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# A Scoping Review of Options for Increasing Biogas Production from Sewage Sludge: Challenges and Opportunities for Enhancing Energy Self-Sufficiency in Wastewater Treatment Plants

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**Abstract:** Treating municipal wastewater is a complex and costly process. With rising energy costs and sustainability targets, wastewater treatment plants (WWTPs) are looking for alternatives to reduce operating costs and carbon dependence. Anaerobic digestion is the most common and established technology used in WWTPs to treat sludge since it can potentially improve energy recovery and reduce sewage treatment costs, mainly due to the generation of biogas. Biogas is a renewable energy resource and can be used in several applications, including heating and producing electricity. By exploring the biogas potential, WWTPs can reduce their operating costs and energy demands. The objective of this paper is to conduct a scoping literature review in order to provide the key concepts underpinning alternatives to improve biogas production and utilisation in WWTPs. In addition, this study aims to provide an overview of the current state-of-the-art that may serve as a quick reference for the research community, WWTP operators, and engineers, including definitions and a general overview of the current state of biogas technologies around the world. Methods to increase biogas production, including co-digestion, pre-treatment, and biological hydrogen methanation, are reviewed, and the alternatives to using biogas are also summarised. This review has identified that co-digestion was the most efficient technique to improve biogas production and methane yield, while pre-treatment of sludge improved sludge biodegradability and reduced sludge treatment costs but also enhanced biogas production. Although many studies have explored different methods to improve biogas production in WWTPs, there is still a need for further investigation, especially regarding the techno-economic feasibility of these methods in full-scale facilities. The current challenges are mainly related to the need for extra investment and increased operating costs to integrate the new techniques into the current system. There is a great interest in alternatives to improve energy efficiency and self-sufficiency in WWTPs. This work provides an important review of the increasing number of recently published research papers that focus on improving biogas generation from sewage sludge in WWTPs.

**Keywords:** wastewater treatment plants; biogas production; sewage sludge



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## 1. Introduction

Wastewater Treatment Plants (WWTPs) play an important role in the water life cycle. The primary objective of these facilities is to remove pollutants from wastewater and send the treated water back to the environment or for reuse [1]. Treating municipal wastewater is a complex and costly process. A significant component of these costs is related to electricity. Previous studies have shown that electricity costs can account for up to 60% of the total operating costs of the WWTP. Likewise, treating 1 mL of wastewater may require up to 1400 kilowatt-hours (kWh) [2]. With an ever-increasing world population, the amount of wastewater, and more stringent effluent standards, the energy demands of WWTPs are expected to continue growing [3].

Sewage sludge is a by-product of the municipal wastewater treatment process, and it must be treated before disposal. Sewage has high levels of pollutants, organic content, and water. Therefore, treating sewage sludge should address those points of reducing pollutants, organic quantity, and water fraction. Although sewage sludge only accounts for 1% to 2% of the total volume of the wastewater treated in a WWTP, its management costs can be very high [4]. A promising solution to treat the sludge in WWTPs is anaerobic digestion. Anaerobic digestion is a biological reaction where organic matter is digested by bacteria and, as a co-product, biogas and digested sludge are generated. Biogas is a renewable fuel that can be treated and used for heating purposes, generating electricity (on-site in WWTPs or exported to the grid), or upgraded and injected into the gas grid, whereas digested sludge is further dewatered and can be used as fertiliser. As a result of multiple benefits, anaerobic digestion is a widely established technology in WWTPs that not only reduces sewage treatment costs but also provides energy recovery and helps plants achieve a higher level of sustainability [5].

With rising electricity costs, sustainability targets, and efficiency goals, more and more plants are looking for alternatives to minimise operating costs and reduce carbon emissions while increasing their energy efficiency [1,6]. As a result, exploring the energy potential of biogas generated from sewage sludge treatment via anaerobic digestion is an area of increasing research. [7–9]. On average, WWTPs with a biogas recovery system consume 40% less net energy than WWTPs without a biogas system [10]. Additionally, improving biogas generation and optimising its utilisation can be an excellent solution to reduce the WWTP's operating costs or even provide revenues if this biogas is sold [11,12].

Because of the many benefits of using anaerobic digestion to treat sewage sludge, several studies have been conducted to improve the anaerobic digestion process, efficiency, biogas production, methane yield, and reduce costs with disposal of the digested sludge. The main approaches investigated by those studies include optimising anaerobic digestion control parameters [13], co-digestion [14], pre-treatment techniques [15,16], and biological hydrogen methanation (BHM) [17]. Figure 1 illustrates the number of studies on alternatives to increasing biogas production from sewage sludge published in the Scopus database in the last ten years.

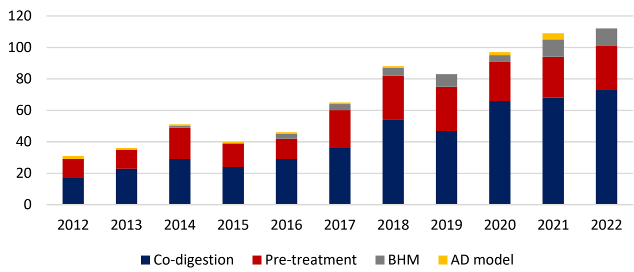


**Figure 1.** Number of studies focused on biogas and methane production from sewage sludge in the last 10 years.

The existing reviews and studies have explored the general concepts of sewage sludge and biogas production and also investigated methods for improving biogas generation from sewage sludge in WWTPs. Ref. [14] reviewed the recent advances in improving biogas generation using co-digestion and pre-treatment methods in WWTPs. Ref. [15] investigated the main pre-treatment processes used in sewage sludge treatment and highlighted the challenges and implementation barriers of the main technologies. Ref. [16] reviewed the recent advances in pre-treatment technologies that can be applied in WWTPs. Ref. [18] reviewed the use of co-digestion and pre-treatment techniques for sewage sludge to improve methane potential and sludge biodegradability. Ref. [19] reviewed the recent advances in biogas production through biological techniques. Ref. [20] reviewed the state-of-the-art on the combination of biomethane production and anaerobic co-digestion in WWTPs, focusing on the biogas production capacity and potential utilisation. Ref. [21] discussed the techniques to improve biogas generation, including co-digestion. Ref. [22] reviewed the use of additives to improve anaerobic digestion performance; advantages and future challenges were also discussed. Ref. [23] reviewed the key concepts of the sewage sludge treatment process, co-digestion, and pre-treatment techniques. However, the majority of these studies focused only on two techniques: co-digestion and pre-treatment. They also do not cover the economic feasibility of those techniques (i.e., co-digestion and pre-treatment) in full-scale WWTPs. The few studies that have performed cost analyses usually conducted the experiments at lab scale, and there is no guarantee that the results related to biogas production, methane yield, and sludge degradability can be accurately replicated in a full-scale plant. In addition, some studies rely on empirical evidence with no validation and do not consider other types of alternatives (apart from co-digestion and pre-treatment techniques). The challenges of validating the results from lab-scale experiments at a full-scale plant are real, especially in relation to its daily operation limitations and costs. WWTPs need to treat a large amount of sewage in a continuous process; therefore, on-site tests are not always possible. Moreover, applying these methods to full-scale plants may require large-scale upgrades to current infrastructure. Therefore, these investigations are necessary to better understand the potential benefits and main challenges of different alternatives to increasing biogas production from sewage sludge.

In this review, it is found that fewer papers have investigated the techno-economic feasibility and viability of co-digestion and pre-treatment techniques applied to sewage sludge in WWTPs. The majority of the studies include the results of the lab-scale experiments (i.e., biogas production, methane yield, and sludge degradability) based on the techniques used; however, cost-benefit analyses are usually not explored. Thus, scoping reviews, which include different types of techniques to improve biogas production, the financial feasibility of techniques and technologies, and highlighting the challenges and opportunities in full-scale WWTPs, are still lacking.

In this context, this paper aims to provide an overview of the most common techniques to improve biogas production in WWTPs. In addition, it also reviews the techno-economic feasibility of these alternatives and the challenges and opportunities for biogas utilisation. To conduct this review, three research questions were included: How is biogas generation improving? Which techniques are most commonly used to maximise biogas production from sewage sludge, and are they economically feasible? What are the challenges and opportunities for biogas in WWTPs? Based on the research questions, the following research objectives were developed: (1) investigate ways to improve biogas generation from sewage sludge in WWTPs, (2) review the most common techniques, explore the biogas production potential and cost-benefits analysis, and present the findings, and (3) identify the challenges and opportunities for the biogas utilisation in WWTPs.

This paper is organized as follows: Section 2 presents the methodology used to perform this review. Section 3 includes the key concepts of anaerobic digestion and biogas production. In this part, the most common methods used to increase biogas production are also presented, and the results from different studies are summarised. Section 4 discusses the challenges and opportunities of biogas utilisation, and the challenges of the methods to increase biogas production are presented. Some studies that performed cost-benefit analyses are also summarised. This study is concluded in Section 5.

