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Design and Techno-economic Analysis of Ammonia Production from Human Waste via Anaerobic Digestion

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ABSTRACT: The increasing concern on climate change has prompted scientists across the world to find new sources of renewable and sustainable energy to reduce the over 75% of global energy dependence on fossil fuels. Improper disposal and treatment of human waste threaten the environmental and public health, and it requires immediate treatment of which anaerobic digestion comes as a rescue for effective and sustainable waste treatment technology. Hence, the objective of this work was to design and evaluate the techno-economic analysis of ammonia production from human waste (HW) via anaerobic digestion (AD) through two process schemes using Aspen Plus process simulator. The models were validated using an existing data, with 4.48 and 4.33% percentage error for the anaerobic digestion (new developed model) and anaerobic digestion with carbon capture and reuse (existing model) respectively. The sensitivity analysis showed that the AD reactors produced the best ammonia outputs at 60°C and 1 atm of 0.172 and 0.0189 kg/h respectively. The highest amount of ammonia for process schemes 1 and 2 is 0.0905 kg/h and 1.2792 kg/h for 10 L/day of organic loading rate (OLR), respectively. The organic loading rate rose as ammonia yield increased. For process scenarios 1 and 2, the best amounts are 0.1423 and 0.001609 kg/h for hydraulic retention durations of 1 and 10 days. Additionally, the net present value (NPV) values of $128,825.54 and $291,876.33, the internal rate of return (IRR) of 17 and 12%, and the payout periods of 6 and 7 years show that both schemes are promising in terms of payout period, although scheme 2 has a higher NPV than scheme 1 and a higher internal rate of return than scheme 1.

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The demand for affordable and clean energy needed to reduce the release of harmful element into the environment has led to the continuous search for sustainable and renewable energy generation options (Ekamba *et al.,* 2023). The use of fossil energy stored over hundreds of millions of years in a few hundred years (Zhao *et al.,* 2020) leads to environmental hazards like the emissions of greenhouse gases (GHG), whose principal gas is carbon dioxide thus contributing to the degree in global warming (Adjama *et al.,* 2022). The future energy system is expected to be able to facilitate the optimum utilization of local energy resources (especially renewable energy) towards a sustainable economy (Aziz *et al.,* 2020). Waste is one of the most promising options for the production of biofuel which act as an alternative source of energy for the sole purpose of augmenting or reducing the dependency on fossil fuel and also to improve the quality of human life (Elalami *et al.,* 2020). This would also help in the stabilization of wastes which is becoming a nuisance to communities. Human waste generation is significantly increasing in the urban areas of Nigeria and have started creating enormous waste disposal problems in the recent past

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(Adjama *et al.,* 2022). It is estimated that approximately 127 kg of HW is generated per person each year (Duan *et al.*, 2020), while the total amount is around 7.6 hundred million tons. HW may constitute a public health risk, especially in Nigeria with inefficient centralized treatment facilities or inadequate decentralized technologies, unlike some developing countries. Hence, having considered the environmental threat and potential health risks, imperative need for suitable treatment and subsequence reuse of HW is figured. HW is rich in high strength organic matter and nutrients thus, it has been considered as a renewable feedstock for different purposes (Duan *et al.*, 2020). For example, HW can be utilized to produce biofuels like methane, bioethanol, biodiesel through various processes, including pyrolysis, anaerobic digestion (AD), hydrothermal liquefaction and others (Adjama *et al.*, 2022). Anaerobic digestion (AD) is one of the unique and well-organized worldwide technology used to treat organic waste streams to generate a renewable energy in the form of biogas (Astals *et al.*, 2015 and Barahmand, 2022). AD is an integrated biochemical process that is operated in four major steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis (Singh *et al.*, 2012) and it is classified into AD with inoculum and AD without inoculum (Abdulkarim *et al.,* 2019). A mixed-culture bacterial community facilitates hydrolysis, acidogenesis and acetogenesis, whereas archaea convert the metabolic products of the previous reactions into methane and ammonia (Astals *et al.,* 2015). Ammonia production from HW which is abundant and nitrogen-rich using anaerobic digestion process, can be carried out at normal temperatures and pressures. The cleavage of the nitrogen–nitrogen triple bond consumes maximum energy in the Haber–Bosch process, on the contrary, nitrogen is already fixed in biomass and organic materials, so ammonia can be easily produced by bacterial destructive metabolism (Adjama *et al.,* 2022). Aspen Plus is an integrated process simulator that is used by process and biochemical engineers to gain insight in existing or proposed chemical processes, for the purpose of design and trouble shooting.

