison, Ijoma et al. (2022) estimated that the 2017 domestic WW generation was 79.72 billion m^3, with a sludge generation of 7.97×10^{11} l and an electricity potential of 46,503 GWh. The estimates of the present study were lower than those of the other studies for WW generation and collection. At the same time, the UN estimates for WW generation and collection were higher; also, the sludge generation and electricity potential were higher in Ijoma et al. (2022) than in the current study. However, the present study focused only on sewer collection, which had a maximum of approximately 27 % in Rivers state (FMWR et al., 2022) and 9.08 % (see Table 2) in the SE zone. Therefore, the estimations in this study may even be higher than those of other studies (Ijoma et al., 2022; Jones et al., 2021), if all collection types were considered.

The discrepancies can be attributed to differences in data sources, spatial scales, and methodologies. Jones et al. (2021) centred on aggregating country-level data from electronic databases, while Ijoma et al. (2022) used country-level domestic freshwater withdrawal data from the World Bank repository. The present study, on the other hand, utilised state-level data from FMWR et al. (2022). Furthermore, the studies might differ in the period covered, with Jones et al. (2021) providing projections based on 2015 data, Ijoma et al. (2022) focusing on 2017, and the present study spanning 2022–2042. On the one hand, the current research seems to have a more thorough and robust approach than the other two studies. It considered state-specific data, including the peculiarities and variations in different states, such as type of sanitation, accessibility to water per capita, and population. This degree of granularity in data can provide more accurate and localised estimates as the unique characteristics of different cities within the country are accounted for. Furthermore, the 20-year period in the current study may capture seasonal, annual, and cyclic variations, delivering a more reliable estimate of overall trends. On the other hand, the previous studies used data that may not capture the spatial irregularity and heterogeneity within different states. Country-level data can provide a broader viewpoint but may not account for the variations in states, which can impact the precision of the estimations. Similarly, the UN estimates were two times more than those of the present study. These estimates were based on population, water supply, water consumption, and the water consumption to WW ratio. These factors were similar to those considered in this study. However, the numerical magnitude ascribed to these factors could not be determined. Like other studies, these estimates were also unavailable at sub-national (geo-political zones, states, etc.) levels. However, estimates from these studies (Ijoma et al., 2022; Jones et al., 2021), the UN (UN-Habitat and WHO, 2021), and the present study contribute valuable information on WW generation, collection, treatment, and sludge generation in Nigeria. The variation in findings and approaches emphasises the need for further

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[39] l/c/d - litres/capita/day

Table 2
Average values of parameters used to estimate wastewater and sludge generation in the zones.

Zone	Pop.[a]	Pop.[a] growth rate (%)	Water access (l/c/d)[b]	WW generation (l/c/d)[b]	WW collection rate (%)	WW collection (l/c/d)[b]
NC	60,914,167	3.91	11.57	10.41	4.43	0.53
NE	45,064,191	3.22	9.67	8.70	4.90	0.41
NW	81,762,275	3.07	9.14	8.23	1.31	0.15
SE	35,611,174	2.90	9.00	8.10	9.08	0.83
SS	48,662,316	3.08	10.50	9.45	6.12	0.70
SW	65,300,488	3.20	8.00	7.20	3.53	0.23

[a] Pop. – Population.
[b] l/c/d - litres/capita/day.

