

Technical and Economic Evaluations of Conventional and Novel Technologies for Energy Resources Production from Wastewater Treatment

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Abstract

Rapid urbanization and industrialization have contributed to the generation of wastewater and the depletion of energy sources. Wastewater is a promising source of energy, if its high organic contents are properly handled. Variety of conventional methods, i.e., anaerobic digestion, gasification, pyrolysis, combined heat and power systems, incineration, hydropower etc. have been used extensively for many years for treating wastewater and recycling the end products to produce energy. But in recent years, novel technologies, including Microbial fuel cells, microalgae-based systems, increased biological phosphate removal recovery, membrane bioreactors, and membrane distillation etc. have emerged as promising alternatives, offering improved performance, energy efficiency, and environmental sustainability. The technical and economical evaluation focuses on evaluating the cost-effectiveness and efficiency of both established and emerging wastewater treatment technologies. This study offers an up-to-date assessment of the shortcomings of traditional technologies and most recent advances in new technologies. Conventional technologies sometimes have lower initial costs but may have greater operational expenses over time. On the other hand, novel technologies can provide better results with economical cost and energy requirements. Novel wastewater treatment technologies focus on specific requirements, local conditions, and long-term sustainability objectives to pave the way for effective and financially viable wastewater treatment systems.

Keywords: Wastewater treatment, economic, environmental sustainability

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1. Introduction

Rapid urbanization and industrialization have all contributed to the generation of wastewater and the depletion of energy sources [1]. Vast amount of pollutants with high organic content in wastewater, if properly handled, can produce an endless source of energy [2]. It is important to communicate the problems related to the depletion of energy supplies and treatment of wastewater. Therefore, various traditional wastewater treatment techniques have been widely implemented for decades to treat wastewater and reuse products for energy production, but in recent years, novel technologies have been emerged as promising alternatives, offering improved performance, energy efficiency, and environmental sustainability [3]. Wastewater produced from different sources is a valuable energy resource due to its composition. Many technologies are in use to treat wastewater and are employed to generate energy and other useful purposes [4]. Anaerobic digestion, incineration, combined heat and power systems, hydroelectric generating, and gasification are some traditional technologies which are used for energy resources production [5]. Anaerobic digestion (AD) is a biological process which employs conversion of organic molecules to energy contents, and is a

reliable method for extraction of energy such as biogas. Because of its low negative impacts and significant potential for recovering bioenergy, anaerobic digestion is especially helpful for addressing organic solid wastes [6]. But, adopting anaerobic digestion for waste treatment still confronts a number of technological, financial, and societal obstacles, including foaming, low buffer capacity, volatile fatty acid (VFA) formation, process instability, expensive shipping and operation costs [7].

Incineration is another thermal waste treatment method which involves the controlled combustion of organic molecules, usually solid waste, at elevated temperatures and convert it into heat. It utilizes controlled burning of waste into ash, gases, and heat. Because of the harmful emissions from incinerating waste, many new technologies were developed [8]. Combined heat and power systems are far more efficient for energy resources recovery with an average efficiency of 85%. Combined heat and power systems generate heat and power by using biogas such as methane that is produced by wastewater treatment facilities. But for economical process the generated waste heat is used for heating purposes, which will result in system costs that are almost competitive [9]. In hydroelectric system, hydropower is another name for the

process of harnessing energy from moving water to produce electricity [10]. But constructing hydropower facilities, particularly space near maximum water flow, civil works and pipe costs, require substantial upfront capital investments [11]. Gasification is another process which is implemented in oxygen-restricted environment. In this process, biodegradable materials are partially oxidized in gasification reactors for the generation of combustible gases, like H_2 , CO and CH_4 [12]. However, gasification is a delicate and difficult process since the raw materials are large and the regular refueling is frequently needed to keep the system working continuously [13].

While considering limitations of traditional technologies, many novel technologies were introduced for energy recovery from wastewater treatment processes. Novel technologies include microbial fuel cells, anaerobic membrane bioreactors, algae-based systems, enhanced biological phosphate removal, and membrane distillation etc. Microbial fuel cells are bio-electrochemical technologies which use microorganisms to convert the chemical energy found in organic substances into electrical energy [14]. Membrane bioreactors (MBRs) clean wastewater by combining biological processes with membrane technology [15]. Microalgae-based systems are effective at removing nitrogen, phosphorus, and carbon dioxide to produce bioelectricity. In enhanced biological phosphorus removal (EBPR), removal & recovery of phosphorous is encouraged, which eliminates demand for chemical precipitants [16]. In short, wastewater treatment saves the environment by reduced contaminants, uses sustainable resources, provides possibility for unwanted goods to be recycled, and handles residual wastes in a more environmentally acceptable way. These factors make wastewater treatment an environmentally benign procedure [4].

2. Potential Of Wastewater as Valuable Energy Resource

2.1. Wastewater Composition

Wastewater can be defined as contaminated water which is harmful for organisms and environment. Composition, quality and quantity of wastewater varies from source to source such as agricultural, domestic or industrial wastewater. Domestic wastewater includes wastewater produced from households, institutions, and commercial buildings [17]. Agricultural wastewater includes wastewater which is produced from agricultural activities, and it mainly contains fertilizers, pesticides, herbicides, animal waste, and other agricultural chemicals. Industrial activities are also the source of variety of contaminants such as heavy metals, chemicals, organic compounds, oils, and solvents. High amounts of temperature variation and pH swings can also be found in industrial wastewater [18]. Generally, wastewater contains organic matter, inorganic components, nutrients (phosphorous, nitrogen, potassium), pathogens and toxic chemicals [17].

2.2. Energy Contents of Wastewater

Rapid urbanization and industrialization have led to generation of wastewater and the depletion of energy sources, which is main concern now a days [19]. Wastewater treatment produces large amounts of energy contents such as chemical, thermal, and kinetic energy. Different studies have estimated that wastewater treatment produces the chemical energy in the range of 10 to 14 kJ per gram of COD, thermal

energy in the range of 21 MJ per cubic meter (5.8 kWh/m³) for a decrease of 5 °C in temperature of wastewater and potential energy would generate just 30 kilo Joule per cubic meter (0.008 kWh/m³) over a 10 m drop. These numbers highlight the potential for energy conservation of innovative wastewater management, emphasizing that the electricity stored in wastewater is approximately 6 to 9 times higher as compared to electric energy required for wastewater treatment. If this energy could be practically utilized, wastewater treatment plants (WWTPs) could become energy-neutral or even in net electricity producers [20]. Sewage sludge, a solid residue which is obtained by wastewater treatment. In first step of treatment, primary sludge is produced which contains energy contents of approximately 23.2 to 29 MJ per kilogram of sludge. In the second step of wastewater treatment, waste activated sludge is produced which contains 18.6 to 23.2 MJ per kilograms of energy contents [21]. Additionally, it is predicted that municipal wastewater contains a total of about 23 W/capita of organic carbon, as well as 6 and 0.8 W/capita of ammonium and phosphate respectively [22].

2.3. Significance of Energy Recovery from Wastewater

Wastewater contains a substantial amount of recoverable energy, offering the potential to reduce treatment costs. Increasing wastewater treatment levels by an estimated 34% could help mitigate the higher nutrient loading resulting from population growth. It is noticed that the generation of natural gas from biogas, a renewable energy resource has the ability to delay the exhaustion of natural gas supplies which are utilized to generate power and heat [23].

2.3.1. Renewable Energy Generation

Wastewater contains organic matter that can be transformed into renewable energy like biogas or electricity. Energy recovery from wastewater helps to diversify the energy resources and reduces dependence on fossil fuels, contributing to the more sustainable and less-carbon energy system [24].

2.3.2. Resource Conservation

Wastewater treatment facilities need a lot of energy throughout the treatment process. By recovering energy from wastewater, it helps to offset a portion of the energy requirements for treatment of wastewater, reducing overall energy usage and promoting resource conservation [24].

2.3.3. Cost Savings

Energy recovery from wastewater can result in cost savings for wastewater treatment facilities. Treatment facilities can lower the price of energy or even make money by selling the power or heat they produce from the biogas produced in an anaerobic digestion process [24-25].

2.3.4. Environmental Benefits

Energy recovery from wastewater has main contribution to maintaining the environment. By capturing and utilizing methane, a strong greenhouse gas that would have been discharged into the environment during the breakdown of organic material in wastewater, it lowers greenhouse gas emissions. Additionally, it lessens the demand for traditional sources of energy, minimizing the

environmental impact of energy generation and reducing air pollution [26].

