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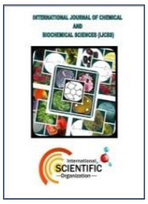

Circular Economy and Sludge from Wastewater to Energy

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Abstract

An urgent global dilemma revolves around the escalating volume of sewage sludge generated by wastewater treatment facilities. This sludge, laden with organic matter, toxic compounds, and heavy metals, poses intricate disposal challenges and grave environmental risks. This sludge contains high concentrations of organic matter, poisonous compounds, and heavy metals, making its disposal complex and environmentally risky. Researchers and experts have developed various methods for converting sewage sludge into energy, including anaerobic digestion, combustion, pyrolysis, gasification, and thermal liquefaction. Recent research has focused on advancing these technologies, assessing their advantages and disadvantages to create financially and environmentally sustainable sewage-to-energy solutions. A revised perspective on the wastewater value chain promotes a circular economy strategy, considering the solid waste remaining after sewage sludge treatment as a valuable resource. The efficiency of each process in recovering matter and energy plays a crucial role in its effectiveness. Scenario analysis helps identify suitable sewage sludge treatment facilities based on factors like sludge quality, quantity, and technological and financial constraints, aligning with circular economy objectives. Around the world demand for advanced wastewater treatment technologies faces challenges from aging infrastructure, stricter environmental regulations, and issues in receiving water environments. Modern wastewater treatment systems aim to remove nutrients and organic carbon and recover valuable products. However, current methods often consume significant energy, chemicals, and resources. Innovation and energy integration are vital strategies for developing sustainable wastewater treatment systems that align with the circular economy, especially considering rapid population growth and urbanization.

Keywords: Sewage, anaerobic digestion, combustion, pyrolysis, gasification, sludge-to-energy, circular economy

Full length article

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1. Introduction

Imagine a world where our ever-growing global population and rapid urbanization are squeezing our precious resources – land, water, food, and energy – to the breaking point. Furthermore, this relentless growth has unleashed environmental woes, turning waste and pollution into menacing adversaries, posing a grave threat to our planet's pursuit of sustainable harmony. These problems are incredibly harmful to the global objective of sustainable development. As a result, there is a growing interest worldwide in sustainable methods of producing, using, and disposing trash. The rising amount of urban wastewater, particularly sewage sludge, is a direct and easily missed effect of the increase in worldwide waste. Any solid, semi-solid, or liquid excreta produced by a wastewater treatment facility is sewage sludge. These processes can produce municipal, commercial, or industrial effluent. Sewage must be thickened and mechanically dewatered due to its physical characteristics (low solid-to-liquid matter ratio), which helps logistics and transport during treatment operations. These procedures aid in boosting the concentration of solid particles in sludge from its initial mostly liquid (three-weight percent solid) state to between ten and twenty-five weight percent [1]. Sludge is generated during the initial processing of raw sewage, involving the removal of large particles. It contains a non-homogeneous mixture of carbohydrates, amino acids, oils, and inorganic compounds formed by bacteria and microorganisms. This mixture poses risks due to its chemical, physical and biological properties. Various methods such as composting, digestion and chemical treatments are employed to stabilize the organic matter in the sludge, destroy pathogens, eliminate odours, and reduce volatile contents. The resulting secondary sludge undergoes further biological processes, such as anaerobic digestion, to recover energy and utilize it as fertilizer. However, the quality of sewage sludge can vary depending on the type of sewage and the treatment techniques employed. Improper sludge disposal has increased waste dumping at sea, particularly in developing regions. In industrialized nations, alternative disposal methods like landfilling, composting, and incineration are used due to legal repercussions for unauthorized dumping [2-3].

With the anticipated increase in sludge production and the need for more sustainable waste management practices, there is a growing focus on upgrading sewage sludge disposal methods. Resource and energy recovery from sludge have gained interest, particularly through anaerobic digestion and thermal processes. However, there are challenges associated with large-scale operations and meeting environmental standards. Efforts to develop sustainable wastewater treatment plants prioritize the removal of carbon-based and nutrient-containing compounds from wastewater sources. Traditional wastewater treatment methods, such as aerobic environments for biological nitrification, are being reconsidered in favor of more resource-conserving and environmentally friendly approaches. Integrating technologies like anaerobic digestion and bio electrochemical systems show promise for energy recovery and eco-friendly wastewater treatment [4-5]. To address the environmental issues related to traditional sludge treatment procedures and waste disposal, the concept of energy recovery from sewage sludge has gained popularity. Biochemical and thermochemical processes such as anaerobic digestion, pyrolysis, and hydrothermal liquefaction offer potential solutions. However, these methods come with their own technological and operational challenges [6].

Considering the abundance of sewage sludge generated by wastewater treatment plants and its potential as a biomass source for fuel and resource recovery, there is a need for further research and development in sludge management and innovative treatment techniques. This study aims to explore the possibilities and challenges of thermochemical and biochemical conversion of sewage sludge, examining various energy recovery pathways and identifying future opportunities [7].

2. Circular economy and sludge from wastewater to energy

a. Waste: The Hidden Resource

To perceive rubbish as a resource is an initial step towards circularity. The redirection of waste streams and using them as chemical supplies should become ubiquitous in the manufacturing of marketable products to achieve complete recycling of molecules and resources. Although it is difficult to eliminate deteriorated materials or products, each given process must limit uncirculated waste. As a result, disposal methods will always be required to ensure the effective flow of materials. Eutrophication and global warming are two important environmental challenges confronting the globe today, and both are mostly caused by excessive consumption of phosphate and nitrogen fertilizers in addition to fossil fuels. The surplus of carbon, nitrous oxide (NO), ammonia, and phosphate debris that is lost to the air and water and disrupts the nitrogen, phosphorus, and carbon dioxide cycles cause many detrimental environmental impacts. Revolutionary chemical and biological modifications that enable effective recycling and reuse are urgently required to tackle these environmental concerns and mitigate the adverse environmental impacts of waste products that result [8]. To successfully minimize or reuse waste, an optimal process design that allows for the efficient split, purification process, recycling, and recovery of waste materials in an environmentally acceptable manner is necessary. Trost's concept of an atom economy in organic chemistry promoted the effectiveness of each synthesis step [9]. Circular chemistry, like this, strives to maximize atom mobility in chemical substances throughout their lives at the production level, irrespective of whether the chemical connections are modified. When employing garbage as a resource, the invention of new chemical reactions that can handle complex waste mixtures as substrates to produce value-added compounds and commodities is a substantial obstacle. When this is considered at the start of a process, products are more adapted to being transformed into discrete waste streams at the end of their lifecycle. As a result, this technique should allow for the total recycling of any source and product [10].

b. Water's Transformative Energy Capacity

Wastewater, sometimes known as “resource water,” is like water because it contains nutrients and energy. Table 1 represents examples of water sources used as energy carriers, and table 2 presents energy input and potential output from different wastewater sources [11].

c. Characteristics of sewage in the chemical industrial sector

Residential liquid waste disposal could be deciphered using social media data analytics. If the purpose is to collect data on industrial waste, a thorough database should be used. The European pollutant release and transfer register divides chemical wastewater contaminants into four categories: organic chemicals containing chlorine to water, additional organic compounds, inorganic substances, and metallic substances. Even though they can occur spontaneously as condenses or products of reaction, the great majority of wastewater produced by the chemical sector does not result from chemical processes. Most frequently, chemical processes (filter, centrifugation, extraction, and distillation) used during the processing steps that follow the reaction result in wastewater production [12]. The following sections provide a list of the various types of wastewaters that are often generated in the chemical manufacturing industry. The following are examples of "process sewage" types more directly related to the chemical process: mother liquors cleaning product wash waters, technological vapors condensates, cool aqueous (waters employed in water-based injection chilling or gaseous stream treatment). Washing unclean water with gas and exhaust gas. Cleaning water and vacuum generating water (condensate from a jet injector or an aqua ring vacuum compressor). Heat pumps are used with subterranean thermal energy storage for cooling and low-degree heating. There are two thermal energy storage system types: aquifer ATES and borehole BTES [13]. Although they can be responsible for up to ninety percent of all pollution releases, these waters only make up twenty-five percent of chemical wastewater. Other types of effluent that have no connection to manufacturing but end up contaminating the water include heat transfer water effluents (typically containing deterioration inhibitors), waters for removing exhaust gases from processes of combustion, incomplete flows generated by water exchange process in exterior wiring, sewage from filters backwash, dirty water from lab along with light-industrial testing, wastewater from municipalities, and rainwater from polluted areas [14]. This group includes roughly eighty-five percent of the total volume of wastewater and typically results in less pollution. Hazardous wastewater can originate from various sources, depending on the impurities it includes, including unreacted reagents or raw materials, product leftovers, excipient portions not extracted from wastewater, intermediary products and by-products of undesirable activities [13].

2.1 Resource Reclamation in Wastewater Treatment

a. Revitalizing Wastewater Nutrients

WWTP fertilizer recycling aids the environment by reducing the requirement for traditional fossil-based fertilizers and water and energy use. To recover nutrients, untreated wastewater, semi-treated sewage streams, and sewage waste may each be employed. Land application of biosolids, either by scattering waste material on the soil's surface or infusing it into the ground, is the oldest method of treating wastewater waste as fertilizer. To treat biosolids before application, the WWTP can apply the following procedures: aerobic or anaerobic digestion, composting purposes, the drying process, and chemical processing (mostly alkaline treatment). Sewage sludge is routinely used to land in developed countries [15]. In 2015, around 968 thousand Magnesium of sewage waste was used in agriculture. In developed countries where wastewater sludge utilization for agriculture is most common, such as Germany and France. The main issues with this bio-solid disposal are health and safety, odour, disturbance, and public acceptance. Furthermore, to directly apply phosphorus to the soil, technical recovery through sewage, plus the ashes of incinerated sludge, can be utilized for recovering phosphorus from wastewater. Currently, the main technology utilized for recycling phosphorus at WWTPs is the struvite crystallizing techniques, like the ones employed by the completely functional Pearl, NuReSys or AirPrex technological advances. Currently, more than 2,000 tons of Magnesium per year is recovered technically throughout developed countries. The main concerns with struvite crystallization are high chemical costs and unwanted struvite formation, which causes blockage of valves, lines, motors, etc [16].

Another method for nutrient recovery is urine isolation from most sewage streams. Urine contains between sixty-five per cent nitrogen and fifty per cent phosphorus, which could be recovered to seventy per cent using the toilets' urine-collection systems. When pee is employed for land application, the urine collecting technique is frequently used in industrialized nations. This technique has not been widely used in industrialized countries because of significant technological issues and a lack of popular acceptance. Aquatic species that consume these substances in wastewater to produce fertilizers or animal meals are another way to recover nutrients. The subspecies are utilized: microalgae, crops, marsh plants, duckweed, etc. The fact that recycling nutrients through aquaculture uses little energy and has positive synergistic effects with wastewater treatment makes it a recognized environmentally friendly method. Despite this, only a few people use the technology. Technically speaking, manufactured wetlands are the only technology being used, but its implementation does not include nutrient recycling for later use [17-18].

b. Towards a Circular Water Economy

The reuse of processed wastewater from wastewater treatment plants for industrial uses, toilet flushing, and replenishing groundwater is a vital part of the present plan for releasing fresh water for consumption at home, improving sewage treatment plants quality of effluent, as well as a result, raising the standard of waters from rivers applied for production of drinking water. Utilizing treated wastewater for agricultural irrigation has several benefits, including reducing the strain on municipal water supplies and minimizing the need for synthetic fertilizers due to nutrient-rich wastewater. Tertiary treated wastewater is recommended for edible crops. Urban wastewater can be reused directly or indirectly for non-potable purposes, but there have been rare cases of unintentional consumption. Common examples of urban water reuse include household gardening and commercial uses like vehicle and toilet cleaning. However, challenges include safety concerns and the cost of separate systems for recycled water distribution. Developed nations like the USA are the leading regions for urban recycling, reusing over 44.5 percent of its wastewater treated to water ecosystems. The explicit discharge of superior sewage treatment plants into underground or surface water supplies to enhance drinking water availability is called indirect potable reuse. Another possibility is to pump wastewater from treatment directly into a system that distributes water for immediate consumable reuse. However, due to extremely strict effluent quality criteria, direct potable reuse significantly raises operational costs. Another significant factor is the need for societal acceptance. Table 3 represents the global water reuse through application following enhanced treatment use [18].