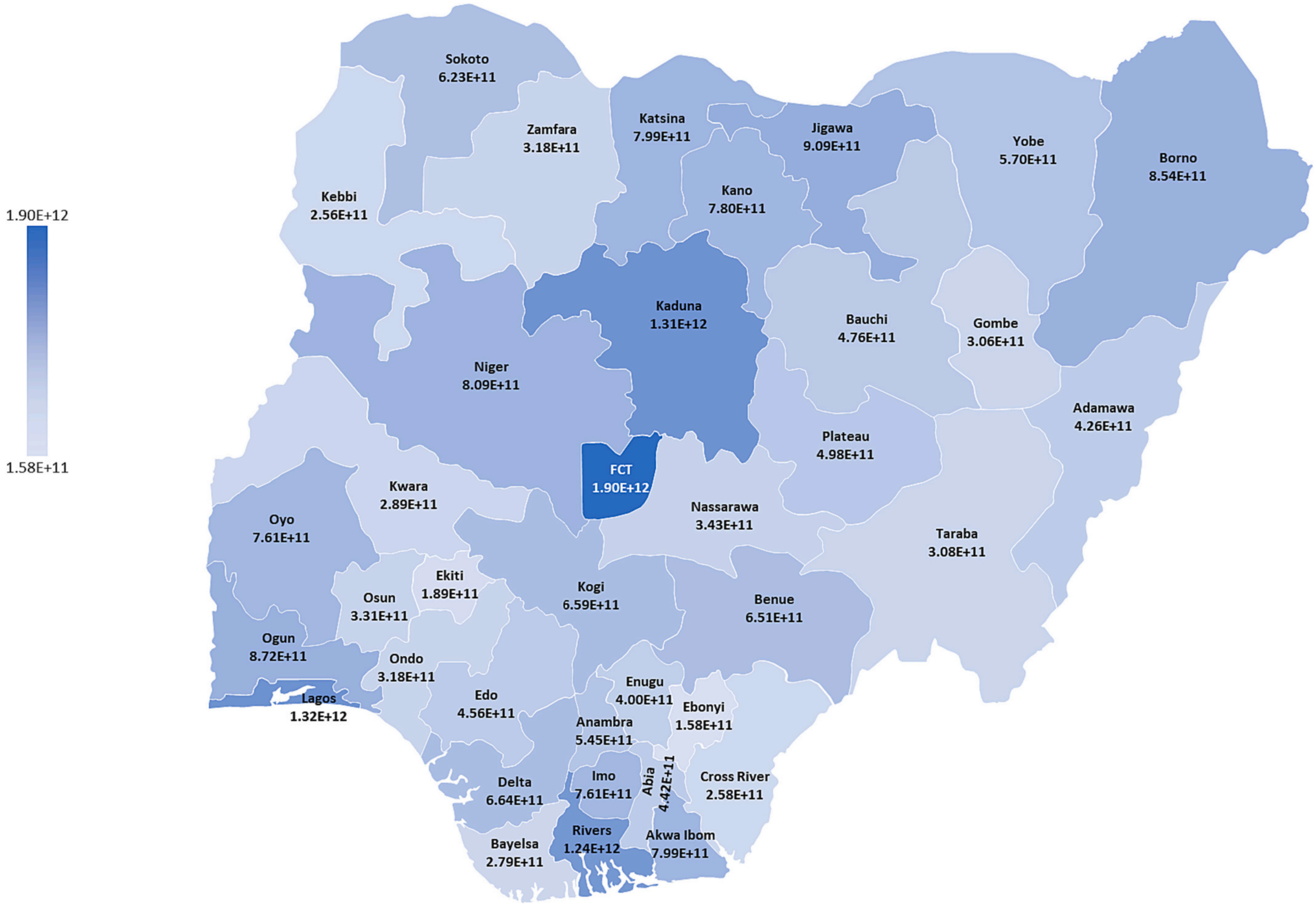

Fig. 2. Estimated 20-year total wastewater generation (litres) distribution across the 36 states in Nigeria (from 2022 to 2042).

research and standardisation of data collection and reporting methods in Nigeria.

As demonstrated in the present study, the higher potential for AD energy generation is consistent with the findings of Ogunjuyigbe et al. (2017) to the extent that AD is the superior technology in Southern Nigeria, attributed to a higher fraction of the putrefiable waste stream. While in the present study, it can be attributed to a higher sewer collection rate. On the contrary, INC showed more energy potential in certain Nigerian cities for MSW (Ogunjuyigbe et al., 2017) and in India (Singh et al., 2020), Colombia (Alzate-Arias et al., 2018), and Turkey (Ozcan et al., 2015) for SWS.

3.2. Economic feasibility of energy recovery technologies

The economic feasibility of the WtE technologies in the various zones was evaluated based on six indicators (NPV, LCC, LCOE, IRR, PBP, and ACS) shown in Table 3. The shading in the cells demonstrates how the rows compare per indicator. The light and dark shades indicated the lowest and highest values, respectively, as shown at the base of the table. The capital cost, O&M cost, and revenue aspects are also presented in Fig. 5. At a glance, INC showed better outcomes in four of the six economic indicators in Table 3. The INC has higher IRR and lower LCC, LCOE, and ACS. While AD is associated with higher values of NPV and lower PBP.

The AD technology presents the highest NPV ranging from 16.3 million USD in NW to 69.58 million USD in NC. It also has the shortest PBP of about four years across all zones. On the one hand, this makes AD financially attractive. On the other hand, AD has the highest values of LCC, ranging from 1.24 million USD in NW to 5.3 million USD in NC, the highest LCOE of USD 0.28/kWh across all zones, and the highest ACS ranging from USD 145,738.24/yr in NW to USD 622,087.43/yr in NC with lowest values of IRR of 9.09 % across all zones. Hence, higher costs