Aspen Plus was chosen among other simulation softwares due to its user friendly, graphic user interface and the ability to perform short time simulation and quick convergence. This research work presents Aspen Plus as the virtual laboratory to gain insight in anaerobic digestion process. Hence, the objective of this paper was to design and evaluate the techno-economic analysis of ammonia production from human waste (HW) via anaerobic digestion (AD) through two process schemes using Aspen Plus software simulator.

MATERIALS AND METHODS

Materials/Tools: The following materials/tools were used in the course of this study as shown in Table 1.

Table 1: Materials/Tools used.

Materials/Tools	**Description/Purpose**
Computer	For installation of Aspen Plus software
Aspen Plus software version 14.1	For process modelling and simulation anaerobic digestion process
Aspen Economic analyzer	To conduct Technoeconomic analysis on the process
Data from reliable data base and literature	Input and operating parameters for simulation (Temperature, pressure, OLR, HRT etc.)

Methods: The procedures of anaerobic digestion and model creation are presented in this chapter. The development of two paths for the faeces-to-ammonia conversion process was done using the Aspen Plus Version 14.1 simulator. The conditions considered for the process are mesophilic to thermophilic temperatures, pressure of 1 to 2 atm and pH below 6 (Table 2). The fluid package chosen was Non-Random Two Liquid (NRTL) because it offers more flexibility in phase equilibria and it takes into account non-ideality in the liquid phase. The process models used were stoichiometry reactors, separator and stripper.

Table 2: Optimum Parameters Used for Anaerobic Digestion

Parameters	**Hydrolysis, Acidogenesis, Acetogenesis**	**Methanogenesis**
Temperature (°C)	25-35	Mesophilic 30-40 Thermophilic 50-60
pH	5.0-6.0	6.7-7.5
C:N ratio	10-45	20-30
Redox potential	400-300mV	Less than 250mV
Trace elements	No specification required	Essential Ni, Co, Mo, Se

(Al-Rubaye et al., 2017) and (Das d 2022).

Table 3: Assumed Parameters used for the Simulation of both Technologies Pathways

Unit Operation	**Aspen Plus Block**	**Uses**	**Parameters**	
Hydrolysis Reactor	Rstioc	Hydrolysis Reaction	Temperature ; 35°C Pressure; 1atm	
AD Digestion	RCSTR	Acidogenic, acetogenic and methanogenic reactions	Temp. Pressure HRT OLR	55°C 2 atm 15 days 5.0 L^{-1} dy^{-1}

Two-Stage Anaerobic Digestion for Ammonia Production: The pathway approach for the ammonia manufacturing is depicted in Figure 1. It was started by opening the Aspen plus (AP) software and a new sheet and specialty chemicals with metrics was selected on the AP template. The component and specifications were selected and input in the properties icon. After that, the simulation icon was clicked and the main flowsheet was displayed. The process unit were selected and necessary and appropriate inputs and specifications were inserted and run for convergence. Necessary adjustments were made and several runs were carried out till it converged. Non-Random Two Liquid (NRTL) fluid package was used because it can compute mole fractions and activity coefficients. The hydrolysis reaction took place at 35°C and 1 atm in a stoichiometric reactor after HW and water were combined and passed through it. The HW component now transforms into a monomer. After that, the slurry was sent into the second reactor, a continuous stirred tank reactor that produced biogas at thermophilic temperature through acidogenic, acetogenic, and methanogenic reactions. Two liquids are located at the bottom of the reactor product, and gases are located at the top. Ammonia was taken out of the top of the gas stream and other gases were taken out of the bottom.