c. Efficient Resource Utilization: Energy Recovery

One key policy tool for sustainability is the recovery of energy at wastewater treatment facilities. It is possible to accomplish this by creating biogas, employing heat pumps to circulate in treatment plant wastewaters, and employing exchangers for heat to recover energies from various exceptionally hot streams. In a wastewater treatment plant (WWTP), the principal energy source is biogas produced through anaerobic digestion, which has an energy capacity of 7 kWh/m^3 (64.5% methane content). According to estimations, wastewater treatment plants that use sludge digestion consume forty-one per cent less net energy than ones that do not. Gas output fluctuates from one to 2.75 m^3/kg of volatile material wiped out, and biogas' low thermal value is around 22 kJ/m^3. Biogas can be used to generate heat or power buildings. The combination of power and heat devices, which create heat and electricity from biogas simultaneously, are the most extensively used in current self-sufficient wastewater treatment plants. To strengthen the energy independence of WWTPs, it is usual practice to improve AD efficiency. Diverse pretreatment techniques for sewage sludge are part of the AD optimizations, which aim to increase the sludge's biodegradability. Mechanical, heating, chemical-based, biological reactions, and multiple combinations can be classified. Physical and thermal prior treatments are the most employed methods today. Cambi, Biothelys, and Exelys are the most extensively used thermal hydrolysis technologies to improve anaerobic digestion in WWTPs. The first WWTP in advanced countries such as North America to adopt the CAMBI technique (Washington, DC, USA) saw an increase in biogas output of 48.5 percent in a reduced hydraulic retention period (fifteen days) [19]. The simultaneous processing of sewage sludge and other reusable materials is another technology that provides many economic and environmental benefits. The co-digestion of natural garbage and wastewater sludge makes wastewater treatment plants energy-neutral and lowers the cost of handling urban and commercial organic waste. The developed regions, e.g., Mossberg (Germany), have been employing combined digestion of sewage waste with six various complementary substrates for a decade. The Mossberg sewage treatment plants generate far greater energy and heat than is required for internal consumption. While the extra heat is used to air out dewatered muck from other water treatment plants, any excess energy is delivered back into the power grid. Local sewage treatment plant discharges are dependable and cost-effective heat sources for heat pumps.

Tables

Table 1: Examples of water as energy carrier.

Energy category	Representation
Heat	Homes' heated water is wasted down the drain but may be used to generate thermal energy.
Geo-thermic	Deep underground layers' heat is utilized for heating.
Tidal	Tidal energy is a type of hydropower that produces electricity by harnessing the power of tides.
Algae	*People can use wastewater to grow algae for biomass.*
Hydrogen	Electrolysis needs energy to create hydrogen from water. H2 is only an energy carrier ideally generated using renewable technologies like wind turbines. Sludge from wastewater can be used to make H_2 by dark fermentation.
Organic carbon	*The sludge generated by WWTPs can either be burned or digested, which results in the production of biogas.*
Kinetic	*Small-scale hydro or microturbine devices might retrieve kinetic energy from the water flow in large-scale water handling systems.*
Osmotic	*(Blue energy) The potential for generating electricity by combining water streams with various salt concentrations is substantial. Where freshwater streams enter the sea, this saltwater gradient energy is available. Reverse electrodialysis can be used to produce electricity from this.*
Bio-electricity	Bacteria are the catalysts in microbial fuel cells to oxidize organic and inorganic materials and produce an electric current.
Underground thermal energy	Heat pumps are utilized with underground thermal energy storage to supply cooling and low-degree heating. There are two thermal energy storage system types: aquifer ATES and borehole BTES.

Table 2: Energy input and potential output from wastewaters.

Energy input	Water sources	Potential output
4 PJ/y	Ground water	25 PJ/y
4 PJ/y	Drinking water	
104.9 PJ/y	Household	55.5 PJ/y Heat recovery
2 PJ/y	Sewerage	
7.9 PJ/y	Treated water	9 PJ/y Biogas generation 1.2 PJ/y Sludge incineration

Table 3: Global water reuse through application following enhanced management.

Utilization	Water reuse
Drainage of land areas	19.50%
Commercial	19%
Immobile urban uses	8.10%
Environmental advancements	7.50%
Recreational	6%
Irrigation for farming	31.50%
Indirect reusing of water	2%
Groundwater replenishment	1.90%
Other sectors	3%

The heat from heat pumps can heat and cool the plant's residential properties, community, and commercial buildings, as well as any nearby infrastructure. The first placements were made around twenty years back. Wastewater heat pumps are widely employed in advanced countries like South Korea, China, Japan, America, and Germany. Thermal ratings for heat pumps start around 20 Megawatt. HIAS sewage treatment plants are the top national utilities in Norway (Hamar and Oslo) for hydropower energy conversion in WWTP, with more than three decades of experience. According to estimates, HP systems may provide an effect of 2.5 MW. The heat pump system delivers approximately four thousand megawatt hours of energy annually, while the heat pump uses six thousand megawatt hours. WWTPs that use extreme temperatures sludge treatment methods (for example, anaerobic digestion and heat drying process) should consider using exchangers for heat to recover power across all elevated temperatures streams, comprising waste, dismiss fluid, condensation fluid, and others. Among the several applications for collected energy are water heating and garbage [17-18].

d. Unlocking Hidden Treasures in Wastewater

Using sewage waste in the building sector fully supports the CE misconceptions. The ash from sewage sludge can manufacture bricks, tiles, and other building supplies. It can also be used as a base material in producing lightweight substances such as concrete, cement, and other products. Furthermore, recovering rare metals such as silver, copper, and gold from the ashes left after igniting sewage waste is technically and economically viable. The studies explain that the world's best technical institutions are investigating the capacity to produce recyclable plastics from polyhydroxyalkanoates collected within biomass developing in sewage treatment reactors. Similar attempts are being undertaken to produce electricity directly, while biological fuel cells (BFCs) are used to remove impurities from wastewater [20].

2.2 Supply network for waste-to-energy

Because of global population growth, the need for energy, and growing trash levels, governmental goals focus on managing waste, reusing materials, preventing climate change, and lowering emissions of greenhouse gases. For this aim, recycling waste into an energy distribution network could be a viable means to accomplish a circular economy. A researcher discussed a few excellent WTE technologies, such as anaerobic digestion, gasification, and combustion. Additionally, they offered solutions for putting the WTE supply chain in place to get through difficult obstacles related to technology, economics, institutions, public concerns, and regulations. The scientists developed a sustainable plan for recycling waste into the energy supply network. This two-phase approach consists of the Micro-stage, which is responsible for the creation and optimized performance of the waste in the energy supply network, and the Macro stage, which is responsible for the distribution and efficiency of waste (including biomass, waste from factories, and other types of waste) along with the organization of the unified treatment hub. Furthermore, the studies recommended a mixed integer linear modelling structure to address undesirable transportation difficulties that increased the amount of energy and fuel manufactured from garbage substrates and optimized the selection of waste conversion methods while accounting for financial and environmental consequences [20].

In support of the waste management system's tactical, strategic, and functional aims, the results assessed the monetary value of trash supplier operations and green disposal choices. Scientists in a study gave a useful method for using the "Organic Fraction of Municipal Solid Waste" at the Varberg, Sweden, WWTP [21]. The World Health Organization is focusing on employing sustainable WTE technology to accomplish the targets of equitable development. Waste management, power, and sustainable biological economy are the most rapidly evolving sectors. A study found that the size of energy production utilizing WTE supply chain technology was handled about the multidimensional environmental sustainability structure, encompassing ecological, social, and financial components. However, extensive study indicates that power recapture from waste is a possible last alternative. Nonetheless, waste disposal is one of the most complicated energy strategy issues. Sustainability transforms rubbish from a "problem" to a "renewable supply." Consequently, one of the initial efforts to approach green cities is to efficiently use urban solid waste as an alternative energy source [18-22].. To increase energy efficiency, the researcher thought a network of several industries that can generate and use energy from trash was necessary. They said that as a technique to improve environmental effectiveness and lessen negative effects, this strategy was previously utilized at the metropolitan scale in various industrialized countries. In this case, it is critical to consider the wastewater supply line as a provider of substances with the possibility to generate energy. This analysis will aid in developing a workable WTE strategy that will encourage teamwork and good relationships between businesses and the waste disposal sector. WTE promises to be a useful method for meeting the CE requirement due to the reuse of resources and the necessity to optimize capital and sustainable development within closed-loop systems supply networks. Minimizing waste, pollution, energy leakage, and resource input could optimize vital resources. The study authors brought up the multi-level supply chain structure as an issue for the CE community that needs further examination [23].

3. Restoration of energy from wastewater sludge.

a. Energy from biogas

The biogas generated by anaerobic digestion is the principal source of energy in wastewater treatment plants, containing methane (70 percent) plus carbon dioxide (fifty percent) along with trace quantities of nitrogen-containing compounds, the element hydrogen, sulphur hydrogen, and vapour of water. AD represents one of the most employed methods to generate biogas in WWTPs. However, several preprocessing procedures, such as irradiation with microwaves, ultra sonification, enzymatic treatment, ozonation, saline or acidic treatment, wet oxidation, and the use of liquid jets, were investigated in an attempt to boost the generation of biogas [23]. Wastewater heat before treatment AD performs together effectively to generate biogas for combined heat and power generation. The combined heat and power and anaerobic digestion technique are currently used in energy-self-sufficient wastewater treatment plants in advanced countries. In this situation, the study found that thermal pretreatment increased hydrocarbon output by 31 percent. When boosting biogas generation (through anaerobic digestion) utilizing the circular economy concept, mixed digestion of food scraps and sewage waste is a viable option. This strategy reduces the total energy expenses of plant functioning while expanding the quantity of readily accessible carbon and creating more methane (more favourable energy equilibrium). According to a study, biogas generation rose from two to 4.1 cubic meters in wastewater treatment plants using co-digestion. The fact that bioenergy may be utilized for producing thermal energy and the gas steam and fuel motor cars, among other purposes, its processing and transformation are critical [24].

b. Energy from biofuels

Because sewage sludge can be utilized as a base for manufacturing biofuels, which could replace nonrenewable gasoline and diesel, curiosity has recently increased. Hydrogen is one of the gas biofuels that can be collected from wastewater. It is an environmentally friendly option due to its high-power generation and safe combustion of the final product (water). Various thermochemical techniques, including the drying process, combustion, and gasification process, were investigated to regain it and improve the generation of hydrogen-rich energy gas from wastewater sludge. The investigation proved that pyrolysis creates a gaseous product with a higher hydrogen propensity compared to wet waste drying [25]. Furthermore, syngas, formed as the carbon dioxide and hydrogen gas mix, can be a green replacement for petroleum-based fuels in producing liquefied biofuels and electricity. The pyrolysis of sewage waste and coal gasification in an atmosphere of oxygen or air are the two stages that contribute to syngas production. At cold temperatures, waste pyrolysis may additionally be utilized to produce bio-oils. The existence of polycyclic aromatic hydrocarbons in the oil, which have mutagenic or cancerous qualities, limits the technique's effectiveness. Microwave induction burning, with a maximum rate of oil output of fifty per cent (time: five and a half min) and negligible quantities of pollutants such as PAH, can tackle this problem. Biodiesel is a type of energy that can be made from sludge. Communal sludge is a lipid feedstock to produce biofuels due to its high concentration of lipids, e.g., free fatty acids, diglycerides, phospholipids, triglycerides, and monoglycerides. The use of oil-producing microbes, as well as prior treatment procedures such as ultra sonification, thermal processing, and alkaline or acid degradation, will boost biodiesel production. A new method for generating fatty acid methyl esters was developed [26]. The final product of fatty acid methyl esters can be increased by initially recovering the dewatered sludge with solvent in an acidic solution, followed by methanolysis. At the same time, the associated total energy use and expenditures are minimized. Following the process's ultimate cleaning by distillation under vacuum, biofuel is recovered with sterols, waxy substances, carotene, aliphatic alcohols, and lycopene, increasing its commercial value. The benefits of biofuel made from sewage include its affordability and quantity of sludge supplies [20].

