OPEN ACCESS

Global Academic Journal of Agriculture and Bio sciences

Available online at https://www.gajrc.com
DOI: https://doi.org/10.36348/gajab.2025.v07i06.003

ISSN:2706-8978 (P)
ISSN: 2707-2568 (O)

Original Research Article

Waste-to-Energy: Sustainable Conversion of Sewage Sludge

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Article History
Received: 03.10.2025
Accepted: 24.11.2025
Published: 28.11.2025

Abstract: Sewage sludge, a major by-product of wastewater treatment, presents both environmental challenges and opportunities for renewable energy recovery. This study evaluates the fuel potential of sewage sludge through proximate and ultimate analyses conducted on samples collected from a wastewater treatment plant. The results show a carbon content of 35.61%, low sulphur content of 1.15%, and a calorific value of 20,999.14 kJ/kg, indicating strong suitability for energy conversion. Favorable volatile matter and elemental composition further support its use as a biomass feedstock. The findings demonstrate that sewage sludge can serve as a viable resource for waste-to-energy technologies including pyrolysis, gasification, and anaerobic digestion. Further pilot-scale investigations are recommended to assess practical efficiency and optimize conversion processes.

Keywords: Sewage Sludge, Waste-To-Energy, Biofuels, Thermochemical Conversion, Anaerobic Digestion, Pyrolysis, Renewable Energy, Biomass.

I. INTRODUCTION

Sludge, a by-product of wastewater treatment, consists largely of water, organic matter, microorganisms, nutrients, and heavy metals such as Ni, Co, and Fe. It may also contain toxic substances that pose risks to human health and the environment if not properly managed. Effective sludge management is therefore essential for protecting public health and advancing a circular economy (Lou *et al.,* 2023). Traditional methods such as incineration, composting, and landfilling are increasingly viewed as unsustainable due to their pollution potential, high energy requirements, and limited resource recovery (Mannina and Mineo, 2023). This highlights the need for more sustainable and environmentally friendly approaches to sewage sludge treatment.

The global usage of the fossil fuel is increasing very rapidly but the sources of the fossil fuels are limited and there is very less probability of finding new sources that would add up much to the present availability. According to the present studies, the availability for coal, petroleum oils and natural gas is expected to be for 113, 53.3 and 55.1 years respectively. Also the use fossil fuels creates the problems like economic vulnerability and global climate change. So there is very much need of exploring new ways to producing fuels which partially reduces the problems caused by the fossil fuels. Some of the ways that can give a better solution are use of the biomass for the energy production.

Sewage sludge is one of the most potential feedstock for biodiesel production in few years to come. It is one of the most important products produced after primary and secondary treatment processes in wastewater treatment plants (Cea *et al.,* 2015). Sewage treatment plants uses several methods in sludge treatment, methods like agricultural use, landfill, composting, incineration, anaerobic digestion and thermochemical processes. Thermochemical processes like hydrothermal method and pyrolysis; prove more viable in recovering the energy potential of the sewage sludge products (Vieira *et al.,* 2017).

Biomass is nothing but the organic material contained by living or recently-living organisms. It is mostly composed of the carbonaceous material. Sewage sludge is one of the biomass sources that could be considered for energy production. It is the residue that is produced at the end of the physicochemical and biological treatment processes employed in waste water treatment. Its physical state is that of a semi solid and may be biologically active. There are two types of sludge produced during the waste water treatment process. First one is the Primary sludge, which is formed in the primary sedimentation tanks as a result of gravity settling of the organic matter and other suspended contents laden in the waste water. This primary sludge formed will become putrescent once the anaerobic bacteria start proliferating and hence has to be removed from the sedimentation tank within a short residence time. Second type of sludge formed is in the secondary sedimentation tank after the biological digestion of the organic load present in the wastewater. This is also known as microbiological sludge. The principal composition of the dry matter content of this sludge comprises of nontoxic organic compounds. The sewage sludge also contains a marginal composition of inorganic materials and toxic substrates.