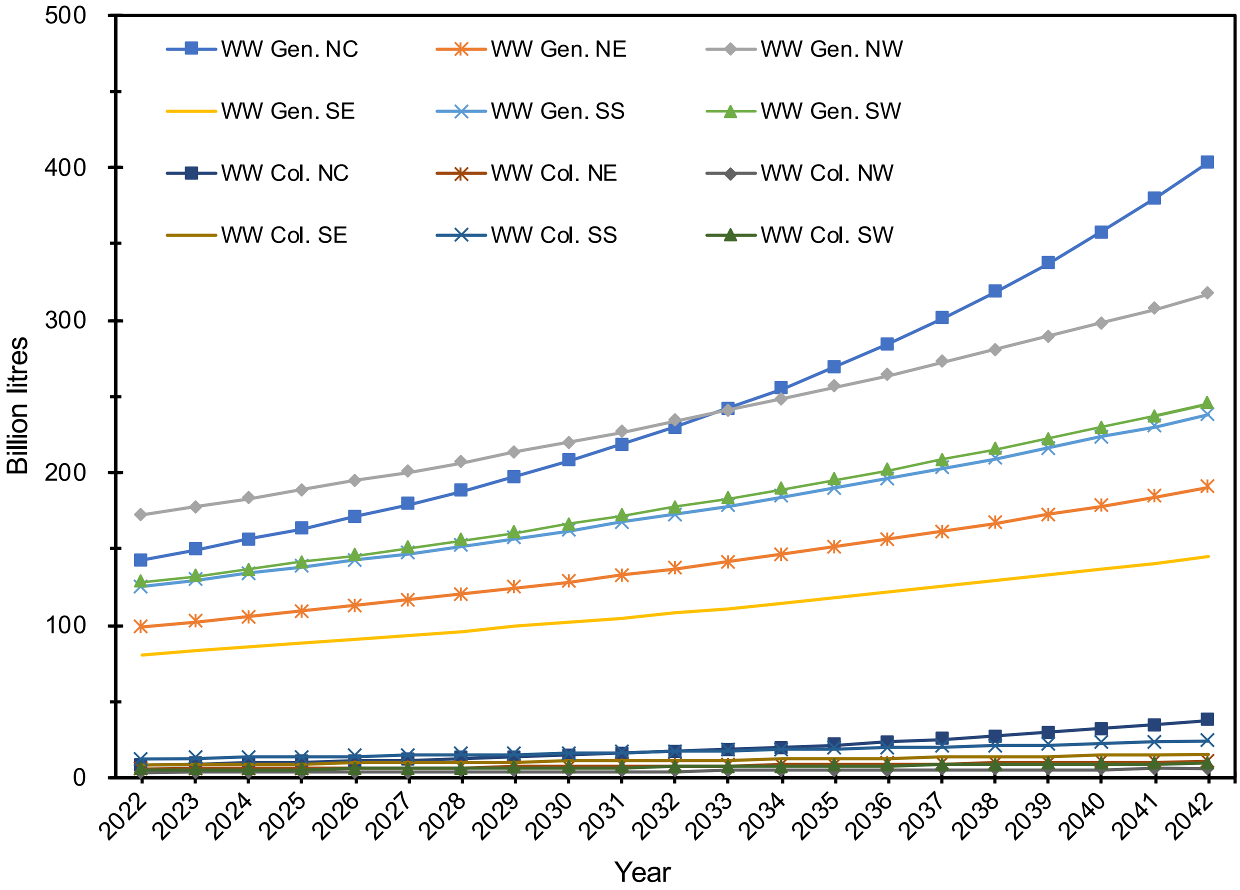

Fig. 3. Comparison of projected wastewater generation and collection across the different zones in Nigeria from 2022 to 2042. (WW Gen. - wastewater generation[a]; WW Col.- wastewater collection[b]).
[a]WW Gen. - Wastewater Generation.
[b]WW Col. - Wastewater Collection.

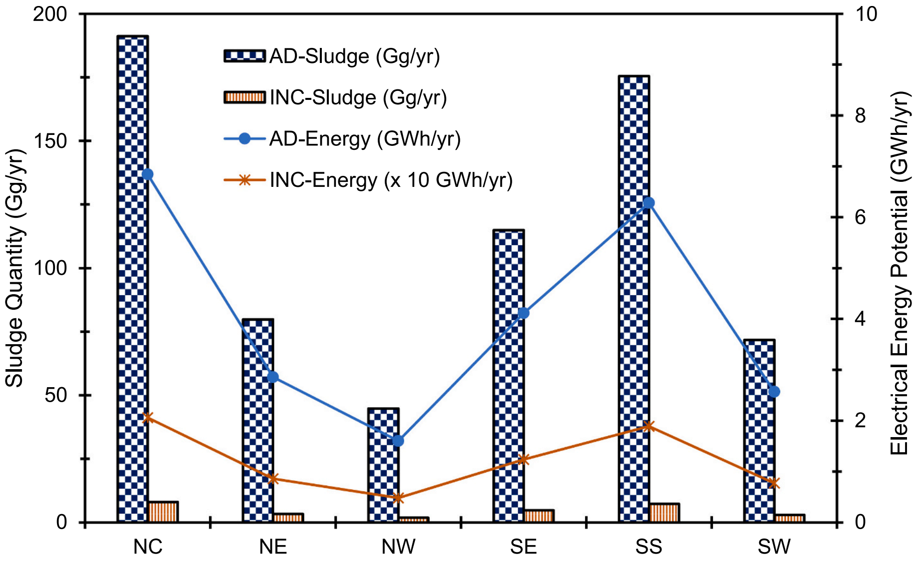

Fig. 4. Projected 20-year average of sludge generation and electrical energy generation for AD and INC technology across various zones in Nigeria.

and lower returns reduce AD's attractiveness and make it less competitive.