Using microbe-powered fuel cells to generate power is a long-term solution for challenges such as excessive filth and the water-to-energy dilemma. Furthermore, advances in sewage treatment could improve microbial fuel cell's utilization of resources and energy. When the share of the electrical charge which leads to the generation of energy is forty percent and hydraulic retaining lengths are twenty hours, the amount of potential power that can be rescued from waste by microbial fuel cells may exceed 0.75 kWh/m^3 [27]. The study also found that using microbial fuel cells boosts the potential of accomplishing energy-efficiency goals in wastewater treatment plants. Energy consumption can range between 0.25 and 0.55 kWh/m^3. In addition, wastewater sludge can be utilized as a fuel for microbial fuel cells to generate electricity. It discovered macrophytes while studying an up-flow-produced wetland microbial fuel cell. Because O2 was used as an electron acceptor at the terminal for electricity output in the microbial fuel cell, it was combined with additional aeration to increase bioelectricity output. Microbial fuel cells are practical at every level because they can eliminate or restore minerals and create power in environments with warm air, balanced pH, and regular pressure. Microbial fuel cells for sewage treatment should ideally incorporate the generation of energy and recovery of nutrients or elimination. The circular economy would be pushed by the recovery of nutrients, which would offer nutrients in wastewater a second opportunity. Although MFC technologies can enhance the treatment performances in WWTPs, their utilization is constrained by the high cost of the electrode materials. This indicates that more thorough research is required regarding expenses and yield increases [23]. Anaerobic ammonium oxidation is an additional recoverable process that can be used due to the considerable energy that can be recovered during the removal of nitrogen from wastewater treatment plants. Anaerobic ammonium oxidation can improve energy efficiency in wastewater treatment facilities by decreasing oxygenation rates and extracting most organic matter from wastewater. Partial nitrification or anaerobic ammonium oxidation may minimize electricity use by decreasing the level of oxygen required for the nitrification procedure and reducing the amount of excess sludge. The paper claims that sewage treatment plants can be turned into power-producing technologies by integrating anaerobic digestion with self-sustaining elimination of nitrogen to recover fuel from the anaerobic ammonium oxidation plant. According to the search, the quantity of thermal power created during processing activities is larger than what is required for plant heating [18]. As a result, surplus thermal power in the wastewater treatment plant can be used as an additional power source for heat pump systems to provide temperature while consuming less power. The technologies exhibit varying levels of scientific and technological sophistication. In technology, cost, and environmental viability, there are still many issues for the lowest TRLs, and further research is required. Figure 1 shows energy generation from coal, oil, gas, hydro and other sources [20].

4. Wastewater sludge management

During the discharge treatment process, sludge from the treatment process, which usually consists of the solid remains in suspensions within the wastewater flow, can be produced in several ways. Primary sludge is produced when wastewater is screened, followed by coagulation and sedimentation, to remove insoluble substances, including grit, grease, and scum. Between 96.5 percent and 98 percent of the settled primary sludge comprises highly putrescible organic materials and water.

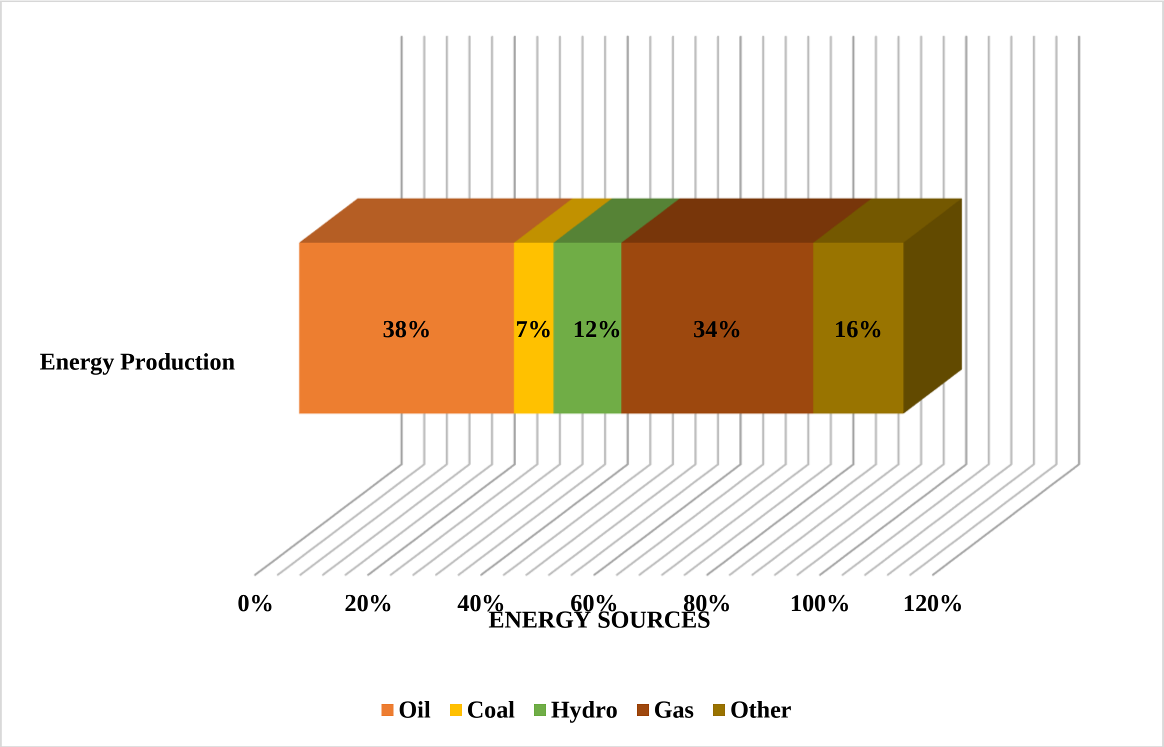

Figure 1: Energy generation from energy sources.

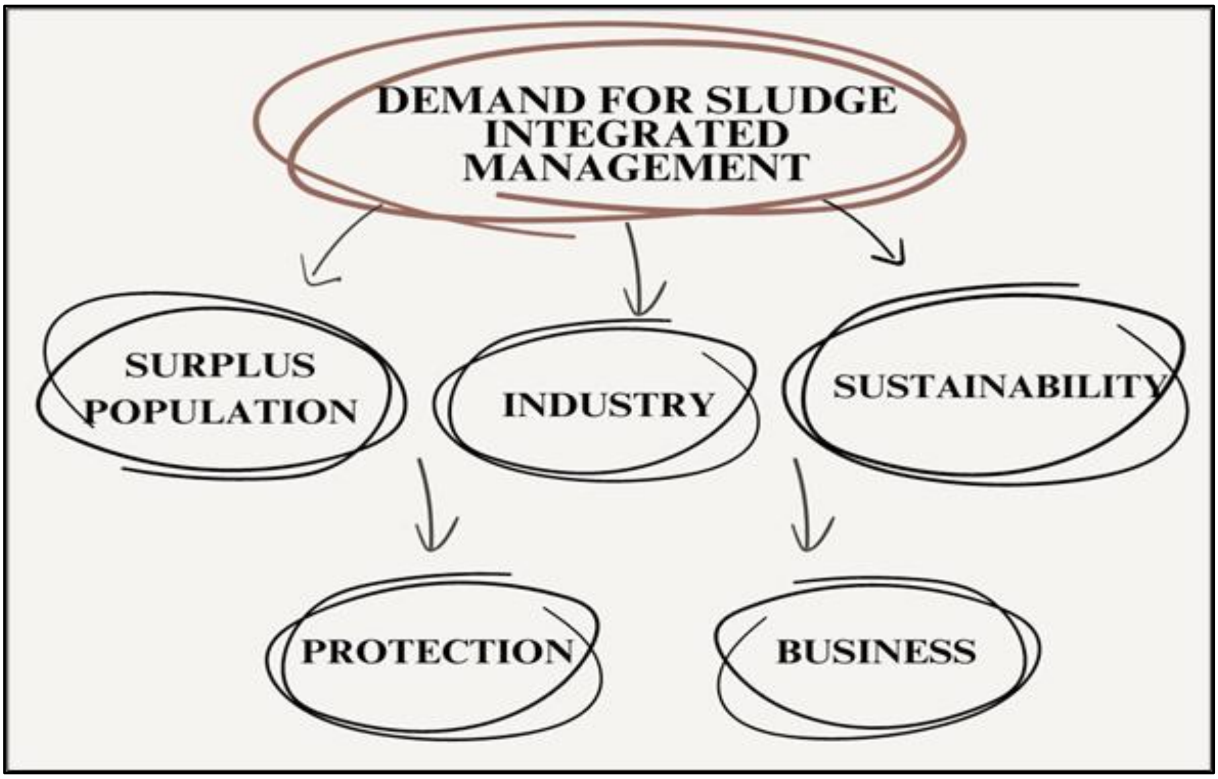

Figure 2: Demand for sludge integrated management.

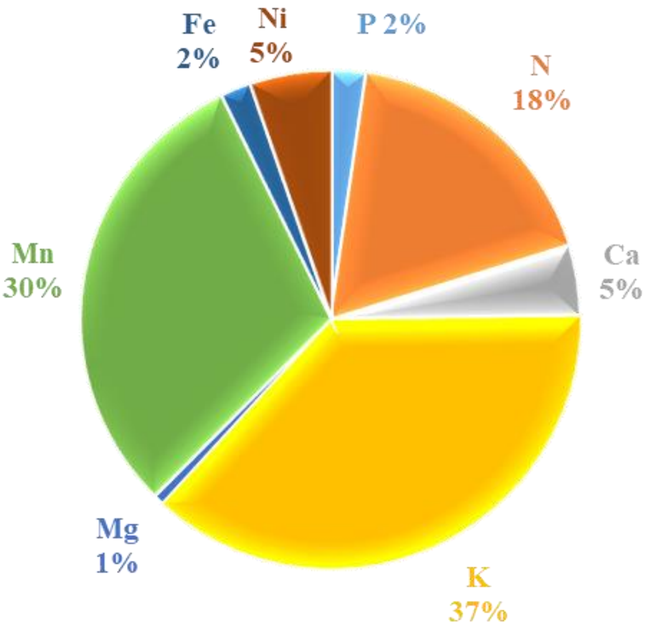

Figure 3: Elements composition mg/kg in sewage sludge.

The wastewater resulting from the initial treatment is organically processed to generate secondary wastewater, also known as waste-activated sludge, which has a complicated sludge with an activated floc structure. Sludge is typically made up of a mix of volatile organics: carbohydrates, proteins, fats, inorganic elements, and any associated water [28]. Primary sludge typically contains a higher proportion of total solids than activated sludge. Nitrogen (3 % for the mainstream and 3.5 % for waste-activated sludge) and phosphorous (0.4 % for the main and 0.95 % for waste-activated sludge) may be extracted to be utilized as fertilizers or conditioners for the soil in both kinds of sludge. Gravitational extraction of the initial sludge frequently results in a higher energy percentage term. However, microbe utilization throughout the second phase of treatment leads to a lesser power percentage for secondary sludge. Figure 2 represents the need for a sludge management system [29].