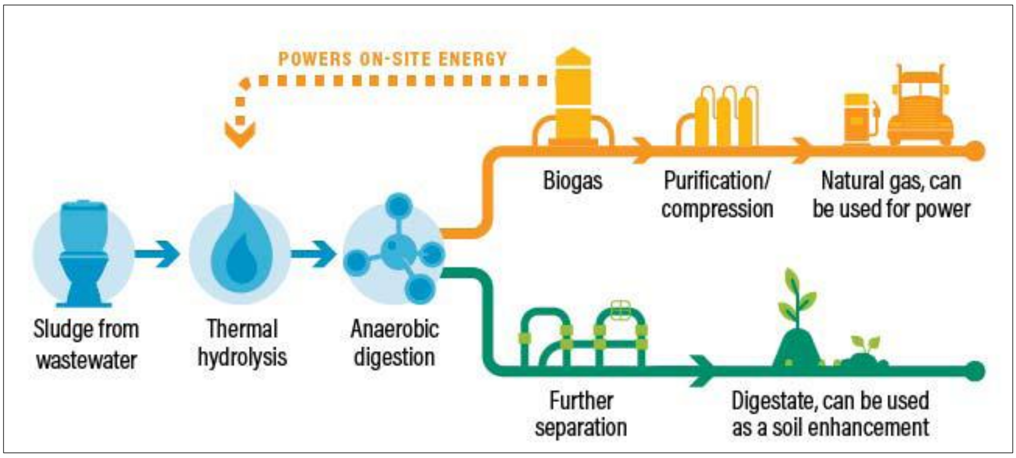

Fig. 1: Potentials of Sewage sludge (Schleifer and Fu, 2018)

It could be used as a potential fuel directly or indirectly which are as explained below.

1. **Direct use:** In this type the biomass is directly burned to obtain heat energy. It is one of the conventional methods still used in the many villages for cooking and other purposes.
2. **Indirect use:** In these methods the biomass is first converted in secondary fuel and then these secondary fuels are used accordingly. It is classified into two types viz.
   a. **Thermochemical conversion:** In this type, the biomass is treated with heat in a controlled medium to obtain fuel. It has two types.
      - **Gasification:** It is a partial oxidation process whereby a carbon source is broken down into CO, CO_2, H_2 and possibly other hydrocarbons such as CH_4. The mix of these gases s known as producer gas and precise characteristics of the gas depends on the gasification parameters like temperature and oxidizer (air, H_2, steam, O_2)
      - **Pyrolysis:** It is a process of conversion of the biomass in the absence of the air, more precisely oxygen. The end product of this process is called as bio-oil from which the liquid fuel is produced.

   b. **Biochemical conversion:** In this type, the biomass is treated by the organisms to produce liquid fuel or gaseous fuel.
      - **Fermentation:** It is a conversion process in which the biomass is converted into liquid fuel by fermentation by micro-organisms such as yeast. The end products of this process are liquid biofuels such as bio-ethanol, bio-butanol and bio-diesel.
      - **Anaerobic digestion:** It is a series of biological processes in which microorganisms break down biodegradable material in absence of oxygen. The product of this process in a called as biogas and it mainly consists of CH_4 and CO_2.

This paper deals with a series of analytical experiments to determine the potency of sewage sludge as an auxiliary fuel in the present scenario. Henceforth the determination of probable methods for its assimilation and utilization are decided upon.

II. LITERATURE REVIEW

Biowastes like sewage sludge can undergo hydrothermal process to dehydrogenize, decompose and degrade to release oil, gas and a solid residue that can be simply separated from the mixture. Alternatively, the sludge can be pyrolysed, which involves thermochemical decomposition of the sludge at high temperatures under pressure in the absence of Oxygen to produce Gas, Char and Tar (Xue *et. al.,* 2015).

Biofuels can be produced from biomass like sewage sludge through processes like pyrolysis, gasification, torrefaction and incineration. But, pyrolysis has been the most widely used process because it can convert biomass like sewage sludge into biofuel products that include Biochar, Syngas and Bio-Oil. The bio-oil product from sewage sludge can be used commodity and specialty products like resins, fertilizer and light aromatics (benzene, xylene and toluene). Pyrolysis can also generate sustainable heat and power. However it can reduce the amount of pollutants released into the atmosphere (Arazo *et al.,* 2017).

Kim Y *et al.,* (2008) conducted a study on the techno-economic viability of use of sewage sludge for pyrolysis and bio oil production. A laboratory scale batch reactor was built and experimentations were conducted. The operating temperature was in the range of 200-500^{0}C and a residence time of 20 minutes was maintained in the gas phase. Nitrogen purge flow was maintained as 50ml/ min .With primary sludge at 500^{o}C maxi um oil production was observed.