2.3.5. Circular Economy Approach

Energy recovery from wastewater is in line with the rules of a circular economy. By utilizing the energy potential of wastewater, it maximizes resource efficiency and closes the loop by transforming waste into a valuable resource [24].

2.3.6. Energy Security and Resilience

Energy recovery from wastewater enhances energy security by diversifying the energy sources and reducing dependence on external energy supply. It also contributes to the resilience of wastewater treatment facilities by providing an additional source of energy, ensuring continuous operations even during disruptions in the energy grid [26].

3. Energy Recovery Technologies

In the realm of wastewater treatment, harnessing the energy from wastewater, an abundant energy resource, has emerged as a crucial element in sustainable resource management. There are many technologies available for wastewater treatment, and the end products are employed in the creation of energy [4].

3.1. Old Technologies

Old technologies for energy recovery in wastewater treatment refer to well-established and traditional methods that have been used for a significant period to extract energy from wastewater. These technologies include anaerobic digestion, gasification, pyrolysis, combined heat and power systems, incineration, and hydropower [5].

3.1.1. Anaerobic Digestion

Anaerobic digestion (AD) is a biological process that decomposes organic matter without utilization of oxygen to create biogas and by-products that are rich in nutrients. [5]. It has capability to reduce organic contents of waste rapidly with lowering energy consumption of treatment method and formation of bacteria-rich biomass or sludge [24]. Additionally, it can be used with a variety of feedstocks, such as domestic waste, industrial waste, agricultural waste, as well as plant materials [27]. Due to its high organic content, activated sludge is used for anaerobic digestion process. Entire process divided into four steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis. Organic substances like carbohydrates, proteins, and lipids are first converted into simpler organic compounds like sugar, fatty acids, amino acids, & other related chemicals by process of hydrolysis. Generation of volatile fatty acids and other hazardous byproducts makes hydrolysis most slow or rate-limiting step in majority of situations [28]. Pre-treating substrates helps to speed up hydrolysis stage in most cases. Reduced organic molecules from hydrolysis step continue to break down into small-chain fatty acids during second stage, known as acidogenesis (or fermentation), along with additional by-products such hydrogen (H_2) & carbon dioxide (CO_2). Third stage of this process, known as acetogenesis, is when organic acids created during acidogenesis step, transformed into acetic acid, carbon dioxide and hydrogen. Methanogenesis, final phase, involves production of methane by two distinct methanogen groups. First group converts acetic acid into carbon dioxide and methane, whereas second group produces methane while utilizing intermediate

Munawar et al., 2026

products H_2 and CO_2 . Biogas is then produced which is mainly mixture of methane and carbon dioxide (Figure 1) [29-31].

3.1.1.1. Significance of Bio-Gas

Biogas is mostly utilized to generate electricity using a traditional combustion process and as fuel. Biogas with a high methane content (about 75%) is utilized to make methanol. It has suggested that converting biogas into biomethane to increase anaerobic digestion's energy efficiency [32].

3.1.1.2. Limitations

Anaerobic digestion is an intricate procedure that calls for the digestion of all organic substrates (such as protein and carbohydrates) in a single step. It is controlled by a number of important factors, including the pH level, temperature, nutrients, ammonia, and others. A stable habitat and an ideal ratio of nutrients and mineral trace elements are necessary for microbial growth. Maintaining important parameters within correct range is essential for anaerobic digestion to work correctly over time [33]. Its industrial applicability constrained by operational challenges, high energy consumption, and high costs etc. (Carrère, Dumas et al. 2010). In order to develop the microbial population and achieve steady operation, anaerobic digestion systems often require a lengthy start-up period. The biogas output could be minimal at this time, making the system more prone to disturbances or imbalances [34].

3.1.2. Incineration

It is a technique for thermal treatment used to minimize waste volume and transform it into ashes, gas and heat. The management of water as well as energy through the combustion of biosolids while generating electricity is an important strategy. For instance, the Hartford Water Pollution Control Facility in Hartford Connecticut is planning to modernize its furnaces and predicts that burning of biosolids will provide 40% of the plant's annual electricity needs. For the incineration of biosolids, there are two commercially accessible equipment options: fluidized bed furnaces and multiple hearth furnaces [35]. Multiple hearth furnaces typically combust mechanically dewatered (wet) sludge, whereas fluidized bed furnaces can combust both wet and semi-dried sludge. More recent technology, fluidized bed furnaces, are capable of continuous operation and are more reliable, stable, and efficient than multiple hearth furnaces. To reduce odor, particulate matter, oxides of nitrogen, acidic gases, hydrocarbons, and heavy metals, incineration techniques call for exhaust gas cleanup. A steam cycle power plant can be powered by biosolids incineration by using either fluidized bed furnaces or multiple hearth furnaces [8].

3.1.2.1. Significance

Incineration processes show many advantages such as significant weight and volume reduction of sludge, little response to sludge composition, high energy recovery for heat or power consumption, sale of energy reduces cost, and bottom ash can be utilized on daily basis as a landfill cover. Additionally, salts and acids can be recovered and it needs less amount of landfill [8].

3.1.2.2. Limitations

Incinerators for sewage sludges may produce large air pollutants. Particulate matter, sulfur dioxide (SO₂), unburned hydrocarbons, carbon monoxide (CO), and metals nitrogen oxides (NO_x) are the main pollutants released. The incinerator's operations may produce emission of intermediate by-products of partially burned material, including hazardous organic compounds. High initial expenditures, potentially high operating expenses based on the use of auxiliary fuels, operational challenges, air emissions, and potential public hostility are drawbacks of incineration [8].

3.1.3. Combined heat and power system

Combined heat and power (CHP) system is one that synchronously produces electricity and heat from a single fuel source. Combined heat and power systems are important for the effective use of energy in both commercial and residential settings. These systems also have less negative environmental effects. A thermal efficiency of more than 80% may be provided by well-built combined heat and power systems [36]. A quantified mass and energy balance technique can be applied to combined heat and power system to assess the carbon and energy balance and to optimize the combined heat and power system. Influential elements include improving the main process's efficiency, upgrading the process equipment, and using additional biodegradable organic waste. A 10% improvement in chemical oxygen demand removal during primary treatment was associated with an estimated 8.5% decrease in overall energy consumption and an 8.8% increase in recoverable energy. This finding shows that ability for energy recovery may be significantly impacted by plant capacity and influent wastewater chemical oxygen demand strength. When sewage sludge and exceptionally biodegradable organic waste are co-digested, energy generation from a wastewater energy recovery facility can be increased. Also choosing the right combined heat and power systems engine is crucial to reduce energy losses, as converting current wastewater treatment plants (WWTPs) into water recovery and energy recovery facilities, is current goal for wastewater treatment sector. Having operations that are providing maximum energy, is the first step towards achieving this goal [37].

3.1.3.1. Significance

The combined heat and power (CHP) system is popular in wastewater treatment facilities and is regarded as the most economical method of obtaining energy from biogas. It is possible to use biogas in CHP systems to offset energy use by up to 40%. For instance, WWTP facilities may generate 2 megawatts of electricity at a rate of 415 billion gallons per day (around 30% chemical oxygen demand (COD) is removed in the main settling and 200 tons of food waste are added). Reduced greenhouse gas (GHG) emissions, increased decentralization of the energy supply, enhanced energy security, the potential to reduce investment and energy loss from distribution and transmission lines, and perhaps lower energy costs for consumers are additional advantages of combined heat and power systems [38].

3.1.3.2. Limitations

The combined heat and power system is not moving forward. Host industries find it challenging to implement CHP systems because of their high capital costs (especially for small operations), and utilities are hesitant to buy their excess electricity. Renewable energy portfolio requirements, regulatory reform, increased tax credits, and additional monetary incentives are a few potential strategies for overcoming these obstacles. In order to produce heat and electricity, CHP systems often rely on particular sources of fuel, such as biomass, biogas, or natural gas. Limitations may result from these fuels' accessibility and availability, especially in isolated areas or places with weak gasoline supply systems. In addition, there may be legal limitations or environmental issues that affect the use of some fuels [9].