As determined by a combination of laboratory measurements, the dissolved level or organic matter load in different wastewater treatment plants impacts biological procedures such as the activated treatment of sludge. Total organic carbon includes soluble recoverable organic substances and stubborn organic chemicals that cannot be broken down organically. Total organic carbon is measured via combustion at incredibly hot temperatures and by the resulting CO2. The total amount of decomposed organics or biological demand for oxygen is calculated by measuring the oxygen consumption of just a tiny "seed" of bacteria placed in a dark-colored container with wastewater for five days. Oxygen levels that dissolve fall throughout this period as decomposing organic carbon is consumed. The total quantity of oxidizable organic matter (biodegradable and nonbiodegradable as well as dispersed and particulate matter) is calculated by the quantity of oxygen that is present in the form of an oxidizing agent required to oxidase enzyme organic components by warming the test specimen in a potent sulfuric acid solution containing potassium dichromate [30]. Sludge handling is one of the most difficult and time-consuming processes encountered by wastewater treatment due to its high level of water, low dewatering ability, and stringent muck reuse or disposal restrictions. Sludge management can account for up to 60% of the total cost of a plant that treats wastewater. Wealthier countries such as Canada generate over three million tons of sludge and biosolids annually, while the United States generates seven million dry tons of sewage waste. The provincial governments in Canada regulate the usage and disposal of sludge; therefore, there are significant variations in the approaches taken to handle biosolids from one province to the next. Sludge management focuses mostly on pathogen removal and volume reduction. Sludge is typically disposed of using three primary methods: incineration, landfill disposal, and land applications as soil conditioners. To meet the standards of a landfill or incinerator, sludge must first be dewatered to 40wt% solids, which is expensive [28-31].

The water component of the sludge must also be evaporated during combustion or incineration, which consumes much energy. Landfill sludge releases undesired additional pollutants into waterways, air, and land. If sludge is used as a conditioner for the soil, the heavy metals found in the sludge might damage the soil's structure. The present wastewater treatment plants must lower their environmental impact by developing sustainable methods to limit the quantity of sludge that must be thrown off or converted into bioenergy. As a result, the present understanding of wastewater sludge has shifted from an impurity to be treated and discarded to a sustainable source for energy restoration. The potential to generate energy from sludge is determined by its chemical makeup and amount of energy, specifically the volatile solid material, which can be categorized as effortlessly recyclable organic matter (approximately 50 per cent in the main sludge and 25 per cent in waste-activated sludge) versus not quickly biodegradable organic substances (about 30% in main sludge and 55% in waste activated sludge). The most important technologies for generating energy from waste are now waste-to-biogas and wastewater-to-bio-oil techniques [3].

5. Environmental Impact and Disposal of Sewage Sludge

Wastewater sludge is considered a bio source since it contains many nutritious substances and harmless organic components [32]. In addition, it contains a variety of pathogenic microbes, parasites, toxic organic materials, heavy metals, and other contaminants that, if treated improperly, could seriously harm water bodies, the environment, and the atmosphere. The inorganic and organic nitrogen in wastewater sludge will eventually yield nitrogen dioxide (of which part will be nitrified to form NO3) through a series of chemical, physical, and biological processes with soil colloid, causing acid rain, photochemical pollution, and ozone layer degradation. Eutrophication, one of the most well-known forms of environmental contamination, would also occur because of nitrogen and phosphorus delivered by rainwater into water bodies. Microorganisms break down amino in deceased animals and plants into ammonia, which is then transformed into nitrogen via nitrification and denitrification. Heavy metals that strengthen through biological accumulation and penetrate the human body via the dietary chain can cause serious health problems. Furthermore, germs in wastewater sludge spread and pollute air and water supplies in various ways. Finding effective management solutions for the secure transportation and processing of wastewater sludge is thus critical [33].

There are now three main sewage sludge disposal or utilization categories: land farming, landfilling, and incineration. Advanced countries, such as China, have extensively used dumps to dispose of sewage sludge. Due to a lack of places to dump waste and the ubiquitous environmental dangers to public health, landfilling has declined in popularity and is now prohibited. The thermal decomposition of hazardous and toxic content during burning can reduce the volume of sewage waste by 69.9 per cent. Instead, the exhaust emissions released into the atmosphere can cause various environmental difficulties, including acid rain, changes in the climate, and the discharge of contaminants into the surroundings due to the leaching process of the ashes. Furthermore, because dewatering or drying the feedstock is required, combustion has become known as a high-cost sludge technique from sewage management. Because of the presence of toxic substances and microorganisms in sewage waste, which may eventually impair the condition of the soil and provide a potential safety concern, utilizing wastewater sludge for agricultural purposes is increasingly considered a hazardous disposal option. Furthermore, the three primary ways of disposal and other alternate techniques of sewage sludge usage have been proposed. Land restoration, landscaping and gardening, forest management, industrial operations, recovery of resources, and energy recovery are examples of these strategies. When it involves recycling energy and commodities from sewage sludge, the thermochemical process holds more promise in terms of financial viability and sustainability for the environment [33].

6. Constitute of sludge

It is critical to investigate the sludge's composition to evaluate the options for generating electricity from sewage sludge. As a starting point, this mixture can be divided into six component groups: (1) Nontoxic organic carbon products (about 59.9%), primarily derived from natural sources, (2) phosphorous-rich and nitrogen-containing elements, and (3) poisonous organic and inorganic contaminants, including (a) heavy metals such as zinc, lead, copper, chromium, nickel, cadmium, mercury, and arsenic (concentrations vary from over one thousand ppm to a little than one ppm) and (b) chemical pesticides, dioxins and linear-alkyl. The fact that all these substances are together in sewage sludge is its main issue. Chemicals made with organic nitrogen, phosphorus, and carbon can be considered useful chemicals [34]. This frequently applies to inorganic substances as well. Environmentally friendly treatment limits the potential harmful impacts of wastewater sludge or byproducts of wastewater sludge processing operations on the surroundings and humans while recycling and recovering useful components. Water must regularly be removed for transportation, disposal, or proper treatment. The number of nitrogen-containing compounds in the sludge is small compared to the extent to which these substances are found in the wastewater itself. The percentage of phosphorus in the waste is affected by the type of wastewater treatment method used. Almost all the readily available phosphorus can be concentrated in the sludge. However, it is also feasible to collect phosphorus directly from the waterline. Figure 3 represents the composition of sewage sludge [32].

a. Sludge characterization

A local sewage treatment plant generates multiple kinds of sludge depending on its processing stage, including the following: Primary sludge: Main sludge is formed when bulky particles, oily grease, and lubricants are separated from untreated wastewater during the initial treatment process, including screening, grit disposal, the flotation process, precipitation, and deposition. Basic sludge typically contains two per cent to nine per cent materials, with the residual 90% (and possibly 99.5%) being liquid [25]. Secondary sludge: Secondary sludge (or waste-modified sludge) is formed when the biologically degradable organic matter of wastewater is digested by microbes undergoing biological processing. The amount of all grains varies from one percent to a rate of three depending on the type of biological purification technique utilized, with the remaining being water. The organic portion of waste-activated wastewater contains the following elements: coal (55 per cent), air (30 per cent), ammonia (20 per cent), gas (9.5 per cent), acid (1.5 per cent) and phosphorus (2 per cent). Tertiary sludge: When nutrient (nitrogen and phosphorus) removal is necessary during the advanced wastewater treatment stages, tertiary sludge is produced. Processes for nutrient removal are typically carried out in tandem with organic matter removal [25]. Chemical sludge is produced by any chemical-based technique utilized in the public wastewater treatment plant like the Chemically Supported Primary Sedimentation Technique. This procedure involves administering a suitable coagulation upstream of the initial sedimentation to reduce the amount of organic matter needed for the following biological remedy. The chemicals and concentrations used influence the sludge's both quantitative and qualitative qualities. Common reagents include lime hydrated, aluminum sulphate, chitosan, and ferric chloride. The suggested dosage variation for chemicals is 9.5 to 50 mg/l with one notable exception of lime hydrated, which has CaOH2 doses ranging from 29.9 to 500 mg/l. Chemical sludge specifically ones generated by chemically assisted primary sedimentation technique might include trace amounts of metals, some of which are caused by the application of chemical coagulating agents. The process of backwashing water following sedimentation or biochemical-physical treatment and coagulation can also produce chemical sludge. The thicker supernatant flocculates [35].

According to the findings, there are variances between primary as well as secondary sludge about pollutants, water, nutrients, and power. Basic sludge includes higher amounts of total and volatile substances than later biological sludge. Secondary sludge on the other hand, is high in nutritional content. Because of the concurrent presence of the initial sedimentation, which is expected of a large wastewater treatment plant, the secondary organic sludge is “purer” regarding metal composition. As a result, primary wastewater is conceptually perfect for energy recovery via anaerobic digestion whereas secondary wastewater is suitable for material extraction via agricultural fertilizer usage. Even though optimum administration at a large the wastewater treatment plant should generate the conditions for their split into two streams secondary and primary are currently combined upstream of the sludge pipeline. The most common technical sequence is thickening purposes, stability (aerobic and anaerobic), physical dehydration and thermal processing (drying and burning) with the last only suited for large wastewater treatment plants [20].

7. Sludge-to-energy processes

In a nutshell, the different techniques for recovering energy from wastewater sewage or rather from the organic molecules in the sludge can be classified as follows: wastewater sludge anaerobic digestion, biofuel production, direct production of electricity in microbial fuel cells, sludge incineration with energy recovery, sewage co-incineration in coal-fired power plants. These treatment procedures are already in use, whereas others remain being studied. Figure 4 represents the methods used for the sludge-to-energy conversions.

7.1 Anaerobic digestion

Without a suitable electron acceptor, a collection of microbes breaks down organic matter into methane and carbon dioxide, which can be used as biogas for producing electricity or heat. Multiple life cycle assessments show that anaerobic digestion is a viable waste in energy systems regarding energy output and greenhouse gas production. Anaerobic breakdown is a tried-and-true technology for energy recovery in wastewater treatment plants. Via the breakdown of primary sludge and biomass generated during typical aerobic treatment, it generates energy from methane-rich biogas. Furthermore, efforts have been undertaken to immediately extract bioenergy from wastewater from towns using anaerobic digestion. Previously, it was considered that high-strength wastewater might be utilized for anaerobic digestion in either mesophilic (28-40°C) or thermophilic (50-57°C) conditions. When psychrophilic methane production occurs, there is potential for wider application in moderate environments. Significant advances in the alteration of anaerobic digestion configuration and process administration, especially to anaerobic membrane bioreactors, have occurred in recent years, making the use of anaerobic digestion for the treatment of low-strength and low-temperature wastewater feasible in temperate areas around the globe [36].

Biomass left over through activated sludge techniques, commonly regarded as an unfavorable byproduct of wastewater treatment, can also be regarded as an unprocessed product for energy production. Anaerobic digestion of activated sludge and other strong organic materials is recognized as an environmentally and energy-friendly technique compared to other solutions such as landfilling, incineration, and composting. A recent mathematical framework suggests that processing each type of sludge independently for material and energy extraction is the optimum course of action. According to full-scale data, even for local sewage treatment plants with secondary biological wastewater treatment in a moderate climate, anaerobic digestion of sewage sludge alone allows wastewater treatment plants to achieve energy sufficiency [37]. Depending on the microbial ecology, first and second-stage digesters are commonly used. Methanogenic and acidogenesis operations are distinguished in a two-stage procedure, preventing acidogenesis in the following stage and improving sludge properties. Due to its slow rate, anaerobic digestion was only employed for wastewater treatment apart from biomass waste stability in the latter part of the twentieth century. The Upstream Anaerobic Wastewater Carrier reactor, created in 1970 and has seen multiple advancements since then, is currently the most popular anaerobic digestion method. As a result, anaerobic digestion is now widely used in exceptionally strong wastewater treatment facilities other than sludge from sewage and waste from municipalities [38].

a. Energy generation, beneficial product, and difficulties

Using stabilized biosolids and biogas are two crucial parts of the effectiveness of the AD process. Biogas comprises sixty-five per cent, forty-five per cent carbon dioxide, moisture, and various trace molecules such as siloxanes and hydrogen sulfide based on the substrate qualities. The impurity in biogas reduces its economic and calorific value as a fuel. For energy production, removing water and H2S through physical-chemical processes like scrubbing or biological processes is crucial, and additional CO2 removal is needed to upgrade to natural gas quality. If purification is neither feasible nor cost-effective, flares are utilized. The potential for producing electricity is lost, but the generated heat can be captured and utilized [39]. Cogeneration of electricity and useable heat is a promising and widely used strategy to boost energy collection at WWTPs with anaerobic digesters. These applications, known as Coupled Heat and Power systems, improve energy-collecting efficiency by generating electric power and heat. According to the studies, the Environmental Protection Agency has advocated using biogas in wastewater treatment plants' combined heat and power systems units. The wastewater treatment combined heat and power systems that might be deployed in 1351 wastewater treatment plants have approximately 411 Megawatt of electrical power and 37,908 million British thermal units, 1 MMBtu 14 293.1 kilowatt of thermal energy per day. Other high-value byproducts of anaerobic digestion, including hydrogen, valuable substances (e.g. as the carboxylate platform and bioplastic), and microbial electrosynthesis, could be produced in future generations. Biosolids (stabilized waste products from anaerobic digestion) can be used on farmland or in nurseries for plants to recover nutrients. However, its use must be carefully examined because of potential atmospheric (contaminants such as metallic substances) and health concerns. Certain microbial consortiums enable the production of biopolymers from biomethane and their use as an energy source. The production of bioplastic feedstock by specialized methanotrophic bacteria treated derived methane is particularly promising. Mango Resources is promoting a carbon-neutral technology that has the potential to be economically effective [39]. Despite knowing that a few studies have focused on microbial community analyses at low-temperature anaerobic digestion, a more detailed understanding of interactions between microbes and social patterns in these distinct environments is necessary, with a special emphasis on methanogenesis in cold settings. In addition, despite the poor solubility of methane, the total quantity dispersed throughout process effluent may be large in the fast mainstream anaerobic digestion. Methane loss as gas that dissolves in wastewater will have a consequence on later removal techniques, the production of energy and emissions of greenhouse gases. Consequently, improved methane extraction efficiency is crucial [38].