## 2. Methodology

In this section, the methodology used to develop this review paper is presented. Scoping reviews aim to identify and map relevant studies that meet the pre-determined criteria by identifying key concepts, the main sources of evidence, and gaps in the research under review. They can serve as a starting point for researchers to gather information, key concepts, and relevant insight about the related topic. Moreover, they can bring experts and researchers up to date with the latest trends and general information about the topic and also provide evidence of the main advantages and drawbacks of the current methods. In this scoping review, we summarised and combined results based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. By using this method, a systematic review was conducted on the subject to find the answers defined in the research questions, using inclusion and exclusion criteria to identify which studies would be included, and then the findings were summarised [24].

As the first step, the literature search was conducted primarily using three online databases—Scopus, IEEE Xplore, and ScienceDirect—of academic papers published in journals and conference proceedings. Google Scholar, Google, and other websites were also used as an alternative to capture more information and technical knowledge that the primary databases were not able to cover, such as government publications and industry reports. The methodology used to conduct this review was based on the established filters, including:

- Search strings: co-digestion OR pre-treatment OR biological hydrogen methanation AND sewage sludge. Maximising OR optim* OR increas* OR improv* AND anaerobic digestion OR biogas production OR generation AND sewage sludge. Biogas production AND Municipal OR sewage wastewater treatment plants OR WWTP
- Year published: From 2012 to 2022
- Language type: English

The search returned 967 results from Scopus, 5460 from ScienceDirect, and 42 from IEEExplore. In addition to that, a total of seven technical reports were found on Google. The returned references were managed by EndNote X9 for duplicate identification. Title and abstract screening were performed based on the following eligibility criteria:

- Peer-to-peer articles, government reports, and industry reports;
- Only documents written in the English language;
- Reports and articles published as journal articles, conference proceedings, symposiums, and technical documentation;
- Published between 2012 and 2022;
- Works with a focus on improving the biodegradability of sewage sludge and alternatives to improve biogas production in WWTPs.

Any articles that did not meet all the inclusion criteria were excluded. Thus, 104 articles were selected for full-text reading, and finally, 72 articles and 5 industry/government reports were included in this review, as shown in Figure 2.

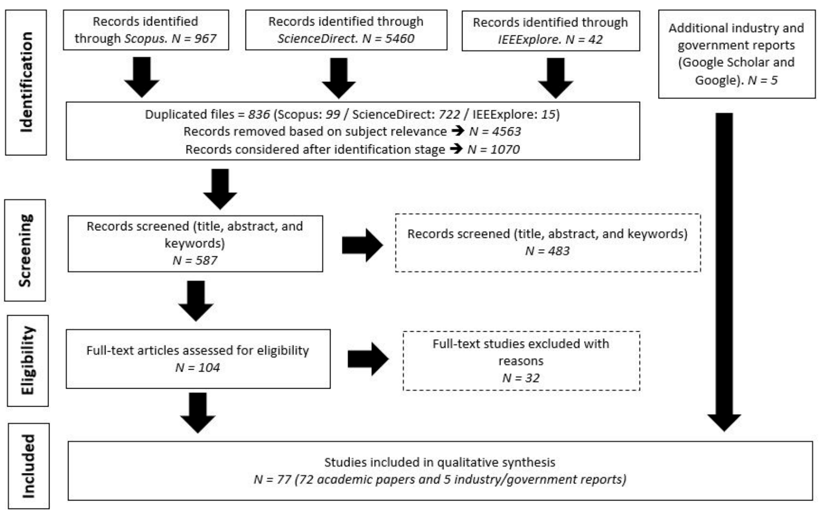


**Figure 2.** PRISMA flow diagram of the search and screening process used in this literature review.

This literature review is limited to the three electronic databases, Google, and Google Scholar. This review focused only on biogas production from sewage sludge. Energy generation from other sources of renewable energy resources was not included, including energy generation from digested sludge (i.e., pyrolysis, gasification, incineration, and liquefaction). Despite the limitations of this scoping review, this work provides a rigorous and comprehensive review. Therefore, it is expected that the insights and results from this study will be useful to get a clear, structured, and comprehensive idea of the current state-of-the-art of increasing biogas production in WWTPs and its techno-economic feasibility.

## 3. Biogas in WWTPs

In this section, key concepts related to the biogas production concept are introduced, including a general background of the main parameters that influence the anaerobic digestion process. Different options found in the literature on the topic of increasing biogas production in WWTPs are also presented, as are the results of research papers.

### 3.1. Biogas Production

The main objective of anaerobic digestion is to reduce the total and volatile solids load in sludge, reduce pathogens, minimise odours, and generate biogas. The biogas generation process in anaerobic digestors is a complex process where microorganisms transform organic matter into biogas, which progresses in four stages: hydrolysis, acidogenesis, acetogenesis, and methanogenesis, as explained below [5,25].

- Hydrolysis: Insoluble compounds (e.g., carbohydrates, fats, and proteins) are broken down by bacteria into soluble elements (monosaccharides, amino acids, and long-chain fatty acids) by enzyme catalysis in hydrolytic bacteria. The main objective of this process is to simplify large molecules [5].
- Acidogenesis: Also called fermentation, in this process, the substrate resulting from hydrolysis is converted into sugar, hydrogen, and intermediate compounds, such as volatile fatty acids (i.e., acetic, propionic, and butyric acids), by a large number of fermentative bacteria. Alcohols, ammonia, and hydrogen sulphide are also produced [5,25].
- Acetogenesis: Compounds produced in the acidogenesis (volatile fatty acids and alcohols) step are transformed into acetate by reducing carbon dioxide or organic acids. Most of the carbon dioxide and hydrogen are produced at this stage [25].
- Methanogenesis: Compounds produced in acetogenesis are catalysed by methanogenic organisms to produce methane and carbon dioxide. This stage is where waste stabilization occurs and is also known as biomethanation [5,25].

Anaerobic digestion and biogas production are influenced by several elements, including feedstock parameters, design, and operational factors. Therefore, it is essential to understand how they influence the operational performance of anaerobic digestion. In addition, some of these parameters can be used as controllable variables in anaerobic digestion models and control strategies to enhance biogas production, methane yield, and quality of the treated wastewater and digested sludge [26,27].

(a) Feedstock parameters

Feedstock parameters and composition have a significant impact on anaerobic digestion efficiency and biogas production. It will determine the biological, chemical, and physical characteristics contained on the substrate. Therefore, quantifying and understanding those parameters are very important [28]. Some of those parameters are explained below.

- Total solids (TS): TS refers to the quantity of residues that remain after the feedstock's dehydration. TS combines the suspended and dissolved solids, and it is expressed as a percentage (%). TS concentration is not always a reliable indicator of organic content in the substrate [25]. In a typical WWTP with primary and secondary treatment, primary sludge consists of about 50% of the total sludge solids [29].
- Suspended solids (SS): Related to the small solid particles that remain in the suspension of the wastewater. It is usually removed in the primary treatment or by water filters [25]. Municipal wastewater is characterized by a large quantity of suspended solids [30].
- Volatile solids (VS): Refers to the quantity of organic solids in wastewater and is an important parameter to evaluate the performance of a WWTP [29,31]. The concentration of VS in the influent wastewater is conventionally assumed to be the same as that in the sludge. The VS of the raw sludge can range from 70% to 75%, and the VS of the digested sludge varies from 45% to 50%. Anaerobic digestion can reduce VS by 40–60% [31,32].
- Volatile suspended solids (VSS): Associated with the quantity of volatile matter present in the solid part of the wastewater [25].

- Chemical oxygen demand (COD): It is the quantity of dissolved oxygen present in the wastewater that breaks down the organic materials. The COD of the influent wastewater usually ranges between 0.3 and 1 g/L, and after treatment, the COD in the effluent can be as low as 0.02 g/L. Monitoring COD is useful for measuring the efficiency of the treatment process and ensuring compliance with regulations for effluent disposal [5,25,29].
- Biological oxygen demand (BOD): The amount of dissolved oxygen required by bacteria and microorganisms to degrade organic matter under anaerobic conditions. In a WWTP, BOD can be related to biodegradability, and sewage sludge is characterized for its low anaerobic biodegradability [33]. The average BOD for municipal wastewater can range from 200–300 mg/L [34].
- Carbon/nitrogen ratio (C/N): Carbon is responsible for providing energy for microbial activity, whereas nitrogen is the primary microbial cell element. If it is high, the anaerobic digestion has difficulty starting the process, whereas if it is low, nitrogen is converted into ammonia, which can decrease the digestion efficiency. Sewage sludge has a low C/N ratio (lower than 10:1); therefore, the addition of a carbon-rich feedstock can increase it (the optimal range is between 20:1 and 30:1 for anaerobic digestion performance) [33,35].

(b) Design and operational parameters

Each of the four stages of anaerobic digestion has its optimal operational conditions; therefore, these factors are extremely important when designing the system. Some of the main parameters are listed below [36].