3.1.4. Hydro-electric generation

In hydropower system, energy is produced by the natural cycle of water and the force of dropping or swiftly moving water [39]. This system uses the potential kinetic power recovered from wastewater flows utilizing tiny hydropower turbine at the outputs of WWTPs. Scientists and engineers alike are becoming more and more interested in hydropower schemes which can be used for multiple purposes, which integrate hydropower turbines into current water structures like the water used for drinking network, the waste water system, navigating locks and dams, desalination facilities, heating and cooling systems [40]. The study of these data revealed that there was little possibility for energy savings utilizing hydropower for smaller-capacity facilities. Only larger plants, which are frequently found in major cities, were determined to have sufficient potential. The selectivity elements that affect hydropower generation include flow rate, type of turbine, monetary incentives, and energy costs. Electricity is often produced at large hydroelectric facilities [41]. The turbine output shaft is connected to generator to produce power. Electromagnetic rotor, also known as conductor, is the main component of the generator. It is housed inside a cylinder called the stator, which also contains a wind made up of electrical wires. The rotor in the stator rotates while operating and produces electricity using the electromagnetic induction process. Using a transmission system made up of elements like switch yards, transformers, and transmission lines, the electricity that is produced is sent to load sites [42].

3.1.4.1. Significance

The demand for energy is rising globally, but its supply is not sustainable. Hydropower is the most practical renewable energy source for contributing significantly to the world's energy needs, particularly for electricity. Although, hydropower makes up a smaller portion of the world's major energy supply, its untapped potential is still rather considerable. It is the most effective method of producing electricity and is utilized in numerous nations. Well-off nations completely rely on hydropower as a source of energy. As a result, technology is reliable and established. Hydropower technology can also serve as a means of storing energy within a larger energy system. A power utility can employ a hydropower storage system for storing energy while utilizing additional sources of energy with varying potential, like wind, to supply a nearly constant load [42].

3.1.4.2. Limitations

Relatively high investment costs and accompanying risks are some of its disadvantages of hydropower system. Small-scale hydropower technology is suited for private investments acting as independent generators of power from an economic standpoint but it is not suitable for larger power points [42]. Additionally, there may be legal and financial difficulties. For example, hydropower projects that utilize the hydraulic head from sewage treatment facilities are ineligible for the Renewable Obligation Certificate in the UK because the flow is regarded as being pumped [43]. A shortage of excess head, flow speed variation, and turbine collapse due to obstructions or destruction from suspended solids in the wastewater (particularly in untreated sewage). Therefore, there is need for a turbine bypass system in the case of turbine interruption at either the entrance or outlet [41]. A test of sensitivity is utilized to thoroughly assess hydropower potential for financial and technical analyses. This analysis looks at flow variation, turbine choice, energy pricing to maximize turbine design flow rate, optimize power output, and shorten economic payback period [41].

3.1.5. Gasification

Gasification involves converting trash into syngas, which can then be utilized to create liquid fuels, chemicals for highly valuable goods, and to produce steam and power. It is the process which is carried out in oxygen-restricted environment in which biodegradable materials are partially oxidized in gasification reactors for the production of combustible gases, such as H_2 , CO and CH_4 [12]. Municipal solid waste is used as a feedstock in the gasification process, not as fuel for a high chemical conversion process. Municipal solid waste could be burned by gasification and can be transformed into a clean, beneficial syngas. Municipal solid waste gasification has considerable environmental advantages, such as lessening the demand for landfill area, cutting down methane emissions from breakdown of organic matter in the landfill, and lessening the risk of groundwater contamination and surface water contamination. Valuable items that can be made from syngas produced by gasification include chemicals, fuel for vehicles, fertilizer, and power [13]. German acronym for gasification process is ETVS-Process (Entwässern, Trocknen, Vergasen, Strom erzeugen, meaning dewatering, drying, gasification, and electricity production) which are four primary steps of this process.

Dewatering the sludge using the high-pressure method "Hydrosoft" is the first step in the procedure. Using internal lower-grade waste heat from the entire process, the resulting filter cake is subsequently processed in an extremely low temperature fluidized bed dryer. In an atmospheric fluidized bed gasifier, lean-gas is made from the dried sludge. After being cleaned, the gas is injected into combined heat and power unit to produce useable heat and electricity to power the entire process and additional applications. The WWTP uses the sewage sludge in a safe and suitable manner right on the premises. A wide range of modifications to the plant are possible to enable the use of various types of trash. The capacities are between 1000 and 8000 tons per year [44]. Along with gas, process also produces coke and pyrolysis oil. Gasification turns out to be more effective for this purpose compared with pyrolysis and combustion. Making hydrogen using sewage sludge is another method for recovering energy. In a fixed bed gasifier, sewage sludge is gasified. End product

gas, which has 10–11% H_2 content, could be used in fuel cells or other applications (Figure 2) [45].

3.1.5.1. Significance

Major environmental problems like climate change caused by the release of greenhouse gases via waste disposal sites, degradation of the environment (soil, water, and air) due to improper waste disposal, burning of fossil fuels, as well as saving precious land utilized for waste disposal that could be better utilized for agricultural purposes are addressed and solved by the gasification of municipal solid waste [46]. Gasification significantly reduces the weight and volume of sludge, reduces the need for landfills and land spreading, requires less oxygen, and produces syngas with a variety of applications (including generation of chemicals, methanol, and power), other benefits of gasification [8]. It also decreases the usage of fossil fuels and lowers transportation expenses for garbage that no more needs to be transported across long distances for disposal [13].

3.1.5.2. Limitations

The gasification process can be considerably impacted by the feedstock's composition. The effectiveness of gasification can be impacted by high moisture, excessive ash, or the presence of pollutants like sulfur or chlorine, which may also raise device corrosion and maintenance needs. To reduce these difficulties, it is crucial to pick and prepare feed stocks appropriately. Initial setup costs are high and is lengthy and multi-stage process. Syngas needs to be cleaned and purified and starting reactions requires a lot of energy restricts usage of gasification process [8].

3.2. Novel Technologies

New and stubborn waste is being produced in manufacturing lines as a result of newly developing and manufactured products. Conventional wastewater technology may not be able to handle these toxins, which would worsen the issues already plaguing the world. Therefore, it is necessary to create new or better energy recovery technologies. Microbial fuel cells, microalgae-based systems, increased biological phosphate removal recovery, membrane bioreactors, and membrane distillation are among the novel wastewater treatment technologies for energy recovery [47].

3.2.1. Microbial Fuel Cells

Microbial fuel cells (Microbial fuel cells) are technologies that oxidize organic and inorganic materials using microorganisms as catalysts to produce energy [14]. They enable the recovery of energy out of the wastewater, while limiting both the energy input and the excess sludge production [48]. Microbial fuel cells consist of biological processes that transform chemical energy (found in a variety of organic material in wastewater) into electric power or other high-value products [49]. In Microbial fuel cells, this energy is retrieved as bioelectricity, whereas in microbial electrolysis cells, it is converted into valuable biofuels like methane, hydrogen, ethanol and hydrogen [50]. Microbial fuel cells work as galvanic cells. The bacteria use substrates to produce electrons, which are then transferred to the positive end (cathode), flow to the anode (negative terminal), and operate under a load (i.e., generate electricity to power a device). According to custom, a positive current travel in the opposite direction of electron transport, from its positive end

to the negative terminal. Otherwise, the system is regarded as a biobattery because the device cannot have the substrate oxidized at its anode replenished, either constantly or occasionally. Direct membrane linked electron transfer, electron shuttles, so-called nanowires, or electron mediators can all transfer electrons to the anode. Electricity was created by microorganisms. To enable electricity production by bacteria that would not normally be able to use the electrode, chemical mediators can be added to the system, such as the neutral red or anthraquinone-2,6-disulfonate (AQDS) [14].

3.2.1.1. Significance

The main uses of microbial fuel cells are the creation of power, wastewater treatment, chemical compound degradation, biohydrogen synthesis, and the manufacture of biosensors. Since the primary objective of MFC is the production of bioelectricity, numerous studies have concentrated on improving power density. To boost the power production, numerous alterations were made, including changes to the substrate, the pH, the anode and cathode, the membrane components, and various microorganisms. Along with the generation of energy, concurrent treatment of wastewater was also extensively researched using microbial fuel cells. In microbial fuel cell, various wastewater types have been treated and used to generate bioelectricity [51].