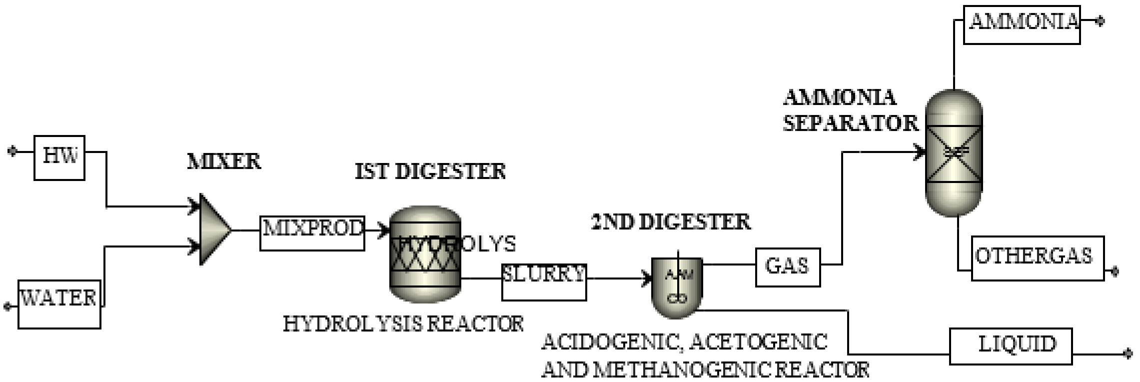

Fig 1: Two Stages Anaerobic Digestion Process for Ammonia Production (New developed model)

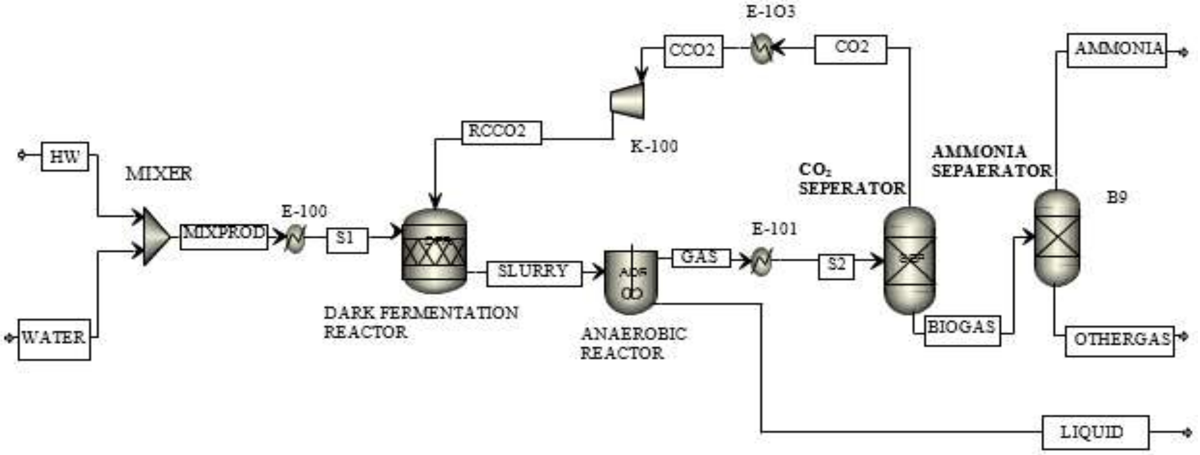

Fig 2: Two Stages Anaerobic Digestion Coupled with Carbon Capture and Recycled with Carbon Capture and Re-use

Mixer: As shown in Figure 1, this is where the HW were mixed with water before transferring into the stoichiometric reactor. Here, no reaction took place and it was done to provide smooth and consistent mixed product with an increase surface area for the reaction.