Whereas for INC technology, it shows the lowest NPV from 0.31 to 1.61 million USD from NW to NC and the longest PBP, 8.89–12.92 years from NC to NW. This indicates reduced profitability and extended time to recoup investments. However, this is curtailed by the associated lower costs, as shown in Fig. 5. The INC has the lowest values of LCC, ranging from 0.1 million USD in NW to 0.34 million USD in NC, lowest LCOE of USD 0.046–0.094/kWh from NW to NC, and lowest ACS ranging from USD 12,092.87/yr in NW to USD 39,751.85/yr in NC.

Table 3
Economic feasibility of AD and INC technology for electricity production from the various zones in Nigeria projected over a 20-year period (2022–2042).

Zone	Tech.*	NPV (USD)	LCC (USD)	LCOE (USD/kWh)	IRR (%)	PBP (years)	ACS (USD/yr)
NC	AD	69,580,016.62	5,296,180.99	0.280	9.09	3.55	622,087.43
	INC	1,605,093.58	338,429.90	0.094	19.30	8.89	39,751.85
NE	AD	29,056,566.15	2,211,681.47	0.280	9.09	3.55	259,783.28
	INC	605,369.87	165,383.33	0.064	22.58	11.08	19,425.86
NW	AD	16,300,713.22	1,240,751.75	0.280	9.09	3.55	145,738.24
	INC	312,157.60	102,953.43	0.046	25.06	12.92	12,092.87
SE	AD	41,838,027.26	3,184,560.38	0.280	9.09	3.55	374,057.27
	INC	912,477.40	223,007.67	0.076	21.15	10.09	26,194.40
SS	AD	63,876,518.26	4,862,051.17	0.280	9.09	3.55	571,094.71
	INC	1,460,516.29	315,508.62	0.091	19.59	9.08	37,059.52
SW	AD	26,128,934.03	1,988,840.62	0.280	9.09	3.55	233,608.47
	INC	536,629.15	151,590.23	0.061	23.02	11.39	17,805.73
░	░	Lowest			▓	▓	Highest

*Tech. - Technology.

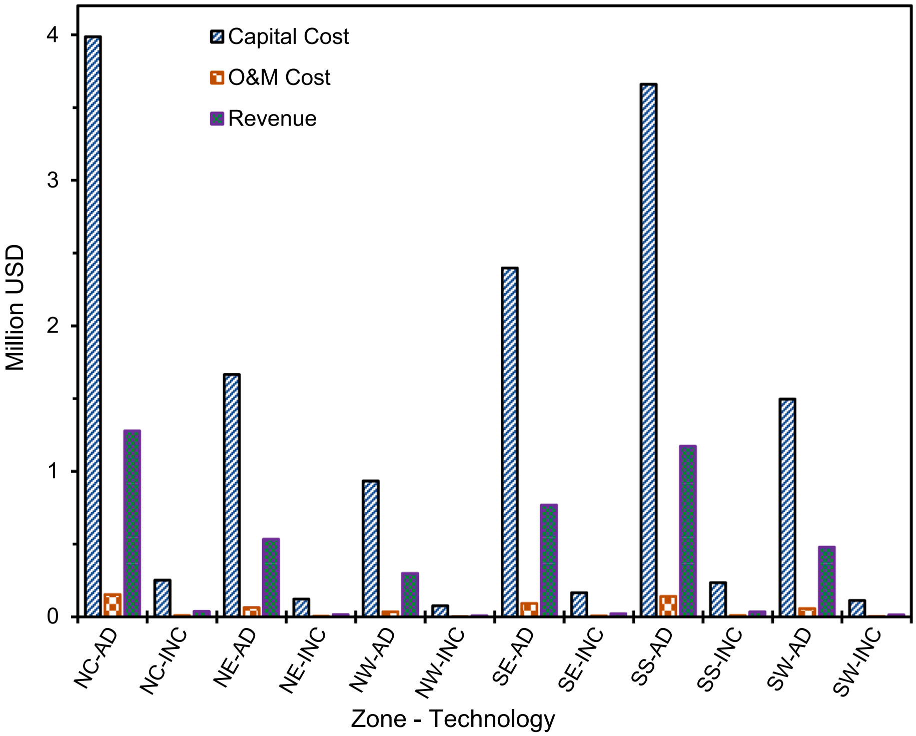

Fig. 5. Capital cost, O&M cost, and revenue of AD and INC technology for electricity production from the various zones in Nigeria projected over a 20-year period between 2022 and 2042.