3.2.2. Anaerobic Membrane bioreactor

Another technology used to treat wastewater, and energy recovery is known as an anaerobic membrane bioreactor, or AnMBR. For the retention of biomass, it is a revolutionary membrane filtration technology. It works by using a membrane bioreactor (MBR). The waste products and sludge are separated, after that the sewage has been filtered and divided. In anaerobic membrane bioreactors, the advantages of anaerobic method and membrane biotechnology is combined. Membranes keep suspended solids and colloidal particles in place and separate solids from liquids. In the bioreactor, the soluble organic matter is broken down by slow-growing anaerobic microorganisms, which create biogas. The anaerobic membrane bioreactor combines the use of low-pressure micro-filtration and ultrafiltration membrane filter technology with an anaerobic bioreactor. The Anaerobic Membrane Bioreactor can separate the solid retention period from the hydraulic retention period, self-sufficient of any wastewater characteristics, biological procedure conditions, and sludge properties. They can produce a high-quality effluent while operating at reasonable hydraulic retention times (HRT 8 h) and low temperatures (15 °C).

Anaerobic membranes bioreactor (Membrane bioreactor) systems are showing promise for popular rehabilitation of domestic wastewater. This is because they produce much less sludge than aerobic treatment [52]. The membrane filtration system is one of an anaerobic membrane bioreactors system's most important part. Crossflow pressurized membrane and submerged membrane filtration are the two different membrane filtering modules that can be used in Anaerobic membrane bioreactors. Externally crossflow membrane filtration typically employs the traditional sheets along with framework or the cylindrical hollow fiber cartridge configurations. The main reason for limiting the anaerobic membrane bioreactors effectiveness is

still membrane fouling. Crossflow for exterior membrane filtration and biogas scouring for submerged membrane filtration are two main methods used in anaerobic membrane bioreactors to manage membrane fouling. Through the development of the aerobic MBR, the membrane-based gas scouring technique has been well developed [53].

3.2.2.1. Significance

Due to their ability to create methane from the consumption of a significant portion of organics in wastewater, anaerobic membrane bioreactors can also be crucial in energy recovery. Anaerobic membrane bioreactors can produce biogas as much as 97% of the influent chemical oxygen demand; also, very little sludge is typically produced in these systems due to the anaerobic microorganism's poor growth yield. The shorter hydraulic retention times that may be reached by using membranes for sludge segregation account for the increased CH₄ content attained in anaerobic membrane bioreactors as compared to traditional anaerobic treatment procedures. Due to substantially lower CO₂ gas solubility (by a factor of around 10), it is removed from the effluent more thoroughly than CH₄ [53].

3.2.3. Algae Based Microbial Fuel Cell Systems

Microbial fuel cells based on microalgae are effective at removing CO₂, nitrogen, and phosphorus from wastewater while also producing bioelectricity and value-added goods from microalgal biomass. Microalgae can be employed as biocatalyst for removal of pollutants i.e., organic matter, nitrogen, phosphate etc. from wastewater in algal bio-electrochemical systems such as microbial carbon capture cells, algae aided cathode systems, or photosynthetic algal microbial fuel cells. These microbial fuel cells are effective for the treatment of wastewater through mutually beneficial relationships of microalgae-bacteria consortia together with power generation, posing a low risk of carbon emissions. Microalgae ability to produce oxygen during the light period minimizes the requirement for external oxygen supplies for the cathodic reactions, so this is beneficial for lowering the cost of aeration since mechanical aeration would otherwise require power [54-55]. Due to its long-term, sustainable power generation, microbial fuel cells are favorable to produce bioelectricity and many value-added goods and biohydrogen utilizing tiny, inexpensive electrical devices.

Microbial fuel cells performance is currently constrained by aeration expenses of cathodic compartment, which account for about 50 % of all operating costs. This disadvantage can be overcome by photosynthetic microalgae microbial fuel cells, because the O₂ supply provided by the algae in the system enhances power generation, enables simultaneous elimination of CO₂, high cathode polarization resistance, and lowers aeration expenses. Due to the inclusion of additional electron acceptors (namely nitrate and sulphate) in the cathode compartment, bioelectricity for production in photosynthetic microalgae microbial fuel cells is believed to occur during the period of light when algae absorb CO₂, ammonium, and create O₂ through photosynthesis as well as during the dark period. The supply of oxygen to the cathode chamber frequently limits the amount of power that algae-based microbial fuel cells can produce. The type of biocatalyst, microbial fuel cells setup and operation, level of light, nutritional origin, membrane type, electrodes size, maximum power density, and scale up are additional

elements that must be considered for the process to be more economically viable. Algal biomass obtained from the cathodic chamber needs to be pretreated in the biorefinery concept to be used. Although this still represents a significant limitation, recent developments in the selection of a biofilm on the cathode enable increased recovery of value-added goods from algae biomass. Alternately, the anodic compartment could use only algal biomass as feedstock [55].

3.2.3.1. Significance

Microalgae are becoming more popular as desirable organisms for use in bioprocesses for removing phosphorus and nitrogen. They are excellent at removing N, P, and chemical oxygen demand from sewage while simultaneously producing oxygen, which can be utilized as an electron acceptor in cathodes that are helped by algae. Both anodes as well as the cathode compartments remove nitrogen and phosphorous, with the cathode compartment removing 55% of the phosphate through algal activity and the anode compartment removing 27% through bacterial activity. The process might be used to clean wastewater without mechanical aeration while simultaneously producing biodiesel, electricity, and capturing carbon [55].

3.2.4. Enhanced Biological Phosphorus Removal and Energy Recovery Method

Enhanced biological phosphorus removal (EBPR) is a treatment process in which microorganisms remove excessive inorganic phosphate from wastewater. A continuously flowing reactor system and a sequential batch reactor (SBR) both have process control structures built for them [56]. Numerous methods and approaches have been suggested under this new paradigm to recover nutrients, energy, and water [57]. The majority of the suggested plans use physicochemical techniques, including struvite precipitation, to collect both phosphorous and nitrogen as a kind of mineral fertilizer [58]. The majority of the nitrogen is preserved as ammonia, which is the preferred as nitrogen source for the majority of the green microalgae, because the enhanced biological phosphate recovery system is operated at a low level of solids retention time (SRT) [59]. The foundation of EBPR is the enhancement of the microbial population with polyphosphate-accumulating species (PAO), which may accumulate phosphorus (P) as polyphosphate (Poly-P) inside of their cells when exposed alternately to anaerobic and aerobic conditions.

After the most of sludge has accumulated, Poly-P which occurs at the conclusion of the aerobic phase in EBPR structures, phosphorous is eliminated during the biomass purge. Then, phosphorus (P) in the sewage can be treated in several ways. It can either be removed from the sludge using biological or thermo-chemical techniques, which has the disadvantage of increased transport and usage costs and the requirement for nitrogen supplementation, or it can be recovered as struvite ($\text{NH}_4\text{MgPO}_4\cdot 6\text{H}_2\text{O}$) by adding additional chemicals and modifying the pH conditions. Nevertheless, typical P recovery rates from anaerobic liquor deposition are around 12% of the influent P. Like other nutrients like nitrogen and potassium, phosphorus (P) is frequently employed in the creation of fertilizers. Phosphate stone, a non-renewable resource that could run out in the next 50 to 100 years, is now used as the primary source of P. A global mass balance, however, reveals that as much as 20% of the

world's output of phosphorus (about 3 metric tons per year) disappears in anthropogenic wastes [60].

3.2.5. Membrane Distillation

A new non-isothermal membrane technique called membrane distillation employs thermal energy to produce a vapor phase of feed stream's volatile molecules, which are primarily water molecules. The penetrated vapors are then condensed on the cold side. The partial pressure difference that exists on both sides of the membrane pores acts as the driving force in membrane distillation. A vapor pressure difference over the membrane is caused by the temperature difference. Only vapors, not liquid solution being distilled, can pass through membrane since the membrane is hydrophobic. Four major configurations for the Membrane distillation method are direct contact membrane distillation (DCMD), air gap membrane distillation (AGMD), sweep gas membrane distillation (SGMD) and vacuum membrane distillation (VMD). The approach is different in that it drives permeation flux by applying a vapor pressure gradient across the membrane's pores. A cold liquid is brought into direct contact with membrane in direct contact membrane distillation (DCMD), an air gap serves as condensing surface at permeate side in air gap membrane distillation (AGMD), a gas is compelled through gap at permeate side in sweep gas membrane distillation (SGMD), & gap channel configuration is subjected to vapour pressure in vacuum membrane distillation (VMD) [61-62].