- pH: The pH for acidogenic bacteria is less sensitive and can range from 4.5 to 8, whereas the optimal value for methanogens is between 6.5 and 7.5. The optimal pH for methane production ranges between 6.8 and 7.2. If the pH is higher or lower than these values, it should be neutralized before feeding into the reactors [25,29,37].
- Alkalinity: A high alkalinity concentration enhances the digester's stability. Low levels can be a consequence of the accumulation of organic acids, the failure of methane-forming bacteria, or the presence of elements that inhibit the bacteria's activities [29,38].
- Temperature: Affects the organic material's properties and influences the growth of bacteria. In anaerobic digestion, the two main operational temperatures are mesophilic (30~38 °C) and thermophilic (50~57 °C). In the acidogenesis stage, the optimal temperature range is 25~35 °C, and in methanogens, it is 32~42 °C [29]. Most WWTPs are designed to operate under mesophilic conditions since it is easier to control, more adaptable to environmental changes, more stable, and cheaper to operate [25,39].
- Retention time: Solid retention time (SRT) and hydraulic retention time (HRT) are the average times that bacteria and feedstock stay in the anaerobic reactor before they are withdrawn, respectively. Usually, in WWTPs, both are considered the same [40]. The HRT depends on the sludge flow and biodegradability, and most plants operate within a 20-day timeframe. Higher HRT decreases the WWTP's treatment capacity, increases operating costs, and requires a higher digester capacity. Shorter HRT reduces digestion efficiency, including poor sludge stabilisation, lower biogas yields, and higher volumes of biosolids [41].
- Organic load rate (OLR): Quantifies the mass of carbon in the digester feedstock in a specific period. It is affected by the feedstock flow, temperature, HRT, digestor type, and volume. Higher OLR can increase biogas production; however, excessive OLR may cause inhibition and decrease anaerobic digestion performance [42,43].
- Digestion volume: In WWTPs, the digester size is directly associated with the sewage sludge flow, OLR, and pre-treatment processes used in the plant [25].
- Digester mixing: The main objective of mixing is to uniformly blend the feedstock to ensure uniform microbial contact and avoid the formation of scum or a bottom layer on the digestor to improve the anaerobic digestion performance. Mixing in WWTPs can be done by impellers, pumps, or gas recirculation [44].
- Digestion stages: Anaerobic digestion can occur in one or two stages. In a two-stage reaction, hydrolysis and acidogenesis are separated from acetogenesis and methanogenesis to

optimise performance. Benefits achieved from that include higher VS reduction, loading rates, biogas production, process stability, reduction of pathogens, and a smaller reactor volume [29]. The major drawback is the higher sensitivity and operating costs [45].

- Digester type: There are a wide variety of anaerobic reactors, each one performing the same function in a slightly different manner. Examples of digesters include the continuous stirred-tank reactor (CSTR), the anaerobic baffled reactor (ABR), the up-flow anaerobic sludge blanket (UASB), the expanded granular sludge bed (EGSB), the anaerobic fluidized bed reactor (AFBR), and the up-flow blanket filter (UBF) [5,13,25].

(c) Inhibition

Inhibiting elements are toxic compounds that can decrease the efficiency of anaerobic digestion or even cause process failure. They can be formed during the process or can be part of the subtract composition [25,39]. Usually, they are identified when VFA increases or the pH, biogas, methane concentration, or microorganism population decreases. The most common types of inhibitors are ammonia, sulphide, heavy metals, salts (i.e., calcium, potassium, magnesium, and sodium), fatty acids, and organic compounds (i.e., benzenes, phenols, alkenes, aldehydes, ketones, pyridine, and pyridine's derivatives) [40].

### *3.2. Optimising Biogas Generation in WWTPs*

Improving anaerobic digestion efficiency enhances biogas production, and consequently, the facilities become less reliant on carbon-intensive electricity grid systems [46]. However, optimising anaerobic digestion is a complex process, mainly due to the non-linear relationships among its parameters and variables. Because of its complexity, sub-optimal anaerobic digestion operations may be frequent in wastewater treatment facilities [47]. The main issues faced during anaerobic digestion are low gas production, maintaining a stable process, and resuming biogas production after a process failure [19]. In addition, limitations result from the first stage of the process (hydrolysis), which requires long retention times caused by the slow degradation of organic matter. The literature identified the most common methods to improve biogas production, including optimising anaerobic digestion performance, co-digestion, pre-treatment techniques, and BHM [21].

(a) Anaerobic digestion optimisation

Improving anaerobic digestion performance involves optimising operational conditions (i.e., reactor's temperature, organic loading rate, retention time, pH) to maximise the process efficiency and biogas production. The most common approach to validating this process is through mathematical modelling, which can replicate the anaerobic digestion process. Anaerobic digestion models are divided into two groups: steady-state and dynamic models. Steady-state models can be used to design the optimal configuration of the biogas system since they can estimate the HRT, reactor capacity, and gas production based on the plant's inputs, especially influent flow and substrate composition. Dynamic models are used to optimise the overall operation's efficiency by improving biogas production and reducing energy consumption. It will also adapt to changes in operating parameters, including feedstock flow and composition, inhibition, temperature, pH, etc. Integrating anaerobic digestion models to improve process efficiency in WWTPs can provide several advantages and benefits, including better monitoring, management, process control, and energy efficiency in the daily operation of the facility [39].

The most common types of anaerobic digestion models found in the literature were based on anaerobic digestion parameters, including temperature, OLR, and HRT. Other models focused on optimising anaerobic digestion stages (i.e., hydrolysis, acetogenesis, and methanogenesis), minimising the formation of inhibitions (i.e., VFA), or aspects of chemical kinetics [39]. One of the most commercial anaerobic digestion models used in anaerobic digestion optimisation is the ADM1. ADM1 was developed by the International Water Association (IWA) task group with the objective of simulating anaerobic digestion conditions to improve process efficiency and, consequently, biogas production. The model describes the biochemical (i.e., kinetic reactions) and physicochemical processes (i.e., liquid-gas transfer, acid-base reactions), and it was developed based on both anaerobic digestion and sludge models [48]. ADM1 has been widely tested on different systems in several configurations, from small-scale lab experiments to full-scale wastewater plants [39]. IWA also developed activated sludge models (ASMs), which aimed to assess the activated sludge process based on the biokinetic rates within the anaerobic bioreactors. Examples of ASM are ASM1, ASM2, ASM2d, and ASM3. ASM1 has become one of the more common models used in academic and industrial projects due to its ability to characterise organic matter in wastewater (measured in COD) and represent the behavior of an activated sludge system. ASM2 is an extension of ASM1, which includes additional parameters such as reaction and element behavior within activated sludge. The main difference between ASM1 and ASM2 is the consideration of cell internal structure details in ASM2, while ASM1 considers this a distributed parameter. ASM2d adds two additional parameters. ASM2 assumes that the microorganisms may grow only in aerobic conditions, whereas ASM2d can allow for growth in both anaerobic and anoxic environments. ASM3 includes the storage component concept, which is described as a non-active particulate, COD [49].

Some studies have investigated the optimisation of anaerobic digestion models to increase biogas production and improve process efficiency. Ref. [47] proposed an optimisation model to maximise the methane concentration and biogas production for WWTPs. The input variables considered in the model were associated with the anaerobic digestion parameters, including temperature, pH, total solids (TS), total volatile solids, alkalinity, OLR, HRT, and volatile fatty acids. Ref. [37] proposed a model that optimises the controllable and uncontrollable variables for the anaerobic digestion of WWTPs. The parameters considered in the optimisation function include temperature, total and volatile solids, pH, organic load, sludge flow rate, and HRT. The authors pointed out that if the optimal system temperature of 39 °C was set, an increase of 5.3% in biogas production could be achieved. Moreover, the biogas generation could increase by almost 21% if all variables were optimised. Some studies have simplified the ADM1 due to its large number of parameters and states [50]. In this model, the main dynamic behavior of the ADM1 model was simplified in a two-stage process. Ref. [51] suggested a framework to optimise biogas generation based on artificial neural and genetic algorithms. The authors claimed the proposed method could provide better results when compared with mathematical modelling. Ref. [26] reviewed the technologies and parameters related to anaerobic digestion, mathematical models, and control strategies to describe the biogas generation process in WWTPs. The authors highlighted that anaerobic digestion control is still challenging due to its scalability and process stability complexity. Ref. [52] investigated some computational methods for optimising biogas production from anaerobic digestion, including at WWTPs. The authors highlighted that optimising those parameters can provide a realistic estimation of biogas generation, providing several benefits for the facilities. Ref. [53] compared the performance of one- and two-stage anaerobic digestion processes treating sewage sludge. The authors conducted lab experiments considering both configurations and different scenarios. The results showed that the two-stage configuration could increase biogas generation by up to 40% compared with the traditional design. In addition, they found that the two-stage model achieved more efficient biogas recovery, digestibility, and volatile suspended solids reduction. However, they could not model the proposed design for an application in a large-scale WWTP to investigate its feasibility. Refs. [54,55] investigated the performance and efficiency of the biogas recirculation technique in the anaerobic digestion system. The authors mentioned that the proposed strategies could provide biogas upgrades, enhance methane production, and reduce net costs for sludge treatment and dewaterability. However, the studies did not perform any economic analysis to analyze the implementation and operating costs of the proposed design.