3.2.1. *Zone-wise analysis*

In the North, the economic analysis showed that in the NC zone, AD technology has a higher NPV of 69.58 compared to INC technology, with an NPV of 1.61 million USD. The AD also has a higher LCC of 5.3 million USD compared to 0.34 million USD for INC. The LCOE for AD is USD 0.280/kWh, while for INC, it is USD 0.094/kWh. The IRR for AD is 9.09

% compared to 19.30 % for INC. The PBP for AD is around 4 years, and 9 years for INC. The ACS for AD is 0.62 million USD/yr, while for INC, it is 0.04 million USD/yr. Similarly, in the NE zone, AD has a higher NPV of 29.06 million USD, compared to 0.61 million USD for INC. The LCOE for AD is USD 0.280/kWh, while that of INC is USD 0.064/kWh. AD has a higher LCC of 2.21 million USD than INC, with an LCC of 0.17 million USD. The IRR for AD is 9.09 %, while that of INC is 22.58 %. The PBP for AD is 3.55 years, compared to 11.08 years for INC. The ACS for AD is 0.26 million USD/yr, while that of INC is 0.02 million USD/yr. Similarly, for the NW zone, AD has an NPV of 16.3 million USD, while INC has an NPV of 0.31 million USD. AD has a higher LCC of 1.24 million USD than INC, with an LCC of 0.1 million USD. The LCOE for AD is USD 0.28/kWh, compared to USD 0.046/kWh for INC. The IRR for AD is 9.09 %, while that of INC is 25.06 %. The PBP for AD is 3.55 years, while that of INC is 12.92 years. The ACS for AD is USD 145,738.24/yr, while that of INC is USD 12,092.87/yr. Therefore, INC technology demonstrates more economic practicality in the North than AD technology. AD has a higher NPV and a shorter PBP than INC, indicating higher profitability and faster cost recovery. However, the LCC, LCOE, and ACS for AD are also higher than INC, meaning a higher startup capital and cost of electricity generation. Likewise, IRR for AD is lower than INC, thus diminishing the economic feasibility of AD against INC.

In the South, the economic analysis shows that in the SE zone, AD technology has a higher NPV of 41.84 compared to INC technology, with an NPV of 0.91 million USD. AD also has a higher LCC of 3.18 million USD compared to 0.22 million USD for INC. The LCOE for AD is USD 0.28/kWh, while for INC, it is USD 0.076/kWh. The IRR for AD is 9.09 % compared to 21.15 % for INC. The PBP for AD is around 4 years, and just over 10 years for INC. The ACS for AD is 0.37 million USD/yr, while for INC, it is 0.03 million USD/yr. Similarly, in the SS zone, AD has a higher NPV of 63.88 million USD, compared to 1.46 million USD for INC. AD also has a higher LCC of 4.86 million USD than INC, with an LCC of 0.32 million USD. The LCOE for AD is USD 0.28/kWh, while that of INC is USD 0.091/kWh. The IRR for AD is 9.09 %, while that of INC is 19.59 %. The PBP for AD is 3.55 years, compared to 9.08 years for INC. The ACS for AD is 0.57 million USD/yr, while that of INC is 0.04 million USD/yr. Likewise, AD has an NPV of 26.13 million USD for the SW zone, while INC has an NPV of 0.54 million USD. AD also has a higher LCC of 2 million USD than INC, with an LCC of 0.15 million USD. The LCOE for AD is USD 0.28/kWh, compared to USD 0.078/kWh for INC. The IRR for AD is 9.09 %, while that of INC is 20.43 %. The PBP for AD is 3.55 years, while that of INC is 8.45 years. The ACS for AD is USD 308,833.18, while for INC, it is USD 23,573.87. Consequently, INC technology demonstrates more economic viability in the South than AD technology. AD has a higher NPV, and a shorter PBP than INC, indicating higher profitability and faster cost recovery. However, the LCC, LCOE, and ACS for AD are also higher than INC, meaning a more increased initial investment and higher cost of electricity generation. Similarly, the IRR for AD is lower than that of INC, implying a lower return on investment.

3.2.2. Economic inferences

The NPV is an indicator of the profitability of investment with time. Analysis in the present study showed that the NPV of AD technology is higher than that of INC technology for all zones in Nigeria. This implies that AD technology can be more economically viable and profitable long-term than INC technology. The total cost of the AD project, including capital costs, O&M costs, over its entire life cycle is higher than that of INC technology for all zones. This suggests that AD technology requires more initial investment than INC technology, which may be attributed to its more complex and sophisticated system design for the AD of waste. However, it is essential to note that AD technology generates higher revenue (see Fig. 5) from electricity sales, compensating for its higher LCC. This is reflected in its higher NPV, indicating that AD technology can yield higher financial returns despite its higher LCC.