The vapor phase must be present in porous membrane for the membrane distillation process to take place since the feed's volatile components evaporate via those pores. The vapor or liquid equilibria of a liquid combination serves as the foundation of the separation mechanism. Only water vapor passes through the barrier to solutions containing non-volatile solutes; as a result, the distillate obtained contains demineralized water. The distinct separation properties of the membrane distillation method separate the dyes from the water in the context of textiles wastewater treatment, allowing for their reuse. Similar to this, saline wastewater can be treated using the membrane distillation process to create pure water and a concentrate that contains the components of the parent solution. The extraction of solutes in a solid state is required since the creation of concentrate frequently does not resolve the issue. Through the membrane distillation process, solutions can be concentrated to a supersaturated state and then crystallized as salts. In addition to concentrating on acid solutions, the membrane distillation method also enables the removal of volatile acids from used solutions. The membrane distillation procedure was also used to treat liquid low-level radioactive waste, and it was successful in eliminating all radionuclides [63].

3.2.5.1. Significance

The integration of membrane distillation process with other processes such as anaerobic membrane bioreactors is a useful technique for improving performance and offers the chance to reclaim valuable resources [64]. Saline wastewater can be separated into concentrate (brine) and pure water using the membrane distillation process. The resulting distillate has an electrical conductivity of 2-4 S/cm. Several substances in the wastewater could create deposits onto the surface of membrane in the membrane distillation procedure. Except for immediate treatment of waste by membrane

distillation, this phenomenon typically had a considerable negative impact on process performance. If wastewater is given proper pretreatment, this annoyance can be avoided. The main benefit of treating wastewater with the membrane distillation method is the potential to remove foulants from the feed. As a multiple phases compact system, membrane distillation is highly adaptable in terms of scale and application [63].

4. Technical and economical evaluations of old and novel technologies

For technology to be sustainable, it must undergo techno-economic evaluations that consider factors including technical viability, economic stability, and the sustainability of the environment. The techno-economic study sheds light on the viability of any technology required to produce bioenergy or biobased goods. Additionally, it is feasible to locate the process bottlenecks that threaten technical viability or financial viability [65]. Although selecting the "Most Appropriate Technology" is a difficult process, doing so could lower the likelihood of future issues and failures. "Most Appropriate Technology" refers to innovation that is socially and environmentally acceptable, as well as commercially feasible (Figure 3) [3].

4.1. Technical and economic evaluations of old technologies

4.1.1. Anaerobic Digestion

One of the more established systems for managing solid waste and producing bioenergy is anaerobic digestion, in which various bacterial and archaeal groups transform organic components into methane and carbon dioxide. Biogas has several uses, which includes cooking, central heating, fuel, electricity generation, and energy storage, due to its comparatively high energy density and simplicity of usage [65]. Due to the inherent variability in the availability of feedstock, properties of the feedstock, separation of waste material, operational concerns, and profitability issues, numerous industries and investors view the production of biogas for the production of energy as a high-risk investment [66]. Many governments have implemented off-take agreements and supportive legislative initiatives to promote private investments in this area to address these concerns. Additionally, other research teams continue their research on anaerobic digestion to overcome obstacles and promote commercialization. According to Waste Management World (2017), the worldwide biogas market will grow to \$50 billion by 2026. Researchers must therefore examine anaerobic digestion from a system's point of view, considering its technological, economic, and environmental advantages. To evaluate the technical viability, financial viability, and environmental effects of anaerobic digestion methods, integrated evaluations must be conducted. Because of market and policy factors, anaerobic digestion is an established technology but many sectors are unable to commercialize [65]. Waste materials and methane-powered electricity are sold to generate revenue for this pricey waste treatment technique [67].

4.1.2. Combined heat and power systems

Cogeneration, also known as combined heat and power systems, produce electricity and usable heat simultaneously from the same energy source. A combined

Munawar et al., 2026

heat and power system uses the heat produced during incineration or gasification for generating steam, which is then utilized to produce power through a steam turbine, or to provide heat for commercial or industrial activities or district heating. Compared to stand alone power and heat generation, combined heat and power systems offer superior total energy efficiency, minimizing wasted energy and greenhouse gas emissions [68]. CHP systems are important for the effective use of energy in both commercial and residential settings. These systems also have less negative environmental effects. A thermal efficiency of more than 80% may be provided by well-built CHP systems [36]. A quantified mass and energy balance technique can be applied to combined heat and power system to assess carbon and energy balance and to optimize combined heat and power system. Influential elements include improving the main process's efficiency, upgrading the process equipment, and using additional biodegradable organic waste.

A 10% improvement in chemical oxygen demand (COD) removal during primary treatment was associated with an estimated 8.5% decrease in overall energy consumption and an 8.8% increase in recoverable energy [37]. Most of the combined heat and power systems typically have 60 to 80% total efficiency. Capital expenditures for combined heat and power systems usually vary from \$1,000 to 5000 dollars/kW for the initial setup and between 0.5 and 4.5 /kWh for maintenance, based on the prime mover. Gas turbines typically have the lowest running costs, ranging from 0.6 to 1.3 cents per kWh, and are the least costly to install, costing between US\$700 and US\$2000/kW [69]. The combined heat and power system is not moving forward. Host industries find it challenging to implement CHP systems because of their high capital costs (especially for small operations), and utilities are hesitant to buy their excess electricity. Also, to produce heat and electricity, CHP systems often rely on particular sources of fuel, such as biomass, biogas, or natural gas [9].

4.1.3. Gasification

Gasification process consists of thermochemical conversion of carbonaceous material into fuel gas rich in CO and H₂, called syngas which can be used as a fuel to generate heat and power, or it can be transformed into chemicals or biofuels. Conditions of gasification process such as pressure, equivalent ratio, and temperature, have an impact on the composition of syngas. Since, biomass is transformed into a combustible gas during gasification, it has greater advantages over other thermochemical processes [70]. Because of its numerous applications and advantages, gasification has gained attention on a global scale. Through gasification, many wastes from agriculture and industry that are currently an issue around the world, particularly in industrialized nations, can be utilized in a sustainable manner. Generation of hydrogen and ethanol from plastic waste is a promising technology that has been showing positive outcomes from both economic & environmental standpoint [71]. It represents an alternate method of processing waste and producing energy. In some regions of world, production of power by gasification is being used to both produce electricity and reduce greenhouse gas emissions [72].

In addition to being more energy efficient than incineration, gasification also has a variety of flexible feedstock alternatives and, when used in conjunction with the

right gas cleaning technology, lower emissions. However, gasification processes can be intricate, and the makeup and contaminants of the feedstock may have an impact on the effectiveness of the process [73]. Due to the wide range of raw materials available, it is exceedingly difficult to develop a sound theory that can adequately explain the entire gasification process in general. Despite its age, the gasification process still has to be optimized in order to reduce the energy efficiency losses caused by a few key issues such as biomass must be dried before conversion and to purify the synthesis gas from impurities to further avoid pollution during combustion [72]. Also, the initial setup costs of gasification process are high and is lengthy and multi-stage process. Syngas needs to be cleaned and purified and starting reactions requires a lot of energy restricts usage of gasification process [8].

4.1.4. Incineration

Incineration involves a direct controlled burning of waste in the presence of oxygen to generate ash, flue gas and heat used to produce electricity [74]. Incineration can reduce solid volume by up to 90%, effectively recover energy, avoid CH₄ release and mitigate soil and water contamination [75]. Additionally, the incinerator's solid waste can be dumped in above-ground landfills or mixed with building materials because it is thought to be inert and hygienically perfect. It should be emphasized that comparing with other municipal solid waste (MSW) treatment technologies, incineration shows better results [76]. However, it's also a good solution for the issue of the global energy crisis. In this sense, incineration offers a means of meeting demand for energy and has garnered a lot of attention due to its higher rate of energy recovery and reduced land occupation [77]. Waste can therefore significantly contribute to reduce the consumption of fossil fuels and to raise the share of renewable energy [78].

Depending on the type of trash and its calorific content, the amount of energy produced by incineration varies; yet, several studies have found that incineration produces more energy than alternative waste treatment techniques [79]. But, the incinerators for sewage sludge may produce large air pollutants. Particulate matter, carbon monoxide (CO), metals nitrogen oxides (NO_x), sulfur dioxide (SO₂), and unburned hydrocarbons are the main pollutants released. The incinerator's operations may produce emissions of intermediate by-products of partially burned material, including hazardous organic compounds, if they are partially burned. High initial expenditures, potentially high operating expenses based on the use of auxiliary fuels, operational challenges, air emissions, and potential public hostility are drawbacks of incineration [8].