Khan R M *et al*., conducted a study on dewatered sewage sludge samples that were dried in vacuum oven under Nitrogen gas flow in the laboratory. The dry samples were analyzed by characterizing the following parameters: C, H, S, N, percentage ash content and heating value. The data set of 30 observations were analyzed by using the Statistical Analytical System (SAS) package. It was found that compared to almost all the fossil fuels (excluding petroleum based fuels), sewage sludge has comparatively a higher H/C ratio. The mean H/C ratio of sewage sludge was 1.65 which was considerably higher than that of the bituminous coals.

Tsai W T (2012) conducted a study in Taiwan on the analysis of the use of biosolids produced after waste water treatment process and its share in the percentage reduction of CO_2. According to the studies it was found that the total amount of energy potential produced from the biosolids generated from waste water treatment was 1100 TJ/year and the environmental benefit of CO_2 mitigation was 57 Gg/year.

III. METHODOLOGY

A. Collection of Raw Materials

The sewage sludge sample required for the analysis was collected from the Wastewater Treatment Plant, located at Idu Industrial Area, Abuja.

B. Proximate Analysis

1). Preparation of Pulverised Sludge

The raw material collected was examined to remove plastic debris and other components with no fuel value. Then it was ground into fine particulate consistency of particle size less than or equal to 2mm. This was stored in airtight containers for analytical use.

Fig. 2: Raw Sludge Collected from wastewater treatment plant

Fig. 3: Pulverised Sludge

2). pH Test

The powdered raw material was tested for pH by preparing an aqueous solution of the sludge conforming to EN 12176 standards. Distilled water or 0.01 mol/l $CaCl_2$ are generally recommended as extractants. The use of a 0.01 mol/l $CaCl_2$ solution will in general yield a lower pH value than will distilled water. Hence distilled water was used.

a. Preparation of Suspension

1 gram of powdered sludge was dissolved in 1 liter of distilled water to obtain a stock solution of 1000mg/L concentration. Shake or mix the suspension for 60 min ± 10 min using a mechanical shaker. Wait for at least 1 hour.

b. Calibration of pH Meter

The pH meter was calibrated using standard solutions of known pH. Potassium hydrogen phtalate ($C_8H_5O_4K$) at pH 4.00, and potassium dihydrogen phosphate (KH_2PO_4) + disodium hydrogen phosphate (Na_2HPO_4) at pH 6.88 was used for this purpose.

c. Measurement of pH

pH in the suspension was measured at room temperature immediately after being stirred. The stirring should be at such a rate to achieve a homogeneous suspension of the soil particles, but air entrainment should be avoided. The values are recorded up to an accuracy of 2 decimal places.

d. Blank Solution Control Determination

The water should be checked for pH before the suspensions are prepared.

3). Total Solid Content and Moisture Content

10 gram of powdered sludge was weighed out for analysis (W_1). The sample was placed in a crucible whose empty weight was determined (W_0). The sample was oven dried in Hot Air oven at a temperature of 130^{0}C for a duration of 1 hour. The weight was determined after oven drying (W_2). The following formulae were used for this purpose.

Total Solids $= W_1 - (W_2 - W_0)$

Moisture content (%) $= ((W_1 - (W_2 - W_0)) / W_1)*100$

4). Fixed Solids and Volatile Solids

The sample dried in the hot air oven (W_2) was further dried in muffle furnace at a temperature of 550^{0}C for a duration of 1 hour. . The final weight was determined after oven drying (W_3). The following formulae were used for this purpose:

Fixed solids $= W_3 - W_0$

Volatile solids $= W_2 - W_3$

5). Empirical Carbon Content

The following empirical correlation was used for this purpose:

Carbon content (%) $= a_{compost}$ * *volatile solids (%)*

Where, $a_{compost} = 5.2$

A. Ultimate Analysis

The ultimate analysis was performed at Centre for Advanced Science Research and Analytical Services (CASRAS) Usmanu Danfodiyo University, Sokoto.