Digester I: This is where the biological process for conversion of organic substrate into biogas by microorganisms, in the absence of air began. The mixed product from the mixer entered the stoichiometric reactor, where hydrolysis took place. The faecal components which are complex biopolymers were broken down to soluble compound by hydrolytic bacteria, at mesophilic temperature of 35°C and at atmospheric temperature of 1 atm. After that, the slurry was sent to the second digester.

Digester II: The slurry from Digester I entered Digester II (Continuous stir tank reactor), where the soluble compounds were converted into intermediate acids by fermentation bacteria. The last stage was referred to as ammoniagenesis, as the acids were converted to NH_3 by ammoniagenes. The process was carried out at an atmospheric pressure of 1 atm and thermophilic temperature of 55°C. At the end of the process, the products were gas and liquid, with gas being the main product and liquid being the by-product.

Separation unit: This consists of the separator, incoming gas stream and outgoing NH_3 and other gas streams. It was realised using air steam to separate the gases, and NH_3 was collect from the top while other gases were collected from the bottom.

:

Ammonia production through a two-Stage DF coupled with AD and carbon captured and recycled: Ghavam *et al.,* (2021) created the anaerobic digestion method with carbon trapped and regenerated to make ammonia from food waste and brown water. Similar reactors are used in both methods; the only difference is how CO_2 is captured and recycled. The HW were mixed with water and then transferred to a stoichiometric reactor, a dark fermentation vessel where hydrolysis reaction broke down the HW components into less complex components. The slurry was then transferred to the Continuous Stirred Tank reactor, where thermophilic anaerobic reactions such acidogenic, acetogenic, and methanogenic reactions produce biogas. The product stream was divided into a liquid at the bottom and a gaseous portion at the top. The top gases underwent forward heating to separate CO_2 from other gases, and the CO_2 was then recycled back into the fermentation reactor in the darkness for further usage (Figure 2). Later, the ammonia was taken out of the other gases by separating them once again.

Costing and evaluation: The cost estimate of the entire process was based on the estimate of the unit costs. The total physical plant cost involving equipment erection, electrical, building, utilities, storages, piping instrumentation etc. was analysed. Also, the fixed cost which includes design and engineering, contractor's fees and other contingency items were determined. Aspen Process Economic Analyser which basically relies on model-based estimation was used to generate project capital cost estimates and operating cost estimates through its main features which involve interactive equipment that determine the operating costs and investment analysis, and automatically generated the process and block flow diagrams. Costing option involved the selection of basis for cost estimation, defining product and feed stream prices, and defined utilities in terms of pricing and associating them with equipment pieces. The key steps involved in the economic evaluation was activating the costing engine (Aspen Process Economic Analyser), mapping out the unit operations to equipment, sizing the equipment, then economic evaluation (this considered the project capital cost and it included the direct cost which refers to material and labour costs, Indirect field costs which referred to Engineering, supervision and construction expenses, and Indirect non-field costs which referred to taxes, permits, contingencies etc.) and viewing the results.

RESULTS AND DISCUSSION

The process models for the anaerobic digestion schemes for ammonia production were validated using data from the literature and simulated to conduct extensive sensitivity analysis on crucial process variables like temperature, organic loading rate, and hydraulic retention time, operating expenses (OPEX), raw materials, and utilities and compared within the developed process scheme.

Models Validation: The table below (Table 4) shows the results obtained when the experimental data and operating conditions obtained from the literature were used to validate the models.