(b) Co-digestion

Co-digestion is a technique where two or more feedstocks are mixed to improve biogas production. Co-digestion is widely used, especially when the C/N ratio of the feedstock is low, and this ratio needs to be increased to an ideal range (20–30) [13,33,56]. Since sewage sludge is known for its low digestibility and low C/N ratio, co-digestion is a common alternative to enhance both methane concentration and biogas generation in

WWTPs [33]. Attractive feedstocks that can be combined with sewage sludge include fats, oils, and grease (FOG), food scraps and waste, food/beverage/dairy processing waste, the organic fraction of municipal solid waste (OFMSW), agricultural residues, livestock manure, biofuel by-products, and other high-strength waste (HSW) [33,57]. Depending on the type of feedstock and mixing ratio, co-digestion can increase biogas production from 25% to 400% compared with single-feedstock digestion [58]. For example, the average biogas production considering only sludge is between 0.9 and 1.1 $m^3/day/m^3$ digester volume, while with co-digestion, it can be around 2.5–4.0 $m^3/day/m^3$ digester volume [20,33]. The choice of substrates used in co-digestion depends on the location of the biogas facility, the availability of the feedstock, and associated costs (i.e., transportation, storage, etc.) [57]. Table 1 summarizes the biogas yield and methane potential of different organic wastes, and Table 2 presents some studies that investigated the use of co-digestion of sewage sludge and different feedstocks to improve biogas production.

**Table 1.** Biogas yield for different feedstocks [18].

| Feedstock | CS | DM | FOG | FW | M | OFMSW | PS | RS | WAS | WS |
|---|---|---|---|---|---|---|---|---|---|---|
| Theoretical $CH_4$ yield (L/kg TS) | 324 | 228 | 622 | 494 | 582 | 211~657 | 418 | 301 | 363 | 300 |
| Experimental $CH_4$ yield (L/kg TS) | 241 | 51 | 580 | 510 | 420 | 170~557 | 213 | 281 | 186 | 245 |

CH4: Methane, CS: Corn stover, DM: Dairy manure, FOG: Fat, oil, and grease, FW: Food waste, M: Microalgae, OFMSW: Organic fraction of municipal solid waste, PS: Primary sludge, RS: Rice straw, WAS: Waste activated sludge, WS: Wheat straw.

The objective of co-digestion is to improve biogas production and methane yield to generate electrical, thermal, or mechanical power, implying extra revenue for WWTPs. Depending on the type and quantity of feedstock used in the co-digestion, the biogas production can increase significantly, resulting in a significant increase in renewable energy, and the demand for the WWTP from the electricity grid can notably decrease or even become energy positive [59]. Implementation of co-digestion in a WWTP is recommended if there is sufficient spare generation capacity, gas storage, or even capability to convert biogas into biomethane to accommodate the increased volume of biogas generation [60].

Several full-scale WWTPs in the U.S., Canada, and Europe have successfully implemented co-digestion in their operations [61,62]. For example, East Bay Municipal Utility District generated USD 2 million in electricity revenues in 2012–2013, and Des Moines Metropolitan Wastewater Reclamation Authority WWTPs trade around 40–50% of their biogas (annual revenue between USD 460,000 and 800,000 yearly). Both facilities in the U.S. implemented co-digestion as an alternative to increasing plant revenues [33]. Other facilities around the world also reported biogas volume improvements resulting from co-digestion, including the Grevesmuhlen (20% energy surplus) and Köhlbrandhöft plants (increased electricity generation by 15%), which are both located in Germany [20].

(c) Pre-treatment techniques

Pre-treatment aims to increase the feedstock's biodegradability and solubility, speed up the anaerobic digestion process, avoid potential process issues with cleaning and operation, reduce sludge volume and weight, and, consequently, increase biogas production, solids reduction, methane concentration, and provide higher-quality biosolids [13,23]. These techniques primarily focus on the lysis or disintegration of the particles, which solubilise and release intracellular matter. This process aims to provide simpler compounds and resources that are bio-available for digestion by microorganisms [39]. By accelerating the process of organic degradation, pre-treatment methods can increase the OLR and reduce the HRT of the digesters, which can result in higher process efficiency. There are several types of pre-treatment methods that can be applied to sewage sludge. They can be classified into different groups based on their operational principles, including biological, chemical, mechanical, and thermal [63].

**Table 2.** Co-digestion studies of sewage sludge and different feedstocks.

| Ref. | Feedstock | Reactor Vol. (L) | T (°C) | Mixing | Mixing Ratio | HRT (d) | OLR (g VS/L. d) | VS Removal (%) | $CH_4$ Production (L/kg VS) | | $CH_4$ Concentration (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Mono | Co-Digestion | Mono | Co-Digestion |
| [64] | SS and SW | 1 | 37 | n.i. | SHW:WMS *w/w* & 4% TS 20% | 20 | 1 | 51.2 | SS:434.8<br>SW: n.i. | 171.1 | SS: 67.2 | 70.5 |
| | | | | | *w/w* & 4% TS 40% | 20 | 1.5 | 53.3 | | 736.4 | | 71.4 |
| | | | | | *w/w* & 4% TS 60% | 18 | 2 | 64.6 | | 674.8 | | 71.5 |
| | | | | | *w/w* & 7% TS 20% | 11 | 2.5 | 63.1 | | 647.7 | | 75.6 |
| | | | | | *w/w* & 7% TS 40% | 11 | 2.3 | 58.6 | | 674.4 | | 74.9 |
| | | | | | *w/w* & 7% TS 60% | 11 | 2.8 | 72.4 | | 674.1 | | 78.3 |
| [65] | SS and FW | 0.5 | 35 | Yes (300 rpm) | FW:SS 30:70 | 30 | 1.77 | 60.58 | SS: 288 | 462 | SS: 68.6 | 64.9 |
| | | | | | | 20 | 2.70 | 58.16 | | 408 | | 65.4 |
| | | | | | | 25 | 2.42 | 63.60 | FW: 537 | 449 | FW: 64.3 | 65.7 |
| [66] | SS and SW | 4.5 | 37 | Yes (160 rpm) | SW: 2.5% | 22.5 | 2.13 | 57 | SS: 234<br>SW: 719 | 396 | n.i. | n.i. |
| | | | | | 5% | | 2.68 | 64 | | 619 | | |
| | | | | | 7.5% | | 3.55 | 61~65 | | 585~644 | | |
| | | | | | 10% | | 4.54 | n.i. | | 551 | | |
| [67] | WAS and GTS | 200 (type A)<br>3.4 (type B) | 36 | Yes | GTS: 10% | 30 | 1.8 | 43 | WAS: 255<br>GTS: 871 | 180 | WAS: 63<br>GTS: 80 | 66 |
| | | | | | 17% | 24 | 2.0 | 36 | | 333 | | 69 |
| | | | | | 19% | 25 | 1.7 | 42 | | 324 | | 67 |
| | | | | | 28% | 26 | 1.6 | 42 | | 292 | | 67 |
| | | | | | 42% | 25 | 1.4 | 39 | | 398 | | 67 |
| | | | | | 60% | 24 | 1.2 | 44 | | 546 | | 69 |
| | | | | | 80% | 24 | 1.0 | 33 | | 454 | | 69 |
| | | | | | 90% | 25 | 0.8 | 17 | | 158 | | 63 |
| [68] | SS and ABP (mix of DTC, DW, DS, and GTS) | 4 | 35 | Yes (300 rpm) | SS:ABP R1 = 7:1 *v/v* | 14 | 3.3 | 61 | SS: 300<br>DTC: 400<br>DW: 230<br>DS: 340<br>GTS: 900 | 380 | n.i. | 65 |
| | | | | | | 20 | 2.4 | | | 400 | | 63 |
| | | | | | | 25 | 1.8 | | | 340 | | 56 |
| | | | | | R2 = 7:1 *v/v* | 14 | 3.7 | 60 | | 400 | | 64 |
| | | | | | | 20 | 2.8 | | | 430 | | 65 |
| | | | | | | 25 | 2.1 | | | 370 | | 59 |
| | | | | | R3 = 3:1 *v/v* | 14 | 4.0 | 65 | | 390 | | 67 |
| | | | | | | 20 | 2.9 | | | 410 | | 65 |
| | | | | | | 25 | 2.2 | | | 340 | | 62 |