4.1.5. Hydro-electric system

Hydropower is a form of sustainable energy that relies on the water cycle and is the most established, trustworthy, and affordable renewable energy generation technology. Wastewater flow is used by turbine systems to produce electrical or mechanical power. The turbine transforms the kinetic energy of wastewater into rotational energy, which can then be used to produce electricity. In wastewater treatment facilities with large flow rates and sizable pressure drops, turbine systems are frequently used. According to the installed electricity capacity, projects are divided into small and large-scale hydropower systems in the Munawar et al., 2026

hydropower classification system. However, the most important results regarding power production and investment costs per kWh depend on environment. It relies on local hydrology, on local population and urban framework, on regional river network, on local building and equipment unit rates, and in circumstances where optimum equipped discharge is partly related to rainwater drainage [42-80]. Hydroelectric projects are evaluated economically by considering a variety of costs, including capital costs (such as building a dam or installing turbines), operational costs (such as upkeep and monitoring), revenue from selling energy or power contracts for purchase, and possible revenue from government subsidies.

Availability of water resources, project size, environmental concerns, and the state of the energy market are all indicators of economic viability. Even though, the potential for hydropower is expected to rise globally. On a country level, it is anticipated that the situation will vary through one country into the next due to global warming. While there are significant hazards in both scenarios, some countries will see enhancement in potential and others will see losses. As a result, adaption strategies should be included in hydropower designs[42-80]. Although hydropower is a CO₂-free source of energy, there are greenhouse gas emissions associated with the development of hydropower schemes, reservoir silting, and breakdown of organic matter (particularly in tropical areas). Hydropower plants may leave a sizable aesthetic and spatial footprints. Assuring that hydropower projects are sustainable in their design and construction is one of the biggest difficulties that the hydropower plants face. In past, hydropower operations occasionally performed poorly in this area. Changes in biodiversity, water quality, population displacement, and potential impact of dams on fish migration are a few of the more significant issues that need to be taken into account and managed while using hydropower plants [42-80].

4.2. Technical and Economic Evaluations of Novel Technologies

4.2.1. Microbial fuel cells (MFC)

The system depends on bacterial metabolism, which oxidizes organic substances and releases electrons that can be collected as a source of electricity. Microbial fuel cells provide the benefit of simultaneous wastewater treatment and continuous energy generation. However, due to their limited power output, more study is required to improve their efficiency and capacity for scaling. This method may qualify as an innovative core technology for the transformation of carbohydrates to energy in the future. Microbial fuel cells advertise themselves as a fundamental technology that is flexible to a wide range of applications and is hence sustainable. Even if the electron donor is present in low concentrations, they convert a wide variety of electron donors with efficient production of energy at moderate to low temperatures. No current technology can meet these requirements[81]. Since the primary objective of MFC is the production of bioelectricity, numerous studies have concentrated on improving power density. To boost the power production, numerous alterations were made, including changes to substrate, the pH, anode and cathode, membrane components, and various microorganisms. [51]. Voltage instability is the main drawback of this method.

To operate a system, you need a stable voltage, but MFC's voltage generation is comparably low. This will result in electricity that is insufficient to operate systems like biosensors, etc. [82]. High internal resistance is another significant restriction; as a result, some electrodes need voltage to move electrons across the circuit effectively. Additionally, oxidant activation loss occurs in MFC along with the drop in oxidant to reduced form conversion [83]. When analyzing economics of Microbial fuel cell projects, capital costs, operational expenses (such as material costs for electrodes and maintenance), generation of energy and earnings, cost savings from wastewater treatment, and potential product revenue typically taken into consideration. System efficiency, substrate accessibility, electrode pricing, and electricity market rates are all factors that affect economic feasibility [84]. Additionally, the effectiveness of proton transport rate is reduced by membrane biofouling. Therefore, to run in continuous mode, a periodic membrane change is required. This will raise the cost of process and serve as a significant roadblock for MFC technology [51].

4.2.2. Anaerobic Membrane Bioreactors

Membrane Bioreactors (MBRs) integrate membrane filtration with biological treatment procedures. They produce high-quality effluent by using membranes to remove sediments and bacteria from the treated wastewater. Membrane bioreactors (MBR) have developed into a cutting-edge technology and are used as a reliable substitute for traditional wastewater treatment procedures because of the tiny footprint they require while delivering higher effluent quality. The addition of the membranes to bioreactor should, however, result in trade-offs between consumption of energy and fouling prevention [85]. Due to the deposit of impurities on the membrane surface and inside of the membrane pores, membrane fouling is an unavoidable phenomenon. Although gas sparging accounts for a sizable amount of consumption of energy for membrane bioreactor operation, it has been frequently used to control membrane fouling because control membrane fouling consumes more than half of energy. Examples of such gas bubbles include aeration and biogas sparging [86]. MBR project economic analyses consider things like upfront expenses, membrane costs, consumption of energy, operational costs (such membrane replacement & cleaning), wastewater treatment cost savings, and potential by-product revenue. Viability of an investment depends on a number of variables, including membrane life, fouling rates, energy costs, and legal requirements [87].

4.2.3. Algae based system

Microalgae are used in algae-based systems to clean wastewater and create biomass, which can then be converted into biofuels as well bioplastics, or other high-value goods. Algae grow faster when operational circumstances and light exposure are optimized because they undergo photosynthesis to collect nutrients and organic components from wastewater. Algae-based systems can produce biomass while simultaneously treating wastewater, creating an energy source that is environmentally friendly and renewable. The maintenance of steady algal growth, effective harvesting, and expensive capital and operating costs is not easy [88]. Algae-based systems are economically evaluated by taking into account aspects like capital expenses, operating costs (such as those associated with algal growing, harvesting, and

dewatering), revenue from sale of biomass or biofuel, prospective profit through co-products, & consumer demand because biofuel products alone were not profitable [89].

4.2.4. Enhanced Biological Phosphate Removal Recovery

Enhanced Biological Phosphate Removal (EBPR) method uses particular microbial populations to specifically remove phosphorus from wastewater. In order for EBPR to function, phosphorus must be taken up by polyphosphate-accumulating organisms and then retrieved as the struvite or other phosphate-rich byproducts. Phosphorus extraction from wastewater lessens the effects of phosphorus discharge on the environment while supplying an important source of nutrients for fertilizers. However, elements including wastewater influent composition, microbial population dynamics, and operational settings can have an impact on how well EBPR systems work [90]. Since sludge high in organics and phosphorus and has traditionally been treated in an expensive and ecologically unfavorable manner by dumping or burning it. It may be useful for power production and phosphorus recovery. However, using EBPR sludge as a substrate and phosphorus supply presents significant difficulties.

First, the macromolecular shape of the organics in the EBPR sludge made it challenging for electricians to directly use them in order to sustain high and consistent electricity generation. Second, majority of phosphorus in EBPR sludge was present intercellularly in form of phosphorus and polyphosphate, and this made it difficult to collect. Therefore, all these difficulties must be overcome before adopting this technique to recover minerals from the EBPR sludge [91]. Economic analyses of enhanced biological phosphate removal projects frequently take into account elements such startup costs, ongoing expenses, phosphorus removal effectiveness, prospective phosphorus revenue, and regulatory compliance costs. Monetary value of the retrieved phosphorus and other variables like influent characteristics and process optimization will determine its feasibility. Need for chemical addition during struvite precipitation results in significant operational expense. For precipitation of struvite, usual Mg level of wastewater from municipalities is quite low. For effective struvite precipitation at specific pH, change in pH is necessary [92].

4.2.5. Membrane distillation (MD)

A hydrophobic membrane is used in the thermal separation during membrane distillation to separate water vapors from the liquid phase through a difference in vapor pressure. By using the thermal energy from the wastewater that has been treated to power the separation process. Membrane distillation can be used for recovery of energy in the treatment of wastewater. Condensing the recovered water vapor allows for the collection of clean water. The benefit of membrane distillation allows for the generation of high-quality water even from complicated or salty wastewater streams. To avoid membrane scaling and fouling, membrane distillation systems may need pre-treatment [93]. The MD process allows solutions to be concentrated up to a supersaturated state, then salts can crystallize. The MD method also enables the concentration of acid solutions, and in the case of volatile acids, the removal of those solutions' spent components. Therefore, utilizing membrane distillation holds promise for boosting both energy and water recovery simultaneously [94-95].