The cost of producing a unit kWh of electricity is more expensive for AD and cheaper for INC technology for all zones. However, both technologies have similar electricity production costs. This observation suggests that the electricity production cost is an unlikely decisive factor in the choice between AD and INC technologies in Nigeria. The rate of recouping the investment in INC technology is higher than that of AD technology for all zones in Nigeria. Investors seeking high financial returns may be more swayed by the INC technology. The superior IRR of INC technology aligns with its lower initial investment and O&M costs than AD technology, reflecting its lower LCC and ACS. Furthermore, <10 % IRR indicates financial infeasibility (Abdallah et al., 2018). Thus, AD technology across all zones fell below 10 %, while the values for INC exceeded this benchmark. Therefore, investors seeking higher returns in the short term may be interested. The INC project may take longer than AD technology to pay for itself. In addition, it falls short of the seven-year PBP threshold for an economically feasible WtE project (Mabalane et al., 2021; Nubi et al., 2022). Although AD technology has a higher initial investment, it generates more revenue from electricity sales coupled with a shorter PBP. Nevertheless, the decision power of PBP is limited, as it fails to consider the time value of money, thus a less comprehensive measure of profitability or attractiveness. As mentioned above, the INC technology in the present study rates better than AD in four (LCC, LCOE, IRR, and ACS) out of six economic indicators. However, the two indicators (NPV, PBP) where AD rates better than INC are arguably important. Similarly, in a study in Colombia, although AD had a more expensive LCOE, it was the preferred option due to the higher IRR. AD was also preferred for the WtE system using MSW based on better NPV, LCOE, and PBP (Ogunjuyigbe et al., 2017). On the contrary, INC was more economically feasible for the generation of energy from MSW in Nigeria (Nubi et al., 2022) with lower LCC, LCOE, and higher IRR. However, AD had higher NPV and shorter PBP. A feasibility study in the United Arab Emirates (UAE) determined that INC is more financially feasible than AD as INC had a better IRR, a lower Profitability Index (PI)[40], and a lower LCOE (Abdallah et al., 2018). Similarly, INC was chosen over AD in Oman based on higher NPV and lower LCOE. However, AD had favourable PI, PBP, and IRR (Abushammala and Qazi, 2021).

Therefore, the selection between AD and INC technologies should reflect the fiscal goal and priorities of the project. Suppose that the focus is on shorter PBP and faster recovery of the initial investment. In that case, AD technology may be preferred due to its relatively shorter PBP compared to INC technology. However, INC technology may be more viable if the project has a longer-term perspective emphasising lower initial capital costs.

3.3. Sensitivity analysis

The outcomes of the sensitivity analyses are presented in Figs. S1–S10 (in the Supplementary information).

The NPV, LCC, and ACS show direct proportionality to SWS production changes for the AD technology, as illustrated in Fig. S1. A 20 % decrease in SWS production resulted in a 20 % decrease in NPV, while a 20 % increase in SWS production led to a 20 % increase in the three parameters. In all zones, a change in SWS production resulted in a change of equal magnitude in NPV, LCC, and ACS. Thus, NPV, LCC, and ACS show a moderate sensitivity to changes in SWS production. Fig. S1 also depicts the insensitivity of IRR, LCOE, and PBP to changes in SWS production in all zones. NPV, LCC, IRR, and ACS show a directly proportional relationship to changes in SWS production for INC technology. A 20 % decrease in SWS production led to a 21.87–22.9 % decrease in NPV, while a 20 % increase in SWS production led to a 22.2–23.45 % increase in NPV, as presented in Fig. S2. For IRR, it was 8.21–15.34 % and 6.83–12.65 %. The resulting changes in ACS are relatively constant (e.g., 16.72 for a 20 % decrease in SWS production). It is also fairly

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[40] PI - Profitability Index

constant (e.g., 4.1 and 5.6 %, respectively, for a 20 % decrease in SWS production) but inversely proportional for LCOE and PBP. In all zones, a change in SWS production resulted in a slightly higher magnitude in NPV and less in LCOE, PBP, IRR, LCC, and ACS, respectively. Thus, NPV, LCC, and ACS show a moderate sensitivity to changes in SWS production and low sensitivity for IRR, PBP, and LCOE. Therefore, NPV, LCC, and ACS are sensitive, while IRR, LCOE, and PBP are insensitive to changes in SWS production for AD technology. On the contrary, NPV is more susceptible to changes in SWS production for INC technology than LCC, ACS, and IRR, respectively, while LCOE and PBP are marginally insensitive.

The impact of changes in the nominal discount rate on the economic feasibility of AD and INC technologies is shown in Figs. S3 and S4, respectively. For both AD and INC technologies, the resultant changes in NPV and LCC are inversely proportional to changes in the nominal discount rate. However, the magnitudes are high and low for NPV and LCC, respectively. Whereas LCOE shows a directly proportional relationship, the resulting magnitude is two times less than the causal. On the other hand, IRR, PBP, and ACS remained unchanged despite changes in nominal discount. Therefore, NPV is more sensitive to changes in nominal discount than LCC and LCOE; while IRR, PBP, and ACS are unaffected for both technologies. But INC showed more sensitivity compared to AD technology.