Table 4: Aspen plus Model of Process Schemes against Experimental Data

Sources	Substrate Feed	Experimental results CH_4 (%)	Scheme 1	Scheme 2	Percentage Error Scheme-1 (%)	Percentage Error Scheme-2 (%)
Duan *et al.,* (2020)	HW	63.40	60.68	60.77	4.48	4.33
Lalander *et al.,* (2018)	HW	60.00	75.51	73.22	20.54	18.06

From Table 4, (Duan *et al.,* 2020) used the following operating conditions for volume, temperature, hydraulic retention time and organic loading rate of 10 litters, 35°C, 25 d and 1.06 volatile solid litre per day. As it was observed from the table, the results of validation using the above operating condition, process scheme 1 and 2 gave the error of 4.48 and 4.33% respectively. Similarly, the operating conditions of Lalander *et al.* (2018) was also used to test and validate the developed process scheme with the following conditions: 37°C, 35 days and 3.380 volatile solid litre per day, the author did not consider the reactor volume in their work, Also, the results of the validation shows that 20.54 and 18.06% difference from the actual experimental sets. In conclusion, both process schemes were validated with minimum difference from the actual experimental values.

Sensitivity Analysis

Effect of AD reactor temperature on ammonia production: Figure 3 shows how temperature influences the anaerobic digester's ammonia production. For both schemes, the ammonia production increased as temperature rose.

Sensitivity Analysis

Effect of AD reactor temperature on ammonia production: Figure 3 shows how temperature influences the anaerobic digester's ammonia production. For both schemes, the ammonia production increased as temperature rose. The other process, scheme 2, only produces 0.0189 kg/h of ammonia at the same temperature as scheme 1, which has a maximum production of 0.1727 kg/h at 60°C. The ammonia rate dropped from 61°C, and from 80 to 100°C it remained constant. The results depicted in Figure 3 agree with those reported in the literature by Duan *et al.* (2020) and Das *et al.* (2022), who obtained higher methane yields in the 50–60°C range. This suggests that the digester's temperature range of 45 to 65°C is more active and is the best.

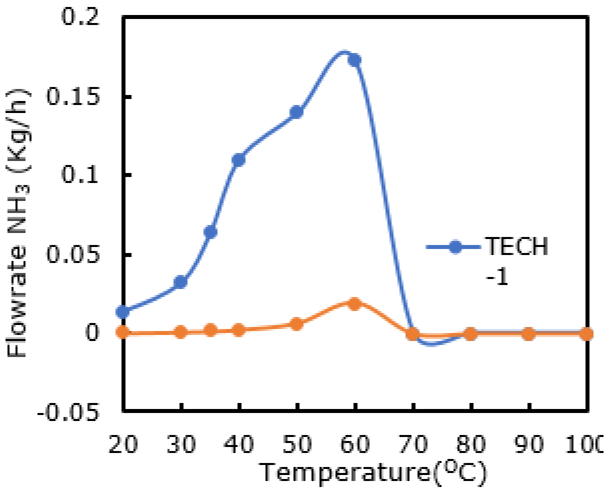

Fig 3: Effect of AD Reactor Temperature on Ammonia Flowrate

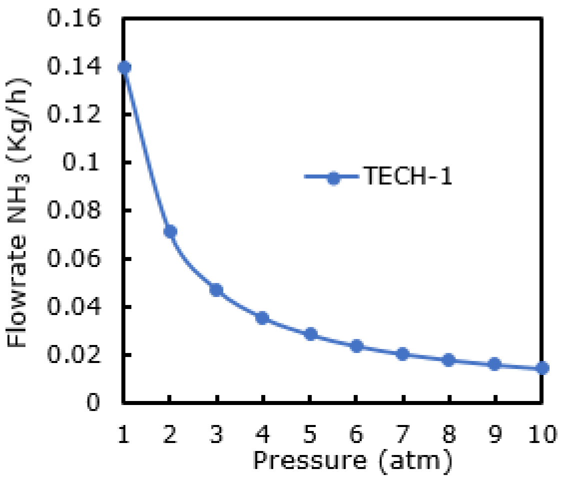

Fig 4a: Effect of AD Reactor Pressure on Mass Flowrate of Ammonia on Process Scheme 1 (one)

Effect of AD reactor pressure on ammonia production: The impact of anaerobic digester temperature along various technical trajectories is shown in Figures 4a and b. Figure 4a revealed that as digester pressure increased, ammonia yield decreased. The lowest pressure produced the highest ammonia yield of 0.138 kg/h, however when pressure rose to 2 atm, the ammonia yields sharply decreased to a lower flowrate. This concurs with the findings of Al-Rubaye *et al.* (2017) that the anaerobic digester is most affected by pressures of 1 to 2 atm. It can even be concluded that pressure around 1 atm is the ideal pressure to identify the highest production of biogas, Figure 4b similarly demonstrated the same influence of pressure on ammonia flowrate in the digester.