**Table 2.** *Cont.*

| Ref. | Feedstock | Reactor Vol. (L) | T (°C) | Mixing | Mixing Ratio | HRT (d) | OLR (g VS/L. d) | VS Removal (%) | $CH_4$ Production (L/kg VS) | | $CH_4$ Concentration (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Mono | Co-Digestion | Mono | Co-Digestion |
| [69] | SS and FW | 6 | 35 | Yes (60 rpm) | SS:FW R2 = 2.4:1 | 8 | 15 | 39.7 | SS: 157~237<br>FW: 377~465 | 215 | SS: 63~65<br>FW: 50~54 | 56 |
| | | | | | | 12 | 10.1 | 43.1 | | 239 | | 58 |
| | | | | | | 16 | 7.5 | 45 | | 261 | | 60 |
| | | | | | | 20 | 6.3 | 45.5 | | 258 | | 59 |
| | | | | | | 30 | 4.6 | 51 | | 303 | | 61 |
| | | | | | R3 = 0.9:1 | 8 | 17.8 | 52.2 | | 288 | | 56 |
| | | | | | | 12 | 11.5 | 55 | | 306 | | 57 |
| | | | | | | 16 | 8.5 | 56 | | 303 | | 56 |
| | | | | | | 20 | 7.2 | 58.1 | | 332 | | 58 |
| | | | | | | 30 | 5.1 | 62.2 | | 350 | | 57 |
| | | | | | R4 = 0.4:1 | 8 | 18.5 | 59.2 | | 304 | | 53 |
| | | | | | | 12 | 12.5 | 65.4 | | 352 | | 54 |
| | | | | | | 16 | 10.3 | 64.9 | | 355 | | 55 |
| | | | | | | 20 | 8.4 | 67 | | 380 | | 56 |
| | | | | | | 30 | 6.4 | 70 | | 400 | | 56 |
| [70] | SS and FW | 5 | 35 | Yes | FW:SSbc 1:1 | 20 | 0.5~7 | 86.2 | SSbc: 507.5<br>SSac: 385.9<br>FW: 625.4 | 404.8 | SSbc: 58.6<br>SSac: 55.9<br>FW: 58.8 | 60.4 |
| | | | | | 1.5:1 | | | 85.2 | | 485 | | 60.4 |
| | | | | | 2:1 | | | 87.7 | | 470 | | 53 |
| | | | | | 1:1.5 | | | 82,8 | | 490.6 | | 60.3 |
| | | | | | 1:2 | | | 84,8 | | 492.1 | | 59.8 |
| | | | | | FW:SSac 1:1 | | | 84 | | 453.7 | | 58.4 |
| | | | | | 1.5:1 | | | 87.1 | | 410 | | 53 |
| | | | | | 2:1 | | | 86.3 | | 384.6 | | 58.6 |
| | | | | | 1:1.5 | | | 86.2 | | 417.5 | | 57.5 |
| | | | | | 1:2 | | | 85.3 | | 471.1 | | 58.9 |

**Table 2.** *Cont.*

| Ref. | Feedstock | Reactor Vol. (L) | T (°C) | Mixing | Mixing Ratio | HRT (d) | OLR (g VS/L. d) | VS Removal (%) | $CH_4$ Production (L/kg VS) | | $CH_4$ Concentration (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | Mono | Co-Digestion | Mono | Co-Digestion |
| [71] | SS, FOG and MSW | 30 | 38 | Yes | oil 0.5% | 34. | 0.91 | n.i. | SS: 325.4 FOG: 682.3 MSW: 748.3 | 428.23 | SS: 76.3 FOG: 73 MSW: 77.1 | 65.1 |
| | | | | | | 20 | 0.91 | | | 422.90 | | 66.4 |
| | | | | | | 23 | 0.74 | | | 231.13 | | 66 |
| | | | | | | 18 | 1.21 | | | 363.23 | | 60.7 |
| | | | | | 1–2% | 23 | 0.64 | | | 225.80 | | 62.1 |
| | | | | | | 28 | 0.98 | | | 265.37 | | 61.8 |
| | | | | | | 14 | 1.51 | | | 432.75 | | 62.6 |
| | | | | | | 10 | 0.97 | | | 398 | | 60.8 |
| [72] | SS, GTS and MSW | 2 × 6 | 37 | Yes (180 rpm) | 5~30% | 20 | S1 *: 1.15~1.35 | S1: 50 | SS: 300 GTS: n.i. MSW: n.i. | S2: 456 S3: 547 | S1: 66 | S1: 66 |
| | | | | | | | S2: 1.44~1.8 | S2: 56.4 | | | | S2: 66 |
| | | | | | | | S3: 2.5 | S3: 64.7 | | | | S3: 69 |
| [73] | SS and FW | 100 | 35 | Yes | n.i. | 11~14 | 1.46~2.1 | SS + MSW: 35~43 | SS: 84 FW: 335 | 90~430 | n.i. | n.i. |
| [74] | SS and CM | 2.5 | 35 | n.i. | SS:CM 4:1 | 63 | n.i. | 49.91 | SS: 319 CM: 251 | 270 | n.i. | n.i. |
| | | | | | 3:2 | | | 52.77 | | 301 | | |
| | | | | | 2:3 | | | 54.8 | | 328 | | |
| | | | | | 1:4 | | | 53.73 | | 323 | | |

ABP: Animal by-products, CM: Cow manure, DS: Dissolved air flotation sludge, DTC: Digestive tract content, DW: Drumsieve waste, FOG: Fat, oil, and grease, FW: Food waste, GTS: Grease trap sludge, MSW: Municipal solid waste, SS: Sewage sludge, SSac: Sewage sludge (after centrifuge), SSbc: Sewage sludge (before centrifuge), SW: Slaughterhouse waste. n.i.—not informed. * S1 (Stage 1): Only SS, S2 (Stage 2): SS + GTS, S3 (Stage 3): SS + GTS + MSW.

- Biological: The main objective of biological treatment is to reduce and remove the organic matter and nutrients (i.e., nitrogen and phosphorous) from the wastewater to follow the effluent disposal requirement and regulatory limits [5]. Some of the most common techniques are aerobic digestion, dual-stage digestion, temperature phase, and enzyme addition [46,75]. Dual digestion aims to physically separate the hydrolysis and methanogenesis stages. The addition of enzymes improves the sludge's stabilisation and biodegradability and promotes better sludge dewaterability and methane generation. Aerobic digestion uses an aeration process to stabilise and reduce the organic matter in the wastewater, and it is typically used in an activated sludge treatment process in WWTP [63].
- Chemical: Chemical methods hydrolyse the organic compounds in sludge by using different reagents. The most common techniques include alkaline and acid hydrolysis, ozonation, and oxidation processes [63]. Alkaline treatment is the most common chemical method used due to its efficiency in adjusting the pH, improving hydrolysis rates, and solubilising organic compounds. Acid hydrolysis and oxidation focused on the enhancement of hydrolysis performance and biogas production, whereas ozonation enhanced biodegradability, hydrolyse potential, and sludge mass reduction [15,76].
- Mechanical: Aims to increase the contact surface area of the particles, making them easily available for the microorganisms to digest [63]. These methods include ultrasound, ultrasonic, microwave, high-pressure homogenizer, and pulse methods; among them, microwave and ultrasound are the most studied and applied in sewage sludge [15]. Usually, they require moderate electricity consumption, and the efficiency of anaerobic digestion of sewage sludge is very low when not combined with other methods [46].
- Thermal: Breakdown of organic matter by exposing it from a low temperature (~70 °C) to a high temperature (150–200 °C) and pressure (600–2500 kPa). The aim of high temperatures is to disrupt the particle structure and solubilise the compounds. These methods have been used to increase the sewage sludge's biodegradability and enhance biogas production and biosolids dewaterability. Thermal hydrolysis is the most widely used pre-treatment in WWTPs [33,46]. Commercial thermal hydrolysis systems are available on the market. Some demonstrate the capacity to increase biogas production by up to 150% after applying 180 °C for a 30-min treatment. Thermal pre-treatment can also operate with increases in OLR, and it lowers HRT [15,39,76].

Table 3 illustrates some studies of sewage sludge pre-treatment to improve biogas generation.

(d) Biological hydrogen methanation (BHM)

BHM is a conversion process that generates methane and water from carbon dioxide and hydrogen using methanogenesis organisms within a bioreactor under anaerobic conditions. The hydrogen used in this process comes from a power-to-gas system (hydrogen is generated when an electrolyser is applied to water). Power-to-gas is a method for generating combustible fuel that acts as a storage technology for variable renewable energy generation [77]. The BHM can be conducted in two ways: in situ or ex situ. In the in situ method, the hydrogen is directly injected into the anaerobic digestor, which reacts with carbon dioxide from the biogas and generates methane. The anaerobic digestion of sewage sludge and the methanation process occur in a unique reactor. In this option, the traditional biogas upgrading system can be reduced, and capital costs can be saved relative to ex situ [78].