The effect of fluctuations in capital cost on the economic feasibility of AD and INC technologies are shown in Figs. S5 and S6, respectively. For AD technology, IRR, LCOE, and PBP remained unaffected regardless of variations in capital cost. However, NPV, LCC, and ACS show a positive linear relationship in magnitude and direction to the changes in capital cost. All six parameters were affected by changes in capital cost for INC technology, as represented in Fig. S6. However, the average magnitude was highest for NPV, similar for LCC and ACS compared to PBP and LCOE. Additionally, regardless of the direction of change in capital cost, NPV, LCC, IRR, and ACS decreased while LCOE and PBP increased. Therefore, NPV, LCC, and ACS are sensitive to changes in capital cost, while IRR, LCOE, and PBP are unchanged for AD. In comparison, NPV was very sensitive to changes in capital cost for INC, followed by LCC, ACS, IRR, and LCOE, while PBP was the least.

The effect of variations in O&M cost on the economic feasibility of AD and INC technologies are illustrated in Figs. S7 and S8, respectively. For AD technology in Fig. S7, the resulting changes in IRR, LCOE, and PBP are negligible. However, NPV, LCC, and ACS showed a positive linear relationship in magnitude and direction to the changes in capital cost. Like the case of capital cost, all six parameters were altered by changes in O&M cost for INC technology, as represented in Fig. S8. However, the resultant changes were directly proportional for NPV, LCC, IRR, and ACS but inversely proportional for LCOE and PBP. In addition, the average magnitude was highest for NPV, similar for LCC and ACS compared to PBP and LCOE. Altogether, NPV, LCC, and ACS are sensitive to changes in O&M cost, while IRR, LCOE, and PBP are unchanged for AD technology. Moreover, NPV was very sensitive to changes in O&M cost for INC, followed by LCC, ACS, IRR, and LCOE, while PBP was the least. All parameters were generally affected more by changes in the capital than O&M cost.

The influence of variations in the selling price of electricity on the economic feasibility of AD and INC technologies are displayed in Figs. S9 and S10, respectively. The LCC, LCOE, and ACS are unaffected by changes in electricity selling prices for both technologies. For AD technology, NPV and IRR show a positive linear relationship in magnitude and direction to the changes in electricity tariff. But PBP shows a negative linear relationship. Also, the average magnitude was highest for PBP and similar for NPV and IRR, respectively. However, NPV and IRR show a positive linear relationship in magnitude and direction for INC technology, as represented in Fig. S10. But PBP shows a negative linear relationship. Also, the average magnitude was highest for IRR than PBP and NPV, respectively. Overall, PBP, NPV, and IRR are sensitive in that order to changes in electricity selling price for AD. The order for INC is IRR, PBP, and NPV. However, both technologies do not influence LCC, LCOE, and ACS.

Ultimately, among the economic viability indicators, NPV demonstrated the most sensitivity to changes in SWS production, nominal discount, costs, and electricity selling price. Similarly, INC proved to be more sensitive among the two technologies. The NPV, LCC, and ACS are sensitive to changes in SWS production, while LCOE and PBP are relatively insensitive for both technologies. Changes in the nominal discount rate significantly impact NPV for both technologies, with INC technology being more sensitive. Capital costs have a notable influence on the indicators compared to O&M costs, with NPV being particularly sensitive to changes in capital costs for INC technology.

Regarding electricity selling prices for both technologies, PBP, NPV, and IRR are sensitive, while LCC, LCOE, and ACS are generally unaffected. The outcome of the sensitivity analysis is consistent with the study in the UAE,[41] where the capital, O&M cost, and the electricity tariff had a low impact on the NPV of AD but a high impact on INC (Abdallah et al., 2018). A study in South Africa concluded that discount rate, capital cost, and energy price have a high effect on the NPV of AD (Mabalane et al., 2021). The sensitivity analysis implies that WtE systems will be more economical if more SWS is generated and measures are put in place to limit the costs as much as possible. At the same time, the electricity tariff does not drop below the current price.

3.4. General implications and limitations

There may be uncertainties or limitations in the analysis presented in the context of the study or discussion. Certain assumptions were made during the investigation, which could be scrutinised. These assumptions may affect the accuracy, reliability, or generalizability of the findings or conclusions drawn from this study.

Firstly, it is assumed that the households sampled in the base data (FMWR et al., 2022) represent Nigeria's total population. Wastewater generation is taken as 90 % of water use, but other studies were established at 80–90 % (Ijoma et al., 2022; Ozcan et al., 2015). Water accessibility, collection rate, population growth rate, capital cost, and O&M cost remained constant over the 20-year period. Additionally, variabilities in investment cost and O&M cost can impact the general economics of WtE technologies. Other expenses such as labour, taxes, and transportation were assumed equal in both scenarios and, therefore, ignored.