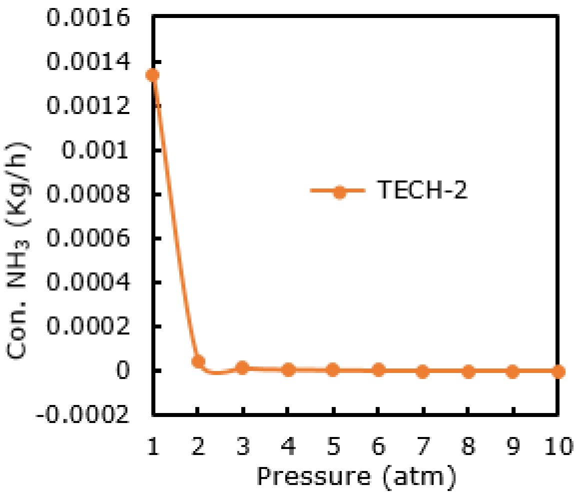

Fig 4b: Effect of AD Reactor Pressure on Mass Flowrate of Ammonia on Process Scheme 2 (two)

Effect of OLR on ammonia production: Figure 5 illustrates how the organic loading rate affects ammonia flowrate. The ammonia flowrate for both systems increased with increase in rate of organic loading. This is in agreement with Duan *et al.* (2020) with the assertion that biogas product increased as organic loading rate increased. In comparison to the highest organic loading rate of 10 L^{-1} dy^{-1} with corresponding ammonia flowrate of 0.09056 and 1.2792 kg/h, the starting organic loading rate of 1.0 L^{-1} dy^{-1} has ammonia flowrate of 0.02289 and 0.1279 kg/h for process schemes 1 and 2, respectively. The best maximum ammonia yield is provided by scheme 2, which is 1.2792 kg/h (99.29%) more than scheme 1's 0.009056 kg/h (0.71%). This means that, in terms of loading rate, scheme 2 has a higher potential than scheme 1. This is because CO_2 is captured and recycled.