7.2 Bio electrochemical systems

A collection of configurations known as bio electrochemical systems (BESs) can utilize the chemical energy contained in biological waste to produce either power or useful products. Microbial fuel cells have traditionally been the most extensively used type of bio electrochemical cells. Microbial fuel cells are considered an environmentally safe renewable energy device for treating wastewater capable of working at cold temperatures and handling minimal-strength effluent. According to studies, lab-sized microbial fuel cells with high chemical oxygen demand removal effectiveness from complex wastewater may be combined with electricity production. Microbial electrolytic cells restore energy in the form of usable molecules with a modest supply via outside power, often a gas such as methane or hydrogen, and facilitate electricity generation from wastewater [40]. Although the focus is on recovering energy from microbial fuel cells and microbial electrolytic cells, it is important to remember that nutrient elimination and restoration technologies comprise an essential and rapidly developing area of research. High nitrogen dioxide emissions from microbial fuel cells for nutrient removal and nitrogen dioxide buildup may present an opportunity for energy recovery via the coupled aerobic-anoxic nitrous decomposition operation. Furthermore, due to the high pH, nutrient recovery may be performed at the cathode via ammonia migration and the removal of protons [38].

7.2.1 Electricity generation: MFCs.

A microbial fuel cell is a device that uses microorganisms as a biological catalyst to convert chemical energy into electricity. In addition to chemical oxygen demand removal, autotrophic denitrification has been studied on microbial fuel cell cathodes; however, performance is influenced by the source of carbon and the ratio of carbon to nitrogen; therefore, actual performance will vary depending on the purpose of the process. Additionally, nitric oxide to nitrogen dioxide has decreased slightly following cathodic denitrification [41]. It is important to highlight that nitrogen oxide is a potent greenhouse gas that must be maintained under check. The degree of substrate deterioration, the activity of bacteria, proton transfer of mass in the fluid, the material of the electrode and development, and operational variables (like pH, buffer availability and temperature change) all influence how well microbial fuel cells perform with the expensive electrode substance frequently serving as a limiting factor. Materials made from carbon are currently the most used in microbial fuel cells. A contemporary trend is the search for cheaper, environmentally friendly, and conductive electrical electrode materials. In the context of nanotechnology (nanotube, nanofiber and nanosheet), unstructured large-scale porous substances, and other modifications, the claimed power density has been enhanced by up to fivefold compared to regular materials. In addition to developing electrode materials, it is vital to progress towards minimal resistance and affordable separators like interchange filters or membranes. Microbial fuel cells’ low power supply and high expense continue to restrict their widespread deployment, making them less environmentally friendly than originally thought. Lab-scale microbial fuel cells' greatest area energy density is 6860 million watts per square meter, and their greatest volumetric power density is 2.87 kilowatts per cubic meter. This laboratory-scale research suggests that scaling up microbial fuel cells is feasible. However, small-scale studies have not yielded equivalent areas or volumetric energy densities. The amount of power in microbial fuel cells was determined to be inversely related to the logarithmic of the anode's surface area, and many studies have demonstrated that scaling up can result in a performance loss of up to tenfold or more. Scaling up normally entails two primary approaches: expanding the ability of every cell and connecting many microbial fuels cell stacks. Microbial fuel cells, on the other hand, suffer from loss of power due to an increase in anode opposition, particularly at the anode's leading-out end. Various novel configurations and operating controls have recently been introduced, with more to come. Because it removes the need for separators and employs passive oxygen transfer to feed electron acceptors, the structure of single chamber, air-cathode microbial fuel cells is considered the most promising. MFCs with several anodes and a single cathode can lessen voltage loss in systems with multiple anodes and cathodes. Other investigators focus on energy harvesting technologies and work to increase output by enhancing converter efficiency. For the generation of electricity, electron transport from microorganisms to electrodes is also essential [42]. There are currently only two recognized routes for the transmission of electrons: indirect transfer via electron shuttles and direct transfer via outer membrane cytochromes or nanowires. It has been shown that genetically altering the electron transport pathway is an effective technique to boost energy output. Several designs for microbial fuel cells of various types of equivalents to chemical energy cells have been developed in recent years by combining bio-electrochemical motion, weight, and energy balances. Although there is still much potential for technological advancement, scaling up more effective MFCs will be easier by developing more advanced MFC models. Figure 5 represents the power generation achieved from wastewater sources.

Utilizing microbial fuel cells may also include energy recovery from chemical and nitrogen oxygen demand. The growth of algae consumes carbon dioxide while producing oxygen. By combining these metabolic activities, algae farming, microbial fuel cells, and aerobic-activated wastewater for chemical oxygen demand minimization have been proposed as a potentially sustainable and energy-positive alternative. Photosynthetic algal microbial fuel cells and microbial capture of carbon cells with algae growth have been created to clean wastewater while producing energy and biomass. Other bio electrochemical systems that have been substantially changed have lately been reported. A Microbial battery, for example, was created. In contrast to microbial fuel cells, which use air cathodes, the microbial battery features an electronic solid-state cathode that can be "recharged" regularly. The study also discloses a novel microbial reverse electrodialysis cell, which stores energy via salinity gradients and waste heat. Because these novel technologies depend on laboratory experiments, more research is required to determine if they can be applied in actual events applications on a massive scale [43]. Advanced methanogenic digesters usually generate 960 watts per cubic meter of energy. The current generation of microbial fuel cells is different since the energy density of microbial fuel cells needs to be increased by a factor of four to be competitive with anaerobic digestion (the usual area energy concentration for microbial fuel cells is 1,000 milliwatts per square meter.) Furthermore, the primary goal of wastewater treatment plants is to get rid of pollutants, with energy production coming in second. Despite these challenges, microbial fuel cells remain among the most promising methods for achieving energy-positive wastewater treatment due to their substantial energy generation ability and low environmental impact [38]. MFC has recently gained popularity among scientists as an exciting new study area. However, there are still certain related problems that restrict its use in the creation of electricity and the treatment of sewage. As a result, an achievable approach for producing clean, safe, carbon dioxide-free energy from renewable sources while also processing wastewater to eliminate contaminants is still required. This strategy can become more beneficial in the business set by overcoming the present obstacles and looking ahead to their potential [44].

7.3 Hydropower Technology for wastewater energy production

One option to consider is hydropower, which generates electricity using mechanical power generated by wastewater. This allows an amount of the energy stored in the sewage that would have been wasted to be used. According to studies in the municipal water field, more understanding and awareness of this option must be needed. Hydropower, a well-known green power source, is now being examined on a limited scale as a viable solution for recovering energy at present water supply systems, including a wastewater treatment plant; there is no consensus on the dimension or capacity-based categorization of hydroelectric systems. For example, in advanced countries, these categories are commonly considered: small hydro with an energy output ranging from one Megawatt to 10 Megawatt; Mini hydro with an energy generation of 100 kilowatts to 1000 kilowatts; Micro-hydro with an energy production of Five-ten kilowatt to 100 kilowatts; and Pico hydro having a strength intensity of as much as five kilowatts. In wealthy countries, the distinction between large-scale and small hydro may be as large as thirty or Fifty Megawatt. Mini hydro systems are typically used to bridge the gap between larger hydropower plants that feed electricity networks and independent off-grid systems that provide energy for consumption in rural or remote areas [45].

8. Thermochemical processing of sewage sludge to generate energy.

Thermochemical technologies are advantageous for wastewater sludge management because they can regain resources and energy, drastically reduce the amount, efficiently eradicate pathogens, and provide other advantages [13]. The main thermochemical methods include combustion, gasification, pyrolysis, and hydrothermal liquefaction. The type and caliber of raw material, the preferred shape of desired goods, local emission requirements, economic reasons, and so on are all important variables in the selection of thermochemical techniques in general. The operational principles of the principal thermochemical techniques are briefly outlined in the section as follows:

8.1 Pyrolysis

Pyrolysis is the thermal decomposition of substances in an inert environment that produces gases, fluids, and char. Condensable and gases that are not condensable combine to form gases. The phenomenon of condensation and cracking caused by heat mechanisms is included in the pyrolysis method. Pyrolysis products are classified as char (the created solid waste), pyrolysis gas (which contains incondensable lower molecular elements), and pyrolysis oil or liquid (which contains condensable volatile constituents). Pyrolysis is more endothermic than combustion, which is quite exothermic; its endothermic energy is around 100 kilo joule per kilogram. The pyrolysis outcomes are affected by heat, reactor stay duration, pressure, and the starting municipal sewage sludge characteristics. Fast pyrolysis is performed at high burning stages, a moderate temperature (500 degrees), a quick gas period of residence (2 sec), and rapid vapour cooling. The main result of this process is pyrolysis products, also known as pyrolysis oil or bio-oil, which can be utilized as a biofuel and a source of important chemical substances. Slow pyrolysis, on the other hand, frequently happens in an inactive (oxygen-free) atmosphere and is distinguished by comparatively low temperatures (350 to 600°C) and heating cycles. It is less harmful than incineration because of the reduced temperatures of operation and a shortage of air, which are the key factors for the creation of furans as well as dioxins. The low operating temperature of pyrolysis is primarily responsible for the shortage of metallic elements in the pyrolysis fuel, which remain trapped in the resulting solid carbon-based char [46].

The pyrolysis application needs to be improved by the system's financial viability and the comparatively complicated nature of the processing equipment. However, pyrolysis's economic feasibility may be greatly boosted if oil production could be increased more and high-value-added consumables can be effectively manufactured from pyrolysis chars. Both char and pyrolysis gas can be used as fuels, while pyrolysis oil can be used as a fuel or raw material in producing chemicals. Compared to combustion, pyrolysis gases from combustion will require fewer steps to meet emission standards. The pyrolysis of sewage waste produces an organic fluid with an excessive amount of water that is brown in appearance. If the result of pyrolysis is liquid, it is vital to recognize both the yield of liquid and the liquid qualities to identify viable liquid applications or upgrade techniques. Although many studies advocate energetic purposes for pyrolysis liquid, the qualities critical for its application as a fuel have served as the focus of the most comprehensive investigation. While there has been some interest in the pyrolysis of wastewater sludge to produce oils, its commercialization could be faster. Char is often the principal byproduct of wastewater sludge pyrolysis during liquid production. The chars' greater combustibility is low, at around five megajoules per kilogram, rendering them unsuitable for combustion or other uses. In addition, the high concentration of contaminants in the chars may need costly flue gas modifications. Legal constraints limit the capacity to landfill char. However, one outstanding feature is the use of wastewater chars in producing adsorbents, which could be useful for eliminating pollutants such as hydrogen sulfide or nitrogen oxides in atmospheric flows. While the method can be energetically independent, users of pyrolysis plants will still face challenges in developing added-value uses for liquid and solid products. The requirement to dry the material being processed precludes pyrolysis from being widely employed. However, the prospects of widespread pyrolysis utilization are increased in the scenario of dehydrated waste and when potassium and phosphate may be obtained [46].