**Table 3.** Pre-treatment methods applied on sewage sludge to improve biogas production.

| Ref. | Method | Substrate | Treatment Details | Anaerobic Digestion | Outcomes |
|---|---|---|---|---|---|
| [79] | Thermal pre-treatment | Mixed sludge (pH 6.9 and 19.3 g VS/L). | Thermal process of 75–225 °C for 15 to 105 min. | Batch and continuous mode. | The optimal treatment was found to be applying 180 °C for 76 min to improve methane production by 40% (from 194.5 to 272.9 mL $CH_4$/g COD). |
| [80] | Thermal pre-treatment | Digested sludge (117.8 g VS/kg and 222.5 g TS/kg) and mixed sludge (19.3 g VS/kg and 27.6 g TS/kg). | Thermal process of 180–200 °C during 30 min. | Mesophilic, batch mode, and 25 days. | Methane yield can improve by up to 50% when compared with raw sludge. The sludge's biodegradability increased from 35% to 62% after thermal pre-treatment. |
| [81] | Thermal pre-treatment | Primary sludge (29 g TS/L) and digested sludge (29 g TS/L). | Thermal process of 150 °C for 30 min at 500 kPa. Thickening ratio of 1.33 | Mesophilic (35 °C) and 20 days. | Thermal pre-treatment and recuperative thickening could improve biogas generation by 15% and sludge biodegradability by 17–50%. |
| [82] | Thermal pre-treatment | Primary, WAS, and digested sludge from 5 different WWTPs. | Thermal treatment was applied at 80 °C for 5 h with an initial pH of 10. | Mesophilic (37 °C), batch mode, and 20 days. | COD solubilization and VS reduction increased by 20% and 44%, respectively. Methane was produced at a higher rate, but the overall yield was not significantly improved. |
| [83] | Thermal pre-treatment | WAS (23.5 g TSS/L, 17.9 g VSS/L, and 22.9 g TCOD/L). | Combination of the thermal process at 70 °C with ammonia (135.4 mg $NH_3$-N/L). | Mesophilic (35 °C), batch mode, and 37 days. | Methane potential improved by 25% for ammonia treatment, 18% for thermal treatment, and 16.5% for the combined ammonia-thermal treatment. Hydrolysis rates increased by 52%, 25%, and 30% for ammonia, thermal, and combined ammonia-thermal, respectively. |
| [84] | Microwave | Mix of primary sludge and WAS. | Microwave pre-treatment at 2450 MHz, ambient pressure, and mechanical stirring at 55 rpm. | Mesophilic (35 °C), batch mode, and 25–30 days. | Methane yield increased by 20% (from 215 to 258 mL/g VS) and VS removal improved by 31% (from 35.3% to 46.8%) for a 1-stage reactor configuration with HRT of 37 days. Methane yield increased from 258 to 288 mL/g VS (11.6% higher than 1-stage reactor) with 26 days of HRT for a two-stage reactor configuration. |
| [85] | Microwave | Mixed sludge (70% of primary and 30% of secondary). | Microwave pre-treatment at 80 W for 5–15 min. | Mesophilic (29 °C), batch mode, and 11 days. | Biogas production and biodegradability rate increased to 11.9% and 38.5%, respectively, compared with the untreated sludge. |
| [86] | Microwave | Mixed sludge (21.9 g TS/L and 17.6 g VS/L). | Microwave pre-treatment at 20 MJ/ kg TS and 700 J/s. | Mesophilic (35 °C), continuous mode, and 22–35 days. | Methane production and biodegradability increased by 20% (155 to 186 mL/g VS) and 34.6% (from 52% to 70%), respectively, when compared with the untreated sludge. |
| [87] | Microwave | Mixed sludge. | Pre-treatment using 400 and 700 W and ranging the energy applied from 0 to 30 kJ/g TS. | Mesophilic (35 °C), batch mode, and up to 90 days. | Methane yield and methane production rate increased by 17% and 43%, respectively. Optimal values for the TS and microwave powers were 20 kJ/g TS and 700 W. OLR increased by 39%. |
| [88] | Microwave | Primary sludge (37.7 g TS/L and 27.1 g VS/L) and WAS (25.6 g TS/L and 21.8 g VS/L) are mixed in a ratio of 30:70 PS–WAS. | Pre-treatment using 975 kJ/L was performed. | Mesophilic (34 °C), batch mode, and HRT up to 25 days. | Methane yield improved by 29%, 41%, 45%, and 43% for an HRT of 5, 10, 20, and 25 days, respectively. VS removal increased by 33.3%, 43.7%, 14%, and 34.3% for an HRT of 5, 10, 20, and 25 days, respectively. |
| [89] | Microwave with sodium citrate (SC) | Raw sludge (48.5 g TS/kg, 33.3 g VS/kg). | Microwave at 850 W, varying between 3 and 30 s, and energy input of 10 to 40 MJ/kg TS. | Mesophilic (37 °C), batch mode, and 30 days. | Methane production improved by 148%. Energy applied was 269.4 kWh for the optimal pre-treatment configuration. Method not economically attractive. |

**Table 3.** *Cont.*

| Ref. | Method | Substrate | Treatment Details | Anaerobic Digestion | Outcomes |
|---|---|---|---|---|---|
| [90] | Ultrasound | Thickened mixed sludge (40/60% of primary–secondary sludges). | Ultrasound operating at 26 kHz and thermal hydrolysis (55 °C). | Mesophilic, batch mode up to 35 days. | Tests were performed for 0.5, 15,500, and 30.5 MJ/kg TS and retention times of 3, 8, and 13 h. Methane yield increased by 50% and maximum rate of methane production was 30~80% higher. |
| [91] | Ultrasound and microwave | Thickened sludge (43.6 g TS/kg and 30.8 g VS/kg). | Ultrasound and microwave were used for treating sludge. The specific energy used in both treatments was 96 kJ/kg sludge. | Mesophilic (37 °C), semi-continuous mode, and up to 67 days. | Biogas increased by 20% and 27% for the microwave and ultrasonic, respectively. Treatments were found not to be economically feasible. |
| [92] | Ultrasonic | WAS (2.58% TS). | Ultrasound at a specific energy of different ranges of values (i.e., 5, 10, 15, 20, 25, 30, and 35 MJ/kg TS) was applied to the sludge. | Mesophilic, batch mode, and 30 days. | Biogas production increased by 8.6%, 22.9%, and 31.4%, by applying 15, 25, and 35 MJ/kg TS, respectively, compared with untreated sludge. |
| [93] | Ultrasonic | Mixed sludge (8% TS and 30/70% of primary-WAS). | Applied ultrasonic (225, 450, and 675 kJ/kg TS) and alkaline (lime ranging from 0.02 to 0.08 g/g TS) pre-treatment methods to sludge. | Mesophilic (37.5 °C), batch mode, and 30 days. | Methane yield enhanced by 60%, 51%, and 73% for the ultrasound treatment of 225, 450, and 675 kJ/kg TS with lime at 0.04 g/g TS when compared with raw sludge. |
| [94] | Ultrasonic | Mixed sludge (132 g TS/kg and 88 g VS/kg). | Ultrasonic conditions: power generator of 150 W, pressure of 1 atm, 25 °C and operation time up to 60 min. | Mesophilic (35 °C), batch mode, and 10 days HRT. | Methane yield increased from 88 to 172 mL /g VS (up to 95%). Biodegradability reached 81% in VS. |
| [95] | Ultrasonic | WAS (23.75 g DS/kg). | Ultrasound conditions: 25 kHz frequency was applied with power up to 1 kW. | Mesophilic (37 °C), batch mode, and 21 days HRT. | Methane production increased by 20%. |
| [96] | Ultrasonic and ultrasonic-ozone | Thickened WAS (15.15 g TS/L and 12.9 g VS/L). | Ultrasonic conditions: 20 kHz frequency and specific energy of 9 kJ/g TS. The ozone amount used was 12 mg $O_3$/g TS. | Mesophilic (37 °C), semi-continuous mode, and 10–20 days HRT. | Biogas production increased by 20.7% and 35.9% for 10 days HRT, and by 7.7% and 25.6% for 20 days HRT for ultrasonic and ultrasonic–ozone, respectively. VS removal improved by 7.6% and 18.3% for 10 days HRT, and by 9.7% and 21.4% for 20 days HRT for ultrasonic and ultrasonic–ozone, respectively. |
| [97] | Microwave, ultrasonic and thermal hydrolysis | Mixed sludge (135 g TS/kg and 92 g VS/kg). | Thermal conditions: 120 °C, 2 atm for 15 min. Ultrasonic conditions: 25 °C, 1 atm, 150 W for 45 min. Microwave conditions: Power range of 100–900 W for 1.4 min. | Mesophilic (35 °C) and batch mode. | Methane production improved by 95%, 29%, and 20% by using sonication, thermal, and microwave, respectively. Sludge solubility increased by 19.2% and 83.4% using thermal and microwave methods, respectively. Ultrasonic, thermal, and microwave required 136, 36, and 20,145 kJ/g TS of specific energy, respectively. |
| [98] | Ozonation and ultrasound | Mix of primary sludge and TWAS (ratio 1:1 DS) with 16.7 g TS/L and 13 g VS/L. | Sequential treatment of ultrasonic (9 kJ/g TS) and ozone (0.036 g $O_3$/g TS). | Mesophilic (35 °C), batch mode, and 30 days HRT. | Biogas production increased by 11% and 15.4% for ultrasonic and ultrasonic-ozone, respectively. Sludge biodegradability improved by 35% with the combined treatment. |
| [99] | Thermal and ultrasonic | Mixture of primary sludge and TWAS (ratio 1:1 DS) with average values of 15.4 g TS/L and 12 g VS/L. | Sludge was treated with ultrasonic at 5 MJ/kg TS and thermal treatment operating at 65 °C. | Mesophilic (35 °C) and batch mode. | Biogas production increased by 20% with the combined treatment. |
| [100] | Thermal pre-treatment | Sludge (33.56 g TS/L and 25.9 g VS/L). | Thermal pre-treatment of 120 °C for 0.5 h at 2 bar. Ultrasonic at 20 kHz and 50 W. | Mesophilic (35 °C) and batch mode. | Methane production increased by 51.27% and 33.61% for thermal and ultrasonic, respectively. Sludge biodegradability increased from 38.1% (raw sludge) to 46.1%, 45,16%, 44%, 45,3%, and 46% for 0.5, 1, 2, 3, and 4 h of thermal treatment. |