In addition, the sludge used in AD is not dewatered, while the sludge used in INC is dewatered and dried. However, the energy used in the dewatering and drying was not considered in the study: which would impact the net energy production. The average values for the LHV of sludge and methane were adopted from sources in the literature. At the same time, a more robust study will involve a proximate and ultimate analysis of the sludge samples from the locations.

Furthermore, the technologies were compared in a mutually exclusive scenario. The comparison assumed that only one technology at a time was used without considering the possibility of using both technologies simultaneously. Therefore, future studies can explore any potential synergy between both and other WtE systems, as well as the co-processing of SWS with MSW. The co-digestion and co-firing of SWS with MSW or agricultural waste materials can enhance the overall organic content thus improving biogas production and combustion in AD and INC, respectively. Other aspects that can be explored in future to tackle the challenges of low heating value and high moisture content of SWS include optimised dewatering using centrifugation, belt press or thermal drying. These processes enhance the organic content of SWS and decrease the moisture content. Process optimization of the AD and INC technologies should also be considered.

Moreover, value recovery from co-products of WtE systems can be an

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[41] UAE - United Arab Emirates

essential aspect of the overall economic feasibility and sustainability of such systems. For instance, recyclable materials recovered from waste streams can be sold or reused, generating additional revenue or reducing waste disposal costs. Digestates from AD can be used as fertilisers in agriculture, potentially providing a valuable source of nutrients for crop growth. Disregarding the possible value recovery opportunities in the economic analysis of WtE systems may result in an incomplete assessment of their overall economic viability and sustainability. Therefore, including a comprehensive analysis of value recovery from co-products in the future could offer a more holistic evaluation of the economic feasibility of WtE systems. Additionally, this analysis focused solely on economic and technical considerations without considering the potential environmental impacts, social implications, or sustainability aspects of the WtE technologies. Environmental pollution, resource depletion, social equity, community impacts, and other social and environmental factors can be contemplated in future studies.

Finally, government support and policy implementation influence the successful performance of WtE projects. Clear legislation and policy enforcement strategies are needed to create an environment that encourages local and foreign investors to participate in AD and INC projects. Financial institutions should be strengthened, and adequate incentives such as subsidies and carbon credits should be provided to attract private sector investments. Integrating WtE systems into existing policies, such as the REMP and the National Environmental Sanitation Policy (NESP), can further support their implementation while increasing energy access. For example, these WtE technologies can contribute to the achievement of SDGs such as clean energy, economic growth, responsible consumption and production, and sustainable cities and communities. But it should be acknowledged that the implementation of WtE policies in Nigeria is still developing and encounters poor implementation challenges. However, informed decision-making through economic analysis and the integration of appropriate sustainable WtE technologies, as part of an integrated MSW management strategy, can support the achievement of the environmental, social, and economic goals outlined in various SDGs.

4. Conclusion

Estimated potential generation of wastewater and sewage sludge was carried out in various zones of Nigeria. The electrical energy potential and economic viability of WtE technologies (AD and INC) were examined. It was revealed in the study that the zones in the North had the highest potential for WW generation, but the southern parts were superior in terms of sewer collection rate. Consequently, the North Central zone is predicted to have the highest wastewater generation and collection potential of 142.8–403.6 and 8.3–37.5 billion litres/yr from 2022 to 2042. The zones with the least wastewater generation and collection potential were South East (80.5–145.1 billion litres/yr) and North West (3.3–5.9 billion litres/yr), respectively. However, the estimates obtained at the national level were less than the UN estimates.

Furthermore, there was a positive linear relationship between sludge generation and electricity potential; AD presented the best technological option, while the North Central zone had the highest generation potential of 6.8 GWh/yr. Finally, in terms of economic feasibility, INC technology showed more feasibility than AD. INC had lower LCC, LCOE, and ACS values and a higher IRR. Still, AD had a competitively higher NPV and shorter PBP. Based on the sensitivity analysis results, the NPV is very sensitive to changes in cost, discount rate, and electricity tariff, especially for INC technology.

CRediT authorship contribution statement

Charles Amarachi Ogbu: Conceptualisation, Methodology, Writing-original draft, Writing - review & editing, Data curation, Statistical analysis. **Tatiana Alexiou Ivanova**: Conceptualisation, Methodology, Resources, Supervision, Funding acquisition, Writing - review & editing. **Temitayo Abayomi Ewemoje**: Methodology, Supervision, Writing - review & editing. **Chinedu Osita Okolie**: Statistical analysis, Writing – review & editing. **Hynek Roubík**: Conceptualisation, Methodology, Resources, Supervision, Funding acquisition, Writing - review & editing.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.166554.

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