8.2 Gasification

It is vital to understand the difference between pyrolysis and gasification. Gasification is converting municipal sewage sludge's carbonaceous substance to a gas that can be ignited and ash under the influence of a responsive surrounding like air or steam. Whereas the pyrolysis technique is a thermochemical process that takes place at extreme temperatures (500 to 1000 degrees Celsius) and in an inert environment, gasification predominantly transforms organic matter into burning gases or syngas utilizing between twenty per cent and forty per cent of the oxygen required for entire ignition. Char or slag, oils and water are all consequences of the gasification process. Temperature, stress, and steam are used in gasification to convert materials into syngas, a combination of carbon monoxide, hydrogen, and other components like gases. The heating value of syngas generated by wastewater sludge is approximately 3.5 megajoules per meter cube. This method can avoid problems that are common during combustion, including a requirement of additional gasoline, sulphur oxides and nitrogen oxides emissions, toxic metals in ash from burning and the possible formation of chlorinated dibenzofurans and dibenzodioxins. This procedure can also use dewatered waste (forty per cent) or sewage dehydrated to a dry matter level of more than 91 per cent [47]. The gasification of garbage is like the gasification of solid fossil fuels. At extreme temperatures (650 to 900 degrees), the organic elements of waste degrade, producing a gas containing hydrogen, carbon monoxide and methane. The resulting gaseous product may also be utilized to create energy for fuel cells. A common gasification gas has a hydrogen concentration 11.17 volume %. In addition to carbon dioxide and the process of gasification substrate, it contains flammable chemicals such as carbon monoxide (10.77 volume per cent), methane (2.09 volume per cent), and carbon sulphide (1.2 volume per cent.) A sequence of intricately timed chemical and thermal breakdown events makes up gasification. The entire process is energy self-sustaining, and steady-state operation requires no energy input. Sludge goes through several intricate physical and chemical transformations during gasification, beginning with water removal. Next, dried MSS is pyrolyzed. Condensable and non-condensable vapours, char, and the ensuing volatile pyrolysis products undergo additional gasification reactions to create permanent gases. The heat in the zones below evaporates moisture from the sewage sludge when it enters the gasifier in the drying zone. The fuel's volume, the recirculation speed, the humidity content of these gases, the variations in temperature among the input and the exhaust gases, and the inner diffusion rate of moisture within the fuel all impact how rapidly the fuel dries out. In this region, sewage with a minimum of 14.9 per cent moisture frequently loses most of its moisture. The ideal wastewater gasification objective is to produce clean, combustible products with excellent efficiency. Combined gasification fuel cell technologies benefit typical waste gasification for power generation. As a result, it is feasible to attain a 30% electricity consumption [48].Because of steam, the gasification process enhances hydrogen production, and the gas has a greater heat-retaining value. Applying steam as a gasification environment creates syngas (a combination of hydrogen and carbon monoxide) through the reformation reaction of methane gas. The change in the reaction caused by Carbon monoxide increases the final amount of hydrogen even further. The research focus is developing practical methods for producing hydrogen from renewable resources, such as MSS. Researchers have looked at the potential hydrogen synthesis from sewage sludge using the downdraft gasification approach. Because damp sludge from sewage provides the method with steam, in this case, either dewatering or drying must occur before gasification. Wastewater constitutes one of the more potential gasification starting materials for hydrogen generation globally [46].

8.3 Combustion

Sewage waste incineration aims to totally oxidize all chemical sludge molecules, including hazardous organic chemicals, at extreme temperatures. The process can be applied to waste that has been physically dewatered or dried. Two possible environmental risks linked with sewage combustion are the release of toxins into the environment and the condition of the ashes. Plenty of standard equipment is accessible to successfully reduce emissions of gases to fulfil the demanding requirements for air quality. Furthermore, there are no substantial environmental concerns about the ash's worth, particularly considering the number of contaminants in the ash. Because of the extreme temperatures in incineration and the composition of inorganic substances in the waste product, metals such as mercury are strongly immobilized and not susceptible to leaching. This ash must be cleaned off or used to create construction supplies. Because the cremation process generates substantial amounts of unclean exhaust gases, the expense of an efficient and adequate gas purification system is rather high. This is the primary reason for the expensive nature of sludge incineration. The manually dewatered waste cake can be dehydrated before burning, or the energy gained from incineration may be utilized to generate electricity. The target of waste incineration systems is the recovery of renewable energy from waste in thermal energy (steam) or electricity. The amount of thermal energy that can be generated is heavily influenced by the amount of water in the wastewater and the customization and efficacy of the combustion, electromechanical dewatering, and drying methods. In conjunction with energy recovery, garbage-burning plants are being employed more than ever. The approach is most commonly utilized on a large scale [6].

8.4 Hydrothermal liquefaction

Throughout the hydrothermal liquefaction thermochemical method, performed with water or another appropriate solvent at extreme temperatures (usually 250-375°C) along with elevated pressures (5-20 Mega Pascal), the natural material is broken apart to produce four outputs. The four outcomes are bio-crude or biomass oil (the desired output), the liquid phase, the energy supplies, and solid leftovers. The three primary steps in the essential reaction routes for the hydrothermal liquefaction of wastewater sludge are: (1) fragmenting down numerous biomolecules (such as amino acids, lipids, and sugars) into a single molecule or oligomer units; (2) departing down the individual monomers or oligomers by splitting, dehydration, deamination, and decarboxylation creating unstable and active parts of tiny molecules; and (3) restructuring of light parts through condensation. Figure 6 depicts the bio-oil output from multiple kinds of sludge, including the main sludge, bacterial sludge, activated sludge, and sludge from sewage treatment plants [49].Solvolysis or hydrolytic processes are required to dissolve macromolecules, e.g., protein, lipids, carbohydrates, etc., into monomer or oligomer components in water or an organic solvent. Higher pressure as well as temperature aid in these processes. The following step is decomposition, which includes the removal of the amino acid composition by water loss, decarboxylation, and deamination processes, in addition to eliminating water, carbon dioxide, and ammonia. It is significant to point out that the dryness and decarboxylation activities reduce the level of oxygen in the bio-oil by releasing carbon dioxide and water vapour, thereby enhancing its degree of stability and energy density. Compared with the initial two phases, specific unstable and reactive products of breakdown called free radicals are compressed, cyclized, and formed polymers in the third step to produce large molecules of char or bio-oil. If a stabilizing element, such as hydrogen, is accessible easily during the process, harmful radicals will be confined, resulting in sustainable bio-oil compounds that have reduced molecular weights. Figure 7 depicts the hydrothermal liquefaction process route [3].

8.5 Technical challenges of sludge to energy processes

8.5.1 Pollutants emission

Because incineration occurs in an oxidizing environment, the sulfur and nitrogen-containing substances in the waste product would turn into air pollutants oxides of nitrogen and Sulphur, causing major environmental hazards such as acid rain and photochemical fog. While burning sewage sludge, Hydrochloric acid and chlorine can be discovered in the exhaust gases because the chlorine in the material is burned, leading to the incinerator deterioration. Chlorine would also serve as the principal chlorine-treated agent in the synthesis of hazardous Polychlorinated furans and dioxins formed in the incineration stage of the oxy-chlorination procedure, which can be helped by the metal species found in fly ash's catalytic activities. Furthermore, poor organic matter combustion generates the gases carbon monoxide and polycyclic aromatic hydrocarbons. Furthermore, to the gas as mentioned earlier contaminants, fly ash contains hazardous metals such as lead, mercury, and cadmium, as well as additional contaminants such as polychlorinated furans and dioxins, all of which pose major health risks such as breathing concerns [50]. Therefore, one of the main technological problems for incineration technology is to limit or reduce the generation or release of these pollutants [33].

8.5.2 High moisture content

The energy recovery efficiency of sewage sludge, in particular secondary sludge, is compromised by the need to dewater or dry it prior to pyrolysis or gasification treatment, even though the right amount of moisture can encourage biochar gasification and tar decomposition [51]. Additionally, sewage sludge with much moisture is pasty, which presents significant difficulties for continuous feeding. In the instance of wastewater sludge, the gasification process, for example, the highest permissible moisture level in the material was indicated to be roughly 24.9 per cent weight per cent in down draft gas generators and 49 per cent weight per cent in updraft gasifiers, but gas output plummeted at moisture values of more than 29.9 per cent. As a result, before introducing waste sludge to the gasification and pyrolysis process, the amount of moisture must be reduced to an acceptable level [33].

8.5.3 Tar issue

Tar is a black, dense, and exceptionally sticky liquid that contains a variety of polycyclic aromatic hydrocarbons, oxygen-containing hydrocarbons and aromatic substances (1-5 rings). Tar formation can result in several issues during the pyrolysis/gasification process, including the development of coke, clogging of the filters and lines, etc., which can seriously disrupt the operation. According to studies, the syngas generated by an air-blown revolving fluid-bed biomass gas generator included approximately 9.9 grams per cubic meter of tar. However, tar levels in various gasifiers could vary between 0.5 to 99.5 grams per cubic meter [52]. However, most syngas applications call for tar content levels of no more than 0.05 g/m^3. As a result of its teratogenic and carcinogenic constituents, tar is also bad for human health. Tar also has a substantial amount of energy that can be converted to gas produced. Tar generation while performing the pyrolysis and gasification operation would thus not merely contribute to unreasonably costly repairs for downstream machinery but also lower the process's overall energy performance [33].

8.5.4 Formation of NOx and SOx precursors

When pyrolyzed or gasified, sewage sludge's 9-weight per cent nitrogen and 1-weight per cent sulphur content would release NOx and SOx precursors, which might eventually result in photochemical smog and acid rain as secondary pollution. For example, ammonia and sulphur in wastewater sludge can be converted to ammonia, hydrogen cyanide, and hydrogen sulphide gases under reducing situations or nitrogen oxides and sulphur oxide gases under oxidation settings. Several studies have been undertaken to reduce the formation of compounds containing sulphur and nitrogen during the combustion and gasification of wastewater sludge. For example, it was revealed that almost all of the ammonium in wastewater sludge existed as amino acids and that the majority of the nitrogen-containing entities created during wastewater sludge pyrolysis were hydrogen cyanide and amine, which can then be converted into oxides of nitrogen [53]. Studying the interaction of nitrogen and sewage waste following pyrolysis and gasification is critical for designing nitrogen oxide reduction techniques. The transportation and conversion of ammonia are complicated due to the variability of wastewater sludge and pyrolysis settings. For example, the wastewater sludge pyrolysis process produced excessive ammonia, but the study showed a significant quantity of hydrogen cyanide. Organic sulphur substances discovered in sewage waste include sulphonic acidic substances, aromatic and aliphatic substances, sulphoxide and sulphur compounds. When the sludge is pyrolyzed or gasified, these compounds decompose to produce sulfur-containing gases. It needs to be pointed out that when exposed to the atmosphere, these gases erode metal surfaces and convert to sulphur oxides[33].

8.5.5 Differences between batch and continuous-flow reactor systems

Whereas hydrothermal liquefaction is a potential technology for converting wastewater sludge into liquid fuel, many technical challenges must be addressed [54] Compression processors must be utilized in high-temperature, high-pressure settings. The HTL reaction creates a corrosive environment that necessitates using resistant materials for reactor construction, such as stainless steel, which raises the overall cost of ownership. Furthermore, components with little solubility in water, such as coal, tar, and heavy residue, are easily deposited in the furnace or downstream units, causing equipment to malfunction. As a result, almost all the sewage sludge hydrothermal liquefaction studies were carried out in a large-scale reactor setup. While the study revealed continuous flow hydrothermal liquefaction of wastewater sludge at the laboratory scale (one kg/h feeding power), an ongoing flow hydrothermal liquefaction mechanism with greater effectiveness and profitability should be developed for large-scale industrial use. However, hydrothermal liquefaction of sludge from sewers needs to gain knowledge regarding commercial placement and functioning [33].