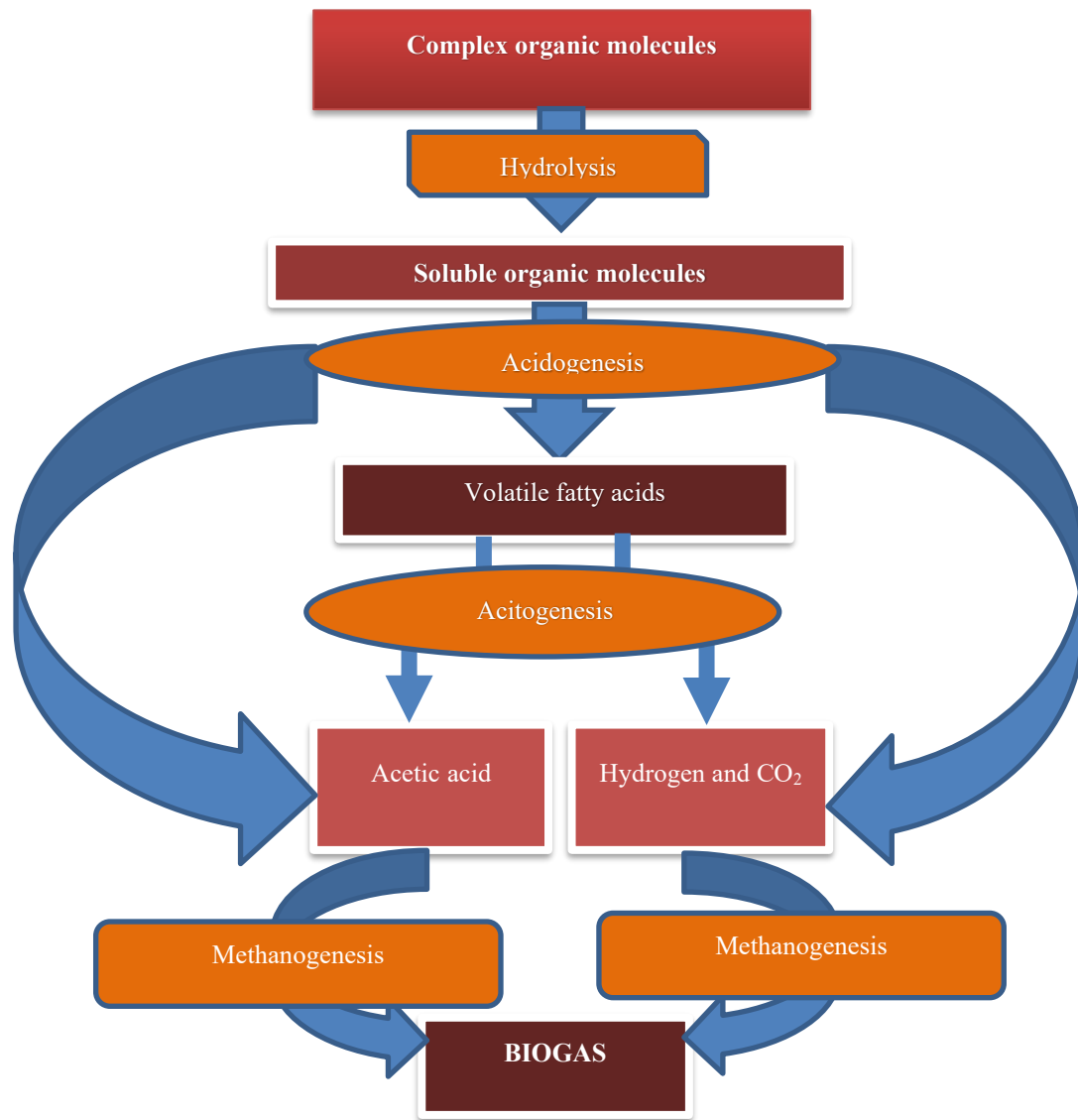


Figure 1: Biogas production by anaerobic digestion [96]

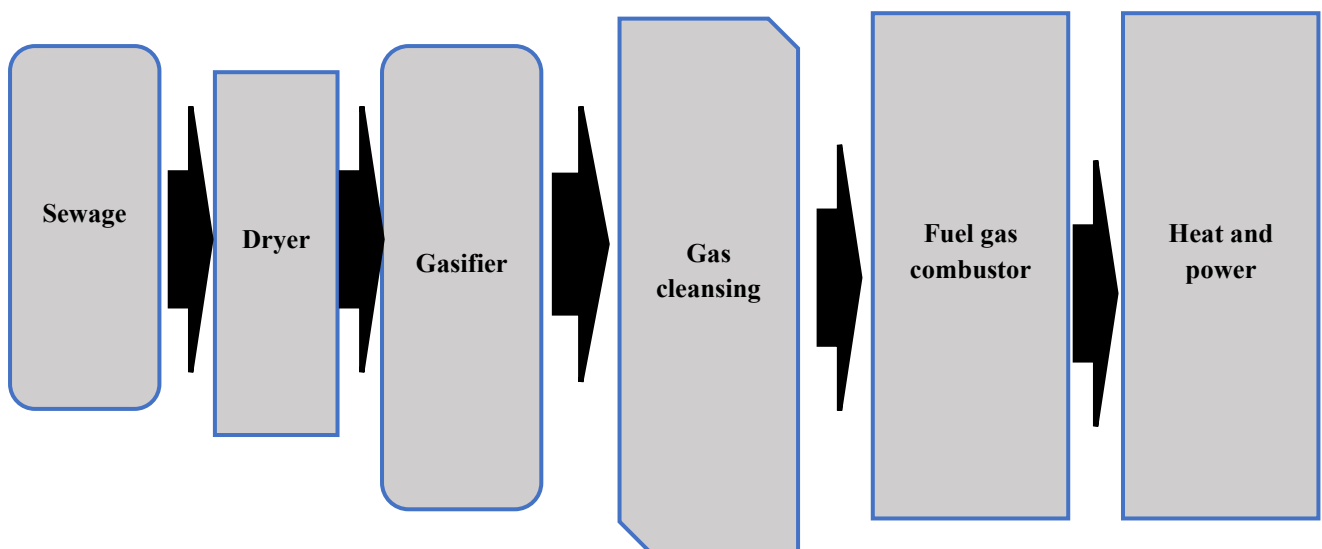


Figure 2: Process of Gasification [13]

Table 1: Comparative analysis of old and novel technologies

Serial no.	Characteristics	Old technologies	Novel technologies
01	Treatment efficiency	Moderate to high treatment efficiency depending on the specific process used, such as activated sludge, trickling filters, or lagoons [6].	High treatment efficiency due to advanced processes such as membrane bioreactors, sequencing batch reactors, or advanced processes. Novel technologies often offer enhanced removal of contaminants, including organic matter, nutrients, and emerging pollutants (Cai, Park et al. 2013; Shantaram, Beyenal et al. 2005)
02	Energy consumption	Due to the necessity of mechanical air circulation, pumping, and mixing, there is a relatively high energy usage [3].	Energy consumption varies depending on the specific technology. Generally novel technologies can generate energy or utilize low-energy processes, reducing overall energy requirements [3].
03	Land requirement	Often require larger land areas due to the use of open ponds or extensive treatment processes (Yuan and Zhu 2016 [3]).	Novel technologies are often designed to be more compact or modular, requiring smaller land areas. Enhanced treatment techniques such as membrane filtration enable more effective use of available space. Due to lower organics and suspended particles in effluents discharge of these technologies, reduce land requirements for underground disposal systems [3].
04	Sludge recovery	Significant sludge generation, requiring further treatment and disposal [97].	Novel technologies focus on sludge minimization through processes such as sludge dewatering, or thermal treatment. Some technologies also enhance sludge treatment and resource recovery by synergetic use of waste, energy and nutrients and integration with other local industries for its maximum usage [3-97].
05	Nutrient recovery	Most of the times, traditional technologies are not helpful in individual nutrient recovery like for phosphorous and nitrogen [3].	Novel technologies emphasize on complete nutrient removal through processes such as enhanced biological phosphorus removal, nitrogen removal via membrane filtration, and the use of specialized microbial systems [3-53].
06	Process complexity	Relatively simple and established processes requiring basic operational knowledge [6].	Novel technologies often involve more advanced processes and automation, need specialized expertise and monitoring or control systems for efficient operation[51-55].
07	Reuse potential	Limited opportunities for water reuse due to the quality of treated effluent and emission of harmful oxides of nitrogen and sulfur and various furans and significant amount of aerosols [20].	Novel technologies focus on enhancing water quality to meet higher reuse standards, enabling applications such as irrigation, industrial processes, and indirect potable reuse [3].
08	Pathogen removal	Traditional technologies are generally not effective in removing most pathogens through processes such as disinfection [3].	Novel technologies often incorporate advanced disinfection methods, such as UV disinfection or membrane filtration, to achieve enhanced pathogen removal and produce high-quality effluents. These effluents can be used for irrigation purposes because of low pathogen content [3].
09	Resource recovery	Limited opportunities for resource recovery, with a primary focus on wastewater treatment [98-99].	New technologies place a strong emphasis on resource recovery, whether it be through the development of value-added by-products such as bioplastics or biofuels, the production of energy, and the recovery of nutrients from sludge [58-100]
10	Scalability	Traditional technologies are generally scalable to accommodate larger wastewater treatment capacities through the addition of units or process modifications [3].	Novel technologies vary in scalability. Some are designed to be modular, allowing for easy expansion, while others may have limitation due to complex processes and specialized equipment [3].
11	Water quality	Traditional technologies are designed to meet regulatory standards for effluent discharge, but may require additional treatment for specific contaminants [29-40].	Novel technologies aim to meet and often exceed stringent water quality standards by incorporating advanced treatment processes and targeted removal of emerging contaminants [51-92].
12	Economic factor	Traditional technologies generally have lower capital costs due to their maturity and widespread use. However, operational and maintenance costs can be significant [101].	Novel technologies often have higher initial capital costs due to their innovative nature, specialized equipment's, and advanced processes. However, they may offer long-term cost savings through improved efficiency, reduced energy, chemical consumption, and resource recovery potential [101].