In the ex situ, the methanation process occurs in a separated digester (Sabatier reactor). In this configuration, carbon dioxide and hydrogen react to produce methane and water vapour. Both methods can require high amounts of energy, especially due to the need to improve the hydrogen solubilisation for efficient uptake by the hydrogenotrophic methanogenic archaea [17]. The main advantage of using the in situ method is lower capital requirements and no requirement for a biogas upgrading system. However, the carbon dioxide concentration should be continuously monitored since the surplus of hydrogen can promote an increase in the pH, which can cause inhibition [101]. Therefore, the operational challenges to maintaining process stability for the acetogenesis and methanogenesis organisms require a more intensive process control, which can lead to higher operating costs [102]. Alternatively, ex situ processes have several benefits, including higher efficiency, i.e., ex situ ranges from 0.08 to 0.39 litre of methane per litre reactor volume per day ($L_{CH_4}/L_{VR}.d$) while in situ values can vary between 0.37 and 688.6 $L_{CH_4}/L_{VR}.d$, being easier to operate and maintain the process stable, and a low risk of process failure [78]. In addition, it allows higher hydrogen loading rates and has higher gas conversion rates [103]. Figure 3 shows the configuration of in situ and ex situ BHM that can be used in a WWTP. BHM is influenced by some factors, including nutrients, reactor design, retention time, pressure, and temperature. Nutrients are necessary for the archaea's growth, and depending on the species, the amount and type of nutrients can range. Examples of nutrients can be a solution containing ammonium, cobalt (II), nickel, sodium chlorides, potassium dihydrogen phosphate, sodium selenite, and others [78]. The type and capacity of the proposed reactor system are directly associated with the amount of carbon dioxide and hydrogen treated, but they also take into consideration the physical constraints, and investment/operating costs. Important parameters for BHM performance include retention time, pressure, and temperature [17].

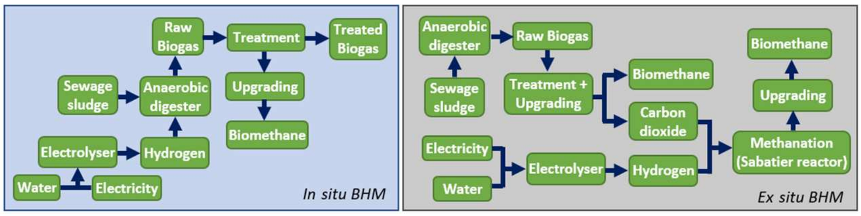


**Figure 3.** Biological Hydrogen Methanation diagrams (in situ and ex situ).

The methane production rate (MPR) is the key parameter to identify the efficiency of the BHM. BHM is a promising technology, but more research is still required to fully assess the efficiency in terms of power and cost, apply the system at full scale, and peform further validation [77,78,104]. In WWTPs, BHM can be used as an alternative to generating more methane, especially for the ex situ method, where the carbon dioxide generated in the biogas upgrading process can be combined with hydrogen in a separate digester and generate additional methane. Research on BHM is summarised in Table 4. The first industrial power-to-gas plant based on methanation at the commercial level in Europe was constructed at the Dietikon WWTP in Switzerland in April 2022. The facility has the capacity to treat 200 $m^3/h$ of raw biogas (from sewage sludge) and includes a biomethane upgrader. A 2.5 MW electrolyser is able to generate approximately 450 $m^3/h$ of hydrogen using renewable energy from a waste incineration facility close to the WWTP [105]. The hydrogen and carbon dioxide are fed into a stirred reactor to produce methane, which will be purified to remove contaminants before being injected into the local gas network system. The author concludes that the amount of carbon dioxide emissions avoided will be equivalent to approximately 2000 households [106].

**Table 4.** Biological hydrogen methanation studies.

| Ref. | Method | Environment | Reactor Type | P (atm) | pH | $H_2$ inj.($L_{H2}/L_{VR}.d$) | $CO_2$ inj.($L_{CO2}/L_{VR}.d$) | Retention Time (h) | $CH_4$ Production Rate ($L_{CH4}/L_{VR}.d$) | $CH_4$ Concentration (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| [102] | Batch ex situ | Thermophilic | CSTR | 0 | 8.5 | 7.3 | 1.8 | 24 | 1.7 | 93 |
| | | | | | 8.5 | 15.4 | 3.9 | | 3.7 | 96 |
| | Continuous ex situ | | | | 8.1 | 14.7 | 3.7 | 2 | 2.9 | 78 |
| | | | | | 7.1 | 47.1 | 11.8 | 0.57 | 8.2 | 70 |
| | Batch in situ | | | | 7.97 | 5 | - | 24 | 1.82 | 65 |
| [107] | Ex situ with mixing (1500 rpm) | Thermophilic | CSTR | 0.74 | 6.85 | 331.2 | 86.4 | 0.09 | 75.3 | 65 |
| | | | | 4.93 | | 576 | 144 | 0.054 | 137.1 | 80 |
| [108] | In situ with mixing (500 rpm) | Thermophilic | CSTR | 1.48 | 7.8 | 2.9 | - | 8 | 0.9 | 93.5 |
| | | | | | | 5.9 | | 4 | 1.5 | 95.4 |
| | | | | | | 11.3 | | 2 | 2.6 | 90 |
| | | | | | | 11.6 | | 2 | 2.7 | 94.2 |
| | | | | | | 22.8 | | 1 | 5.3 | 90.8 |
| [109] | Ex situ with mixing (700 rpm) | Thermophilic | CSTR | 0 | 6.85 | 345 | 86 | 0.076 | 47.9 | 22 |
| | | | | | | 46 | 11.5 | 0.76 | 10 | 85 |
| | | | | 0.2 | | 230.4 | 57.6 | 0.117 | 46.9 | 42 |
| | | | | | | 100 | 28 | 0.13 | 16 | 74 |
| | | | | | 7.35 | 960 | 240 | 0.022 | 65.6 | 7 |
| [110] | In situ with mixing (150 to 300 rpm) | Thermophilic | CSTR | 0 | 7.75 | 3.17 | 0.86 | 14.4 | 1.4 | 53 |
| [111] | In situ and liquid recirculation (0.58 $m^3$/h) | Mesophilic | AF | 1 | 7.91 | 71.3 | 36.5 | 28 | 9.42 | 63 |
| | | | | | | 143.5 | 36.5 | 18 | 7.12 | 57 |
| [112] | Continuous ex situ | Mesophilic | TB | 0 | 7.3 | 4.8 | 1.15 | 4 | 1.2 | 98~100 |
| | | | | | | 6 | 1.4 | | 1.5 | 98 |
| [113] | Ex situ | Thermophilic | M | 0 | 7.4 | 9.9 | 2.4 | 3.1 | 2.4 | 79 |
| [114] | Ex situ | Thermophilic | HFM | 0 | 7.2 | 10 | 2.6 | 2.8 | 2 | 84 |
| | | | | | | 20 | 5.2 | 1.37 | 3.8 | 75 |
| | | | | | | 45.2 | 11.2 | 0.64 | 9.5 | 65 |
| [115] | In situ with mixing (155 rpm) | Thermophilic | UASB | 0 | 7.9 | 7.92 | 2 | 3.29 | 1.8 | 81 |
| | | | | | 7.9 | | | 3.18 | 1.8 | 66 |
| | | | | | 8.2 | | | 2.83 | 1.5 | 52 |

**Table 4.** *Cont.*

| Ref. | Method | Environment | Reactor Type | P (atm) | pH | $H_2$ inj.($L_{H2}/L_{VR}.d$) | $CO_2$ inj.($L_{CO2}/L_{VR}.d$) | Retention Time (h) | $CH_4$ Production Rate ($L_{CH4}/L_{VR}.d$) | $CH_4$ Concentration (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| [116] | Ex situ | Mesophilic | BPF | 0 | - | 83.2 | 20.8 | 0.37 | 20 | 97 |
| | | | | | | 120 | 30 | 0.27 | 30 | 90 |
| | | | | | | 114.4 | 28.6 | 0.27 | 27 | 75 |
| [117] | Ex situ | Thermophilic | FB | 0 | 6.8–6.9 | 19.8 | 5 | 144 | 4 | 46 |
| | | | | | | 11 | 2.7 | | 1.7 | 26 |
| | | | | | | 7 | 1.7 | | 1.7 | 87 |
| [118] | Ex situ | Mesophilic<br>Thermophilic | B | 0 | 7–7.5 | 0.36 | 0.09 | 24 | 0.19 | 79<br>81 |

AF: anaerobic filter, B: batch, BPF: biofilm plug-flow, CSTR: Continuous stirred-tank reactor, FB: fixed bed, HFM: hollow-fiber membrane, M: membrane, TB: tricked bed, UASB: up-flow anaerobic sludge blanket.

## 4. Challenges and Opportunities

In this section, the main challenges of implementing co-digestion and pre-treatment methods are presented. In addition, the topic of economic feasibility and viability of co-digestion and pre-treatment methods in WWTPs is explored, and a methodology to evaluate the cost-benefits is presented. Some studies that conducted economic analysis are also summarised, but not many studies have performed that. In sequence, a snapshot of the biogas production in WWTPs around the world is presented, as are the opportunities for biogas utilisation, including generation potential and the different alternatives to using biogas. Finally, government incentives and subsidies provided in some countries are summarised.