8.5.6 Product Separation

The products produced after hydrothermal liquefaction need to be separated. Most of the research published thus far in the literature has extracted bio-crude oil from solid residues and aqueous phases using organic solvents. However, little attention has been given to how these organic solvents affect the quantity and grade of biological crude oil goods. Using a solvent made from organic materials enhances the total expense of the hydrothermal liquefaction process. The solvent used needs to be returned through distillation or extraction, and tiny particles of biological crude oil can evaporate alongside the solvent, lowering bio-crude yield. As a result, the practical and cost-effective method for separating biological crude oil from the hydrothermal liquefaction process remains a challenge. The following Figure 8 shows the solutions to the discussed technical challenges of energy conversion techniques [33].

9. Circular economy for generating energy through wastewater resource management

The look into it envisioned the circular economy as a lake that recycles products and resources, generates employment, uses less energy, and produces less trash [55] .. He says, "Cleaning and reusing a glass bottle is faster and less expensive than recycling the glass or producing a new bottle from minerals." According to one study, the circular economy is characterized as "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops" from a holistic point of view. They felt legislators, authorities, and nongovernmental organizations had adopted the concept on a neighbourhood, local, national, and global level. This is possible through long-term layout, servicing, maintenance, recycling, reuse, refurbishing and reprocessing. Water is a limited resource under severe pressure worldwide due to climate change, fast population increase, and poor management [56]. As a crucial component of sustainable and steady development, preserving resource security significantly burdens societies. Therefore, recovering resources from unorthodox water sources can offer a profitable chance to lower maintenance costs. Wastewater management and CE as a special opportunity to reduce water use can raise the living level. Wastewater management includes beneficial resource recovery, aligning with CE aims, and water reuse. Unlike an ongoing economy, a circular economy as an appropriate framework tries to deal with waste products in a beneficial sense by engaging policymakers, scholars, analysts, and political leaders in extended, multifunctional progress. Wastewater is an advantageous resource from the perspective of CE for recovering water, energy, and minerals. In the overall scheme of municipal management of resources, the circular economy approach can be a critical strategy for achieving the dual goals of wastewater treatment and recovering energy. According to the researcher, the main problem with the CE concept is the drive for perpetual economic expansion without considering environmental externalities. Therefore, integrated systems are more important than ever since they present by-products of one system for the benefit of other systems. The study analyzed the consequences of changing from a linear framework to a circular economy on the future viability of goods created from sewage supplies. They saw manufacturers, participants, and administrators as crucial players in promoting the recovery of technological advances in related businesses. Additionally, it is necessary to assess the waste materials' capacity considering the CE standards. Collaboration between policy associations, scientific institutions, and financial cooperatives will be necessary to transition to CE. Additional research and scientific focus should be paid to material recovery through sewerage and social and economic change processes [23].

9.1 Concept of circular economy for energy revival in the wastewater and water sector

The circular approaches to obtaining energy from sewage should be considered to lessen the negative environmental consequences of the manufacturing industry [57]. Like other industrial units, the CE concept is appropriate for the wastewater treatment industry. Energy efficiency will increase thanks to waste material recovery and recycling. SDGs and linear economies need to mix better. Consequently, CE is seen as a sensible solution because of multisectoral security and resource constraints issues. In this case, handling sludge for wastewater treatment is required to regain important raw materials and energy. A fresh circular economy model approach was proposed in a study as a systematic method for assessing the community or local wastewater and water supply sector regarding environmental management and planning. This framework covers the six actions listed below. It shows various methods of adopting circular economy ecological principles in the sewage and drainage while considering environmental, technology, organizational and social changes. In addition to having an extensive understanding of identity management, physiological science, the natural world, and population fluctuations of system-critical microbes, efficient bacterial biotechnology will improve the recovery stability of processes and reduce emissions of greenhouse gases impacts in the circular economy system. Offering more relevant practices for handling energy and waste products, concentrating on all kinds of supplies and junk, making strategic decisions for the future, and gaining cooperation from all parties may help the growth of a circular economy. Figure 9 shows the concept of circular economy [23].

9.2 Learnings, viewpoints, and opportunities

Repealing wastewater resources consistently positively affects the environment and the economy. The first step in recovering resources from wastewater is to implement an effective, affordable, and practical wastewater treatment system. In this regard, one of the most crucial variables that significantly impact the technology choices made by WWTPs and resource recovery procedures is influent concentration. Usually, these high-concentration influents require specialized treatment procedures to adhere to stringent effluent standards. Considering the obvious challenge faced by high influent concentrations, the significant potential for worldwide warming advantages such as minimal consumption of energy, affordable prices and an increased likelihood of recovering nutrients can be highly appealing. Furthermore, because of their restricted functions, tiny amounts of the effluent may be ineffective for recovering resources. It may be reasonable and effective to connect WWTPs with energy generation facilities to produce cleaner energy. The feasibility of executing such system connections without potential energy users around the wastewater treatment plants and unknown fluctuations related to energy supply and demand needs to be considered. Each plant for reusing wastewater that has been created has a particular link between infrastructures, intricate financial, social, and political aspects and the consumption of water and energy limits. For various parts of the world, the most practicable wastewater reuse strategy should be based on these variables and technological constraints. Additionally, one of the main obstacles to wastewater management initiatives is cost-effectiveness. In developed countries, buildings and water and wastewater treatment services account for around thirty-five % of municipal energy budgets. To consider wastewater reuse for various uses, the study prioritized "top existing technological advancement," implementing "choice assistance systems," and techniques centred on managing risks. To overcome the challenges in the future, a plan of action will be essential. To satisfy the circular economy targets for the recovery of energy in the sewage sector, the following procedures can be executed: Enlisting public support as a crucial element in carrying out essential tasks; Implementing new policies that address technological, political, decisional, social, and economic elements to help the wastewater and energy sectors become fully CE; Regulating the wastewater cycle by selecting the wastewater treatment system type that best addresses the risks, difficulties, and management of unforeseen occurrences; Increasing capacity and expertise to develop worldwide, nationwide and regional action strategies; Coordination of funding and investments to improve the general efficiency of wastewater treatment systems; Applying quality requirements to the finished product rather than the unprocessed product in order to promote consumer acceptance of superior components generated from wastewater from towns and cities and to promote the recovered use of fertilizer products as well as other sewage byproducts as an essential part of the CE; The emphasis is changing from sewage treatment into water reuse and recovery of resources by analyzing the possibilities of reusing wastewater for cost recovery. Developing strong wastewater treatment systems; instead of individual projects limited to a certain industry, coordinated systems incorporating sewage treatment and recycling are implemented. It can be accomplished to obtain the full benefits of managing wastewater for energy production while reducing unnecessary costs [23].

10. Future Perspectives

Most of this research ignores the energy, life span, external factors, and economic consequences of these energy transformation methodologies, which must be considered for sustainable development because technological feasibility depends on waste decomposition and gas conversion effectiveness. In addition to process parameter optimization to increase digestate biodegradability, these technique options need a thorough life cycle assessment to determine their viability. This is because these strategies are not necessarily energy, environmental, or cost-effective, and their impacts must be studied before they can be used. These procedures demand additional expense, power, or chemical components for maximum output production [23].

Various flue gas purification and pollutant control procedures must be used to reduce chemical discharge; however, some especially hazardous components, including cadmium, lead and mercury, may be discharged as vapour. Furthermore, the potential utilization of the leftover ash or slags for additional uses, specifically the ones with high phosphorus levels along with low levels of hazardous chemicals such as metals such as mercury or aromatic polycyclic hydrocarbons, which are suitable for agricultural recycling or in the building sector must be considered. Co-utilization of wastewater alongside other powers, including biomass, coal, other waste materials, petroleum, or gas, has been investigated as a means of refusing the high expenses related to techniques of tar elimination, ineffective application or recycling of char produced, boosting calorific value, and enhancing energy system productivity.

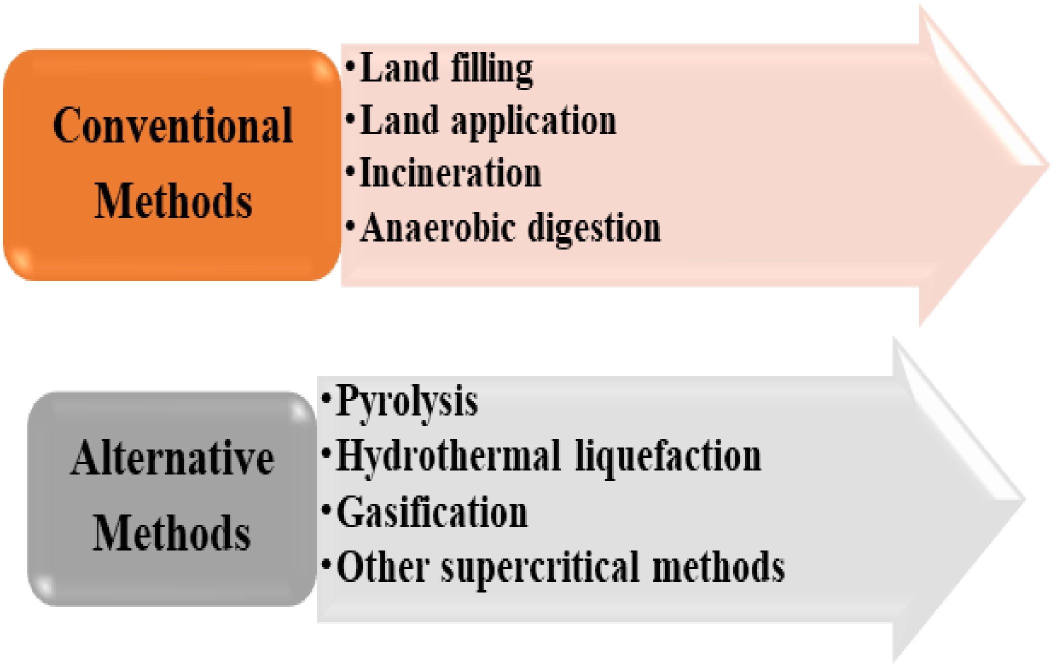

Figure 4: Conventional methods and Alternative methods for wastewater sludge.