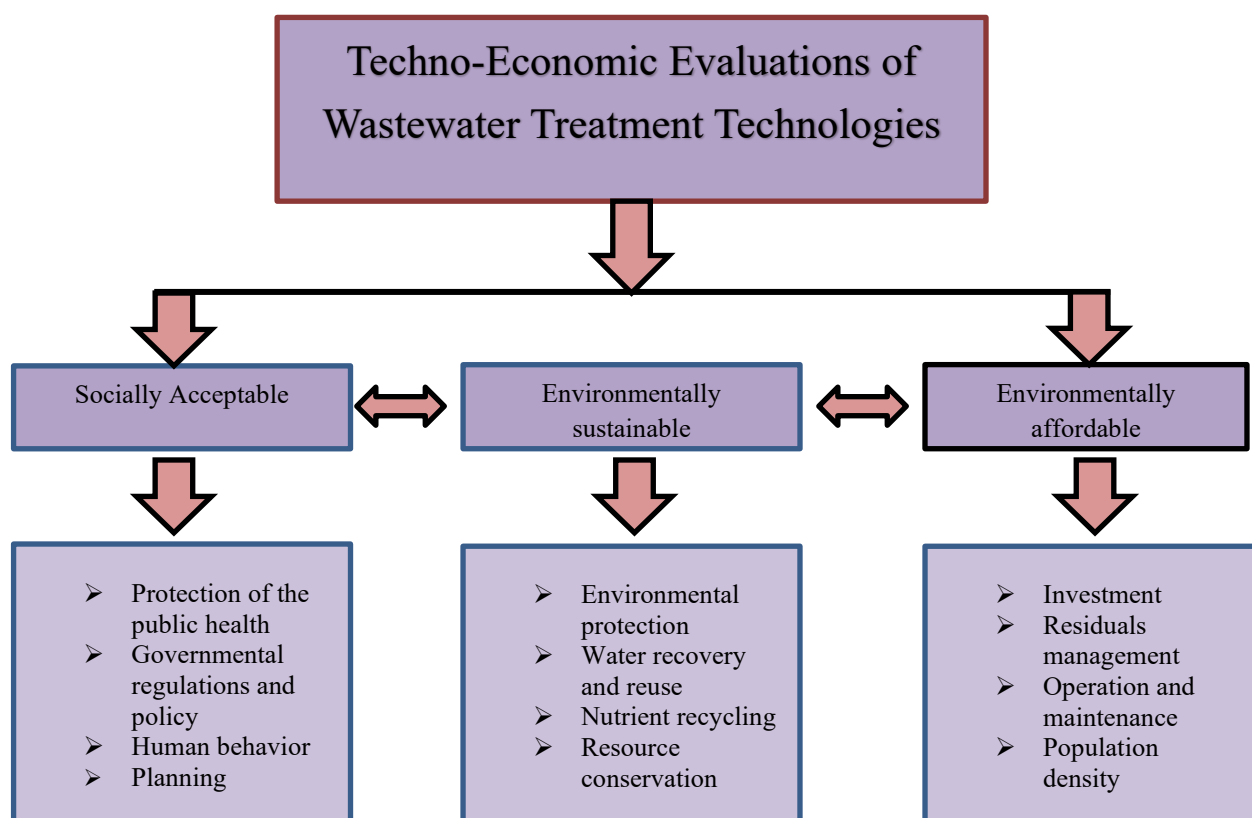


Figure 3: Technical and economical evaluations of wastewater treatment technologies [3]

The wettability and fouling of membranes are the key issues preventing the application of MD. When the MD process is operating, the wastewater frequently contains several components that may precipitate on the surface of membrane. Due to this, even with use of sophisticated pretreatment systems, some effluent cannot be immediately treated by membrane techniques. This work presented the impact of fouling on the MD process efficiency during the process of treatment of several types of wastewaters. If wastewater is given proper pretreatment, this annoyance can be avoided. The main benefit of treating wastewater with MD method is potential to remove foulants from the feed [63]. The cost of the membrane, the life span of membrane (such as replacing it due to scaling and fouling), consumption of energy, operational costs, revenue from the sale of purified water, and possible cost savings from the use of waste heat are all aspects that are taken into account when evaluating the economics of membrane distillation process [64].

5. Environmental Impacts of Wastewater Treatment Technologies

Technologies for wastewater treatment reduce water pollution, purify wastewater, and recover energy; nevertheless, they may also contribute to airborne pollutants since they require energy or materials with related emissions. However, resource recovery (such as water reuse) and energy recovery (such as anaerobic digestion) allow us to counteract the negative environmental effects of wastewater treatment. When external energy and chemical intake and consumption occur, wastewater treatment systems have a net negative global environmental impact. Life cycle analyses (LCAs) are being used increasingly frequently to assess the

Munawar et al., 2026

environmental effects of wastewater systems and to propose solutions for improvement. Finding resource recovery systems that actually achieve net-zero environmental effect is necessary [102]. For instance, it is well known that wastewater treatment methods have a negative influence on greenhouse gas emissions (GHG) [103-104]. Additionally, global warming is probably biggest problem currently affecting civilization due to escalating rate of energy use [105]. Another method of reducing negative effects on environment is the recovery of nutrients (N and P) from wastewater. To fully trade off energy and resource usage, however, we still need to find more effective recovery technologies or high-value goods [106]. Comparative analysis of old and novel technologies is given in Table 1.

6. Conclusions and future perspectives

Vast amounts of pollutants with high organic content in wastewater, if properly handled, can produce an endless source of energy. Therefore, technical and economic assessments of wastewater treatment technologies are essential for establishing viability, effectiveness, and affordability of various treatment options. These evaluations provide valuable insights into the performance, operational requirements, and potential benefits of different treatment options. Economic evaluations, consider capital costs, operational costs, energy consumption, maintenance requirements, and potential revenue streams. They provide a comprehensive analysis of the financial aspects of wastewater treatment technologies such as cost estimation, profitability assessment, and comparison of different treatment alternatives. Economic evaluations also help in evaluating long-term sustainability and economic viability of

wastewater treatment investments. Technical evaluations include treatment efficiency, process stability, reliability, and ability to meet effluent quality standards. They help in understanding capabilities and limitations of each technology, enabling informed decision-making regarding the selection and implementation of appropriate treatment technology. Best practices and the transfer of ideas in the field of energy recovery from treatment of wastewater can be facilitated through working together, exchanging information, and creation of forums for researchers, business leaders, and policymakers. Government should develop financial incentives and encouraging regulations to promote the use of energy recovery techniques for energy recovery from wastewater.

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