The details of the CHN analyzer are as follows:

Table 1: Specifications of the CHN analyzer

Make/Model	Elementar Vario EL III
Operation Modes	CHNS, CHN, CNS, CN, N, S and O
Detection Ranges* C	:0.004 – 30 mg abs (or 100%)
H	:0.002 – 3 mg abs (or 100%)

Make/Model	Elementar Vario EL III
N	:0.001 – 10 mg abs (or 100%)
S	:0.005 – 6 mg abs (or 100%)
O	:0.005 – 2 mg abs (or 100%)
Standard deviation	:0.1% abs
Sample weight	:0.02 mg up to approx. 1 gm
Digestion temperatures	:950 – 1200°C

A sample weighing 12.57mg was analyzed for carbon, hydrogen, nitrogen and Sulphur content.

IV. RESULTS AND DISCUSSIONS

A. Proximate Analysis

Table 2: Proximate analysis results

Parameter	Value
pH	7.54
Moisture content	86.02%
Fixed solids	94.36%
Volatile solids	5.64%
Empirical carbon	29.33%

The pH of this study was found to be less than the pH (8.34) reported by Veira *et al.,* (2017) in a study titled *"Green Bio-oil obtained from digested sewage sludge: new substitute bio-fuel to diesel oil in thermoelectric plants"* which suggested that important parameters like pH, calorific values and density in a biofuel derived from sewage sludge are related to corrosive aspects, amont of energy in the fuel, pumping and injecting systems.

B. Ultimate Analysis

Table 3: Ultimate analysis results

Parameter	Value
Nitrogen	5.29%
Carbon	35.61%
Sulphur	1.15%
Hydrogen	6.44%

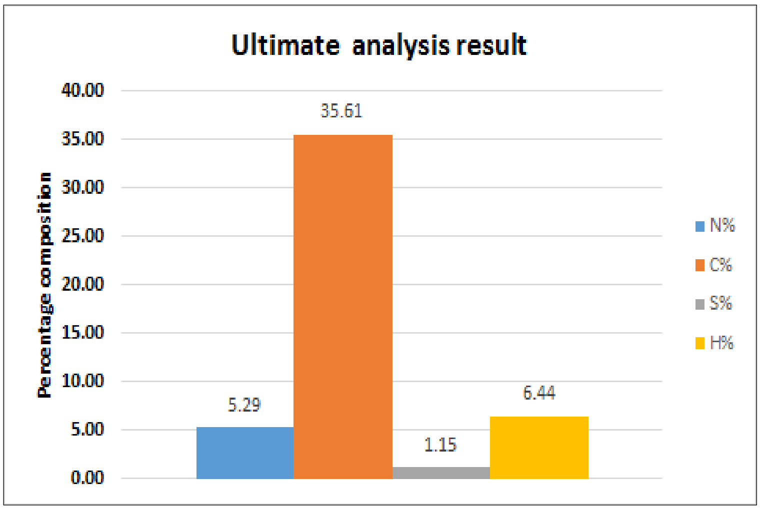

Fig. 4: Ultimate analysis result (graphical representation)

C. Estimated Calorific Value

Based on the ultimate analysis composition data and the corresponding heating values of the constituents; the overall heating value of the sludge sample was determined as

Calorific Value = 20999.144 kJ/ kg

Depending upon the composition, the appropriate method of the conversion to fuel is selected. The requirement of biomass for some conversion processes is as follows:

1. **Anaerobic digestion:**
    a. C/N ratio should be between 8-20 for optimum output

b. Substrate concentration should be less than 10%.
c. pH value should be between 6.8-7.2. Below 6.3 it is toxic effect on methanogenic bacteria.
d. Nutrient availability should be in adequate amount if it is in excess or less then it can result in inhibitory action.

2. **Pyrolysis and gasification:** The biomass should contain the heavy/large organic molecules so as to allow for the thermochemical decomposition to smaller molecules.

V. CONCLUSION

Sewage sludge demonstrates strong potential as a renewable fuel due to its relatively high carbon content and low Sulphur levels, which minimize environmental risks during combustion. The proximate analysis revealed favorable volatile matter and carbon percentages, while the ultimate analysis provided precise elemental composition confirming its suitability for energy conversion. Additionally, the calorific value further supports its viability as an auxiliary fuel source. Based on these findings, sludge can be effectively utilized through pathways such as pyrolysis, gasification, and anaerobic digestion; however, further experimental studies are recommended to evaluate its practical performance in full-scale pyrolysis and biodigestion systems.

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