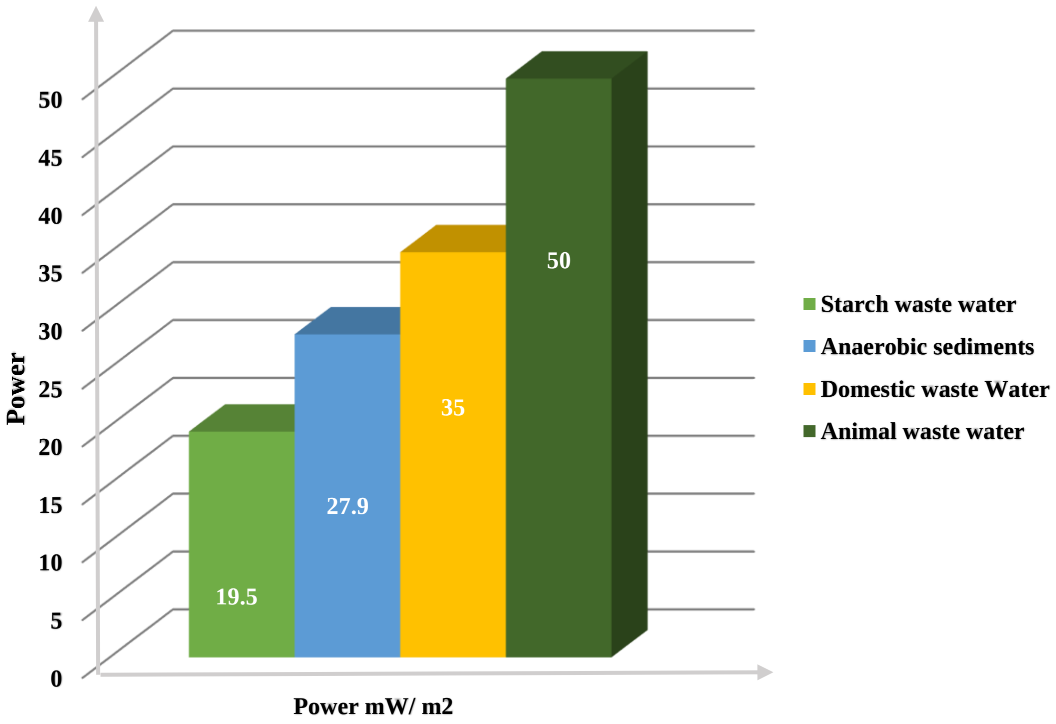

Figure 5: Power densities achieved from wastewater

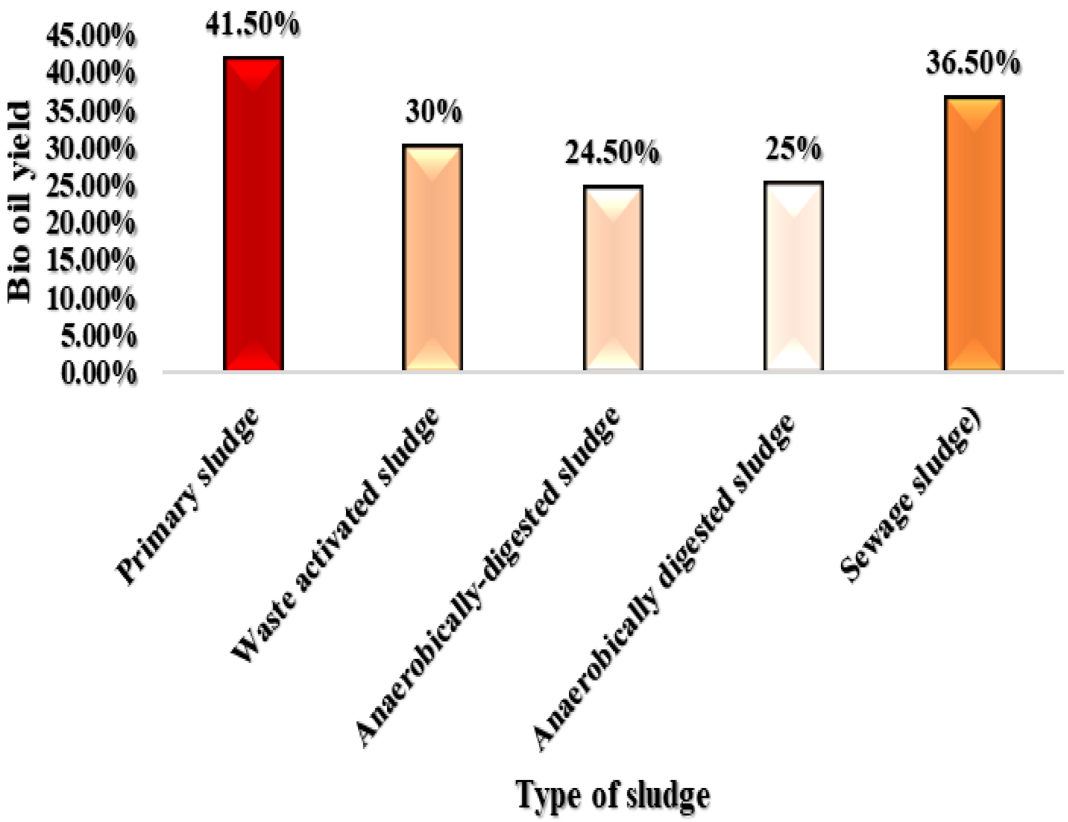

Figure 6: Bio oil yield from different types of sludge.

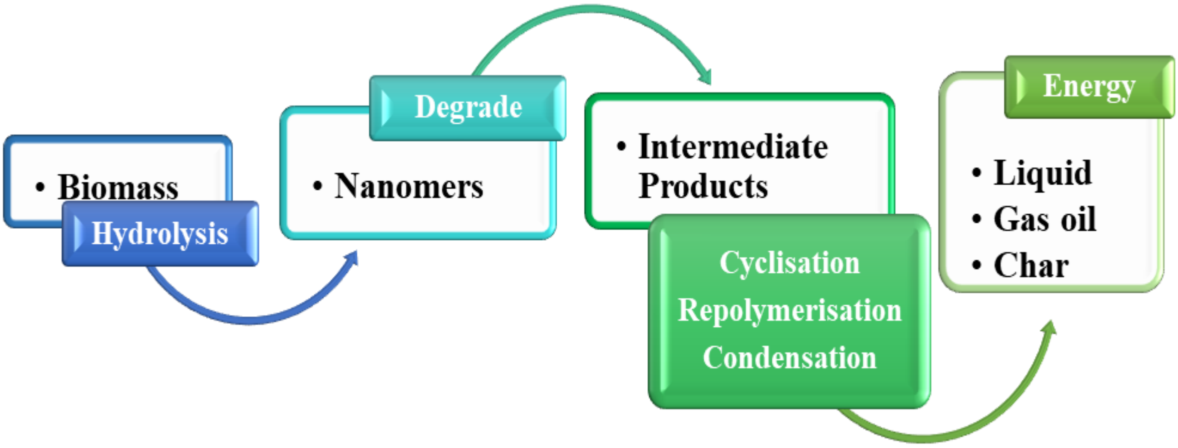

Figure 7: Hydrothermal Liquefaction reaction pathway

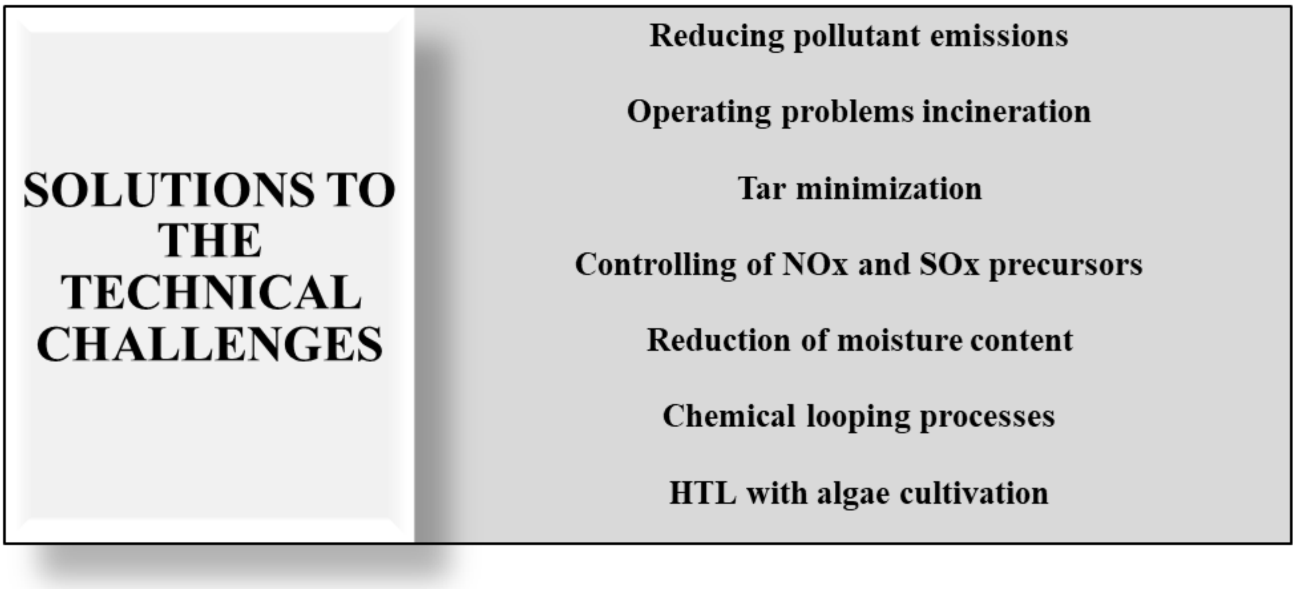

Figure 8: Solutions to the technical challenges of sludge to energy techniques.

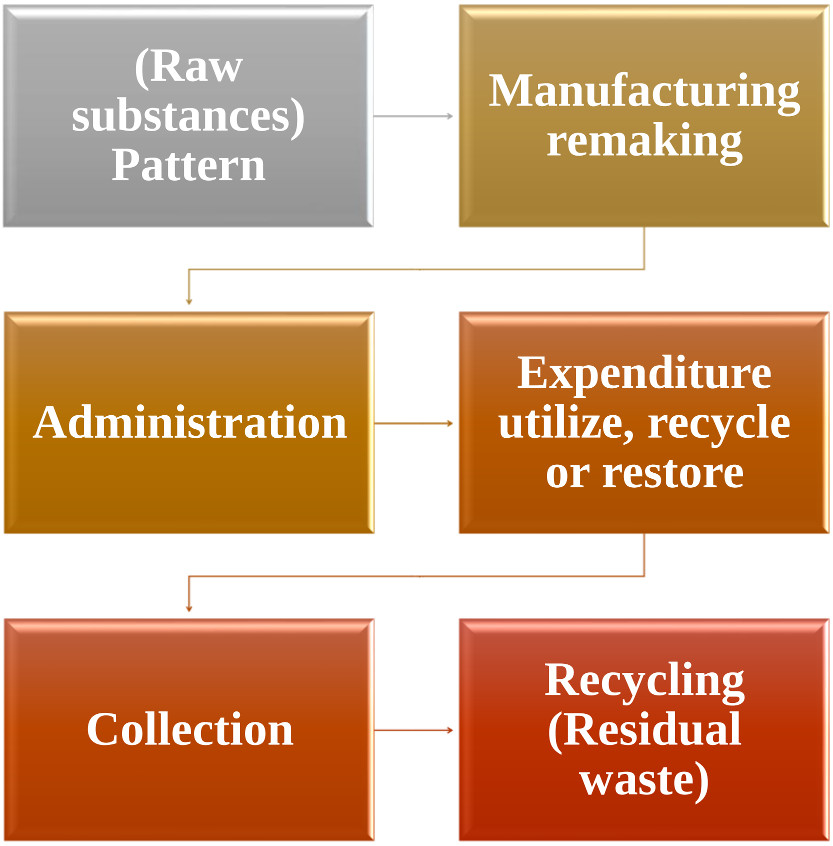

Figure 9: Representation of circular economy.

For a facility to meet appropriate energy, external factors, and financial success standards during the processing, the financial and technical viability of co-utilization, conditions for experimentation efficiency to enhance method or production, and financial and sustainable methods for pre-processing should be carefully investigated via special attention given to their effects on operation effectiveness, contaminants development, combustion exhaust greenhouse gases, and ash-related troubles [23].

11. Conclusions

The worldwide supply of waste products has been gradually increasing as global population growth and industrialization have increased. Historical wastewater sludge disposal methods, like agriculture and garbage dumps, are no longer sustainable and illegal in many countries and regions. Therefore, developing ecologically acceptable and commercially feasible methods for properly handling sewage sludge is critically necessary. Because of the conversion of waste to bioenergy, sludge has evolved from something that needs to be treated and discarded to a green resource for recovering energy. Bio-oil and biogas are the principal renewable energy sources likely to be generated from wastewater by hydrothermal processes and anaerobic digestion. Thermochemical technique is currently viable for managing sewage sludge due to its several benefits, including simultaneous volume reduction, pathogen eradication, and energy recovery. According to this report, municipal sludge can be used as a feedstock for electricity. Examining all the techniques discussed in the study reveals the need for further development and research on wastewater co-utilization, operational optimized performance, and effective scientific scale-up to maximize the energy produced while minimizing expenses and pollutants. Despite the thermochemical platform's commitment, its outcomes are often of poor quality since wastewater sludge is so intricate and various methodologies are tied to various functional technical difficulties. Many other approaches have been created or worked on to address these problems. Methods for avoiding pollutant discharge and operational problems in burning plants, tar reduction and elimination, controlling the emission of nitrogen oxides and sulphur oxides beginning while combustion and the gasification process, reducing the amount of moisture concentration in wastewater sludge, chemical substances repeating methods for capturing carbon dioxide, hydrothermal liquefaction paired with green algae cultural backgrounds and so on are examples. The study is expected to shed light on the possible commercialization of sustainable and profitable conversion techniques for sludge from wastewater management and energy generation from wastewater sludge.

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