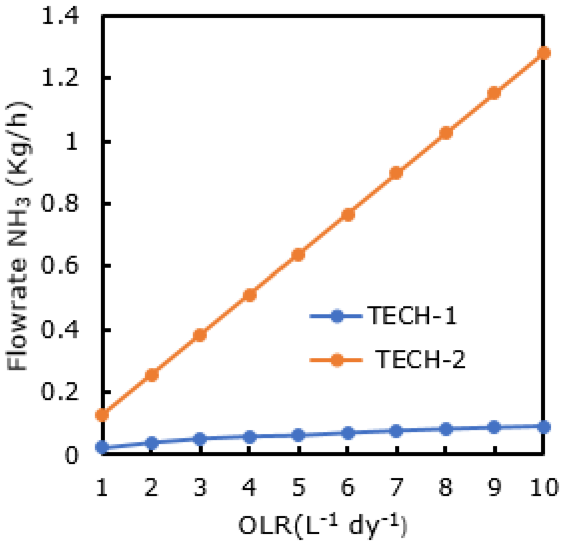

Fig 5: Effect of OLR on Ammonia Flowrate for Process Schemes 1 and 2

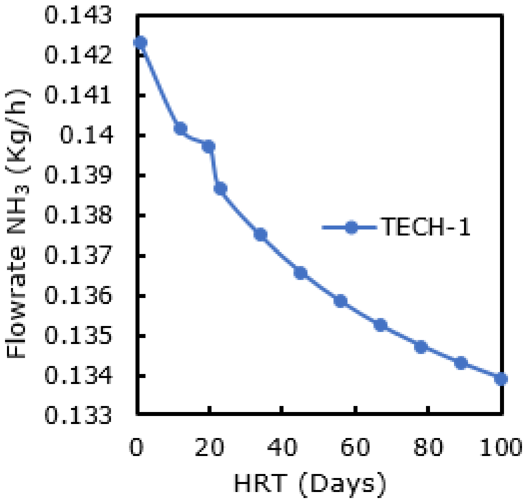

Fig 6a: Effect of HRT on Ammonia Mass Flowrate Process Scheme 1 (one)

Effect of HRT on ammonia production: The impact of hydraulic retention time on the ammonia product is seen in Figures 6a and b. The results from Figure 6a revealed that the ammonia yield increased with decreasing hydraulic retention time in days; the highest yield of 0.4234 kg/h was obtained at 1-day HRT compared to the lowest yield of 0.1339 kg/h at 100-day HRT. It can be deduced that process scheme 1 produced a high yield of ammonia with a decreased HRT requirement; this is consistent with Das *et al.* (2022) and Duan *et al.* (2020) findings. Ammonia production from biogas increases as HRT falls, in contrast to Figure 6b, which shows the reverse trend. From the graph, it can be seen that ammonia yield increases as HRT length increased, reaching a maximum of 0.001609 kg/h at 100 days and a minimum of 0.001156 kg/h at one day. This can be explained by the fact that scheme 1 produces ammonia at a maximum yield of 0.142 kg/h, 19.93% more than the maximum production of 0.001609 kg/h obtained from scheme 2.

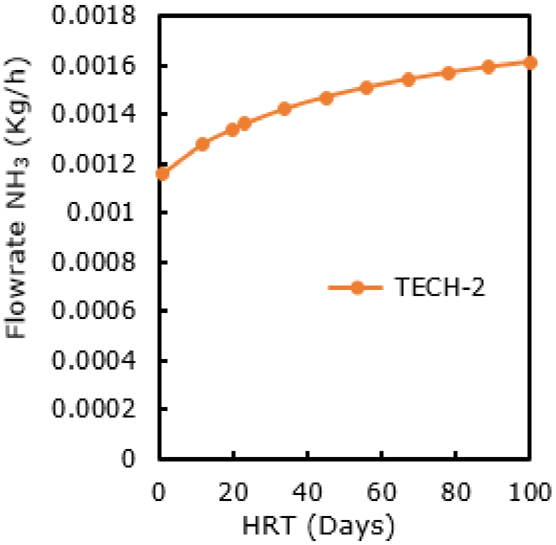

Fig 6b: Effect of HRT on Ammonia Flowrate Process Scheme 2 (two)

Techno-Economic Analysis: The economic model was developed using the possible operating and capital expenditures (OPEX) for the two scenarios. The economic model considered economic instruments like internal Rate of Return (IRR), Net Present Value (NPV), and Payback Time (Payout Period) as indicators of viability (Fuess & Zaiat, 2020). Also shown in Table 5 were the raw material and product prices for the two paths and hypotheses used to run the Aspen Plus Economic Analysis. Other presumptions for the economic analysis include that the organic loading rate remained constant, that the plant operated for 30 years, that startup lasted 22 hours per day, and that the June 2023 projection for the fundamental engineering and economic price exchange rate. June 2023 Dollar to Naira conversion rate (1USD= 760NGN) was used.

Table 5: Economic Assumptions

Raw materials	**Cost NGN/kg**	**References**
Feed		
Ordure	950	(Sillero *et al.*, 2023)
Water	0.16036	(Sillero *et al.*, 2023)
Product		
Ammonia	212,800	(Tena *et al.*, 2022)
Liquid	3,800	(Khatun *et al.*, 2023)
Biogas	7,600	(Fuss & Zaiat, 2022)

Exchange rate: (1USD= 760NGN)

Table 6: Complete Summary of Techno-Economic Analysis

Description	Tech-1	Tech-2
Total Project Capital Cost [NGN]	3,615,076,800	8,679,124,000
Total Operating Cost [NGN /Year]	998,419,600	1,611,086,000
Total Raw Materials Cost [NGN /Year]	1,261,843.2	1,261,843.2
Total Product Sales [NGN /Year]	12,415,664	14,060,532
Total Utilities Cost [NGN /Year]	33,176,508	33,853,060
Desired Rate of Return [Percent/'Year]	20	20
Pay Out Period [Year]	6	7
Equipment Cost [NGN]	113,544,000	1,034,436,000
Total Installed Cost [NGN]	508,820,000	1,360,172,000
ESCAP (Project Capital Escalation) [%]	5	5
ESRAW (Raw Material Escalation) [%]	3.5	3.5
IRR (Internal Return Rate) [%]	17	12

Exchange rate: (1USD= 760NGN)

The techno-economic analysis is frequently used to determine the economic viability of a well-established process by comparing its cost-benefit analysis to that of existing or emerging technologies (Tena *et al.,* 2022).

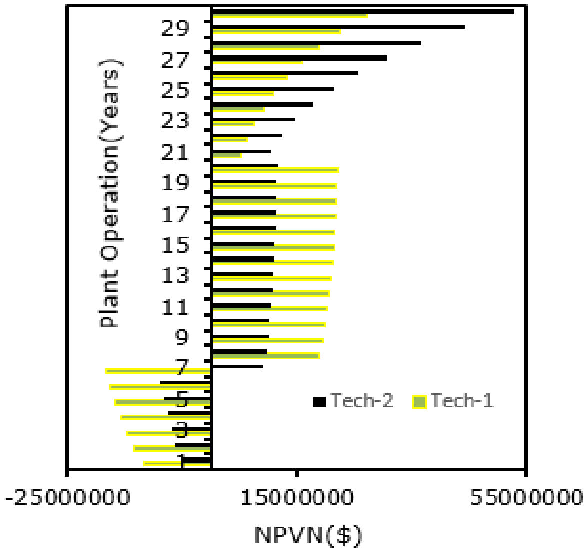

Fig: 7: Net Present Values Against Plant Operation Years

The thorough techno-economic analysis carried out for the two technological routes is presented in Table 6. The table shows that technology 2 route, with a total project capital cost of 8,679,124,000 NGN, has the greatest capital cost overall. This is 140.08% higher than the cost of technology path 1, which is 3,615,076,800 NGN. The carbon capture system in the second technology pathway is the reason for this outcome. Additionally, a 9-year payback period and a 20-year anticipated rate of return have been noted for the project. Both technology routes have strong economic potential at this point. According to Sillero *et al.,* (2023), a significant engineering project's economic viability is indicated by a payout duration and targeted rate of return of no longer than 20 and 35 years, respectively.

Figure 7 shows the pay-out period (P.O.P.) and net present value (NPV) for both technologies. According to the graph, Technology 1 and 2 have 6- and 7-year payout periods, respectively, with average NPV values of $128,825.54 (#97,907,410.4) and $291,876.33 (#221,826,010.8). But it may be inferred that technology 2 has a rate that is 55.86% greater than technology 1. The most effective economic indicator tools, according to Sillero *et al.,* (2023), are the NPV and P.O.P. All technology paths have payback periods of 6 and 7, respectively, of the project lifetime (30 years), demonstrating the financial sustainability of the planned plant. Although the economies of both technology routes are strong, technology 2 is a more lucrative than technology 1.

Conclusions: The aim of this work to produce ammonia from human waste via two stage anaerobic digestion process using Aspen Plus was achieved. The simulation results obtained may serve as basis for future research on amount of ammonia from anaerobic digestion of human waste. The results of the sensitivity analysis could be used to determine the more suitable temperature, pressure, hydraulic retention time and organic loading rate when carrying out experiment on anaerobic digestion. The economic analysis also shows that the two AD schemes are economically viable.

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