### *4.1. Challenges of Implementing Co-Digestion and Pre-Treatment Methods*

As stated, co-digestion of sewage sludge with high-strength feedstocks can increase biogas production and methane yield. However, implementing co-digestion in WWTPs can add new challenges for re-designing the process operation, which may require infrastructural updates and/or upgrades [33], including:

- Digester overloading: The addition of new feedstocks (i.e., FOG and FW) can lead to high OLR, longer HRT, foaming issues, and process interferences. In addition, it may increase biosolids (the solid portion of digested sludge) yields and the accumulation of solids in the bottom of the digester [20,61,119].
- Digestion instability: High variability of co-digestion feedstock characteristics (variations in composition and volume) may cause process instability (i.e., pH fluctuation) due to the addition of a new substrate into the system [33,58,120].
- Digestion inhibition: Digestion of high-strength organic matter can produce inhibitory products during the anaerobic digestion process, including ammonia, organic acids, and heavy metals, which can decrease process efficiency, especially affecting the methanogenic bacteria. In addition, the use of co-digestion can promote sludge flotation, digester foaming, pipe and pump blocking, and system clogging [61,119].
- System upgrading: Some upgrade/update may be needed to store the new substrate and increase biogas production and biosolids amounts. Examples of installations include storage tanks (for biogas and feedstock) and systems (i.e., pumps, pipelines, mixers, biogas upgrade equipment, increased power system capacity, or enlarged reactor volume). Therefore, it may require extra expenditure with investment and operating costs [33,62,119].

WWTP operators are increasingly interested in understanding the technical challenges and opportunities for implementing co-digestion at their facilities. Many of these plants may be suitable for co-digestion; however, their economic viability must be evaluated first. The Environmental Protection Agency (EPA) in the U.S. developed a co-digestion assessment tool (known as Co-EAT) to assess the economic and physical feasibility, biogas production, and biosolids characteristics. The model also considers capital costs and biosolids residual costs in the methodology [62].

As mentioned previously, pre-treatment techniques can improve energy/process efficiency, which can lead to economic retrofits, but at the same time, these techniques can also be energy intensive [63]. These methods are still facing economic and environmental challenges due to high energy requirements, high investment, and high operation costs, which can sometimes make them unsuitable or financially unviable. In addition, most of these techniques have been studied and applied in experiments only at the lab scale and have not been tested or used in full-scale plants, with only a few having been implemented and evaluated in full-scale WWTPs. Therefore, pre-feasibility and technical studies should be carried out to evaluate if these methods are cost-effective or not [15,63,76].

### *4.2. Economic Feasibility of Co-Digestion and Pre-Treatment Methods*

One of the main driving forces for the implementation of a new technology to improve energy efficiency in a WWTP is the overall cost (capital, operation, savings, and revenues). Techno-economic analysis and optimisation studies are usually necessary to determine the potential benefits related to the selected method [14]. In addition, since WWTPs can vary in size, capacity, location, effluent requirements, etc., there is no one-size-fits-all solution in designing the optimal solution for a specific WWTP, and the design and techno-economic analysis may vary from plant to plant [121].

Depending on the analysis, the economic viability can be high-level or very complex with multiple factors, including investment, operating and maintenance costs, plant capacity, physical constraints, effluent requirements, sustainability targets, energy cost rate, etc. Revenue generation requires the analysis of a variety of factors, including energy tariffs (for electricity and gas) for both purchasing and selling power, biogas quantity, technical capacity constraints (i.e., power system units, upgrading technology, storage size), and incentives (i.e., government, private, system operator). In addition, depending on the size and capacity of a utility, they can become market participants (for electricity and/or gas) and buy/sell energy directly from/to the market, depending on the price at any given moment and other factors. However, an understanding of the risks and benefits is required before this significant change to electricity procurement strategies [11,14].

A simple comparative assessment can be calculated in terms of CAPEX (capital expenditure), OPEX (operational expenditure), and potential revenues, as shown in (1) [122]. In (1), $C_{CAPEX_{AD}}$ include the capital costs for the construction (if it is a new plant) or the costs for updating/upgrading an existing plant (if required), and $C_{CAPEX_{method}}$ is the capital costs of the selected method (i.e., co-digestion, pre-treatment, BHM), which can also include the upgrading system for biomethane. $C_{OPEX_{AD}}$ and $C_{OPEX_{method}}$ are the operating and maintenance costs for the anaerobic digestion system and the selected method, respectively. $C_{OPEX_{Biosolids}}$ is related to the operating costs for the disposal of biosolids and $C_{Benefits}$ takes into consideration the potential benefits (i.e., revenue from exporting biomethane to the grid, revenue from selling electricity to the grid, and benefits from reducing facilities' operating costs).

$$C_{Total} = C_{CAPEX_{AD}} + C_{CAPEX_{method}} + \sum_t [C_{OPEX_{AD}}(t) + C_{OPEX_{Method}}(t) + C_{OPEX_{Biosolids}}(t) - C_{Benefits}(t)] \quad (1)$$

A quick feasibility analysis can be conducted by comparing the total costs ($C_{Total}$) before and after the implementation of a selected method within a defined period (i.e., 20 years). If the total cost after the implementation is lower than before, the selected method can be cost-effective; otherwise, it may not be. It is expected that the investment and operating costs for the selected method will be very high in the beginning (especially the capital), but it is expected the costs over the years will decrease, considering that more benefits and/or operating costs with biosolids will count. However, biogas plants can receive incentives and subsidies, which can help reduce this high investment cost. For example, in Australia, three main biogas projects (Jandakot Bioenergy Plant, Goulburn Bioenergy Project, and Malabar Biomethane Project) received a total of AUD 11.8 million in financial support (the total investment costs for all three projects were around AUD 19.5~21.6 million) [105,123,124]. Sometimes, even if the implementation costs of a specific method are not cost-attractive (at least in the first moment), WWTPs may decide to choose it for other reasons, which can include receiving financial support or subsidies, meeting sustainability targets, improving processing efficiency, etc.

The financial viability of co-digestion and pre-treatment techniques requires techno-economic analysis to evaluate their feasibility in a full-scale WWTP. However, few studies have investigated this in the literature. Ref. [60] studied the impact of co-digestion of food waste and sewage sludge on biogas production in a full-scale WWTP in Germany. The annual cost of the feedstock was considered to be 6000 EUR/year. The total investment cost to implement co-digestion was EUR 2.2 million, which included a blower upgrade, food waste storage system, and solar dryer. Overall, the food waste cost was 0.08 EUR/kWh.y, but the energy costs saved by using co-digestion were 1.55 EUR/kWh.y, so the net gain from co-digestion was 1.47 EUR/kWh.y. Ref [125] investigated the economic feasibility of co-digestion in a full-scale WWTP in Austria. In the study, the potential methane yield was analysed through lab experiments using sewage sludge samples collected before and after the implementation of co-digestion in a WWTP. Two substrates were used: food waste and grease trap sludge. The authors found that the electricity produced from the co-digestion system could cover the associated costs of the plant. The benefits-to-cost ratio ranged from 1.08 to 1.14. Ref. [126] studied the techno-economic feasibility of using co-digestion in a WWTP that treats around 2.27 ML/d in Oman. In the cost-benefit analysis, the investment costs of the anaerobic digester, power system unit (upgrading systems and electricity generators), and operational and maintenance costs were considered. The operation and maintenance costs of the digester, the electricity rate, and the power generation costs were considered fixed for the entire period of 20 years. Considering co-digestion, the net present value and internal return rate calculated were AUD 285,047 and 13.5%, respectively, and without co-digestion, they were AUD 393,483 and 19.4%. The study did not consider the gate fees (or costs) associated with feedstock or the additional costs for operating the co-digestion plant. Ref. [127] identified full-scale WWTP projects that used co-digestion to increase biogas production and generate extra revenue in the U.S. Of the twelve hundred WWTPs identified, one hundred and thirty-three use co-digestion, and six case studies were discussed. Biogas production using co-digestion increased by 120% in the Victor Valley Regional Water Reclamation Facility, 77% in the Dubuque Water and Resource Recovery Center, and doubled in the Stevens Point Waste Treatment Plant. In the Clearwater Road Wastewater Treatment Facility, co-digestion improved the biogas generation by more than 40% and raised the biogas production by 180% in the Central Marin Sanitation Agency Treatment Plant. The Joint Water Pollution Control Plant co-digested 84 tons of food waste, which helped increase biogas production by 2831.7 $m^3$/d. However, no techno-economic feasibility study was performed.

Some researchers have studied the economic feasibility of pre-treatment techniques applied to sewage sludge. Ref. [128] performed an economic analysis of the thermal hydrolysis method in a WWTP in Spain with a capacity of treating 118 mL/d (equivalent to 833,000 inhabitants). The analyses included investment cost, annual cash flow, payback period, and net present value for twenty-five years under five scenarios. The results showed that biogas production was enhanced by 55%. An additional operational cost (135,321 EUR/year) was required, and the dewatered sludge cost was reduced by 60% (from 455,600 EUR/year to 170,800 EUR/year). The authors determined that the main purpose of using thermal treatment was to decrease sludge volume rather than enhance biogas production and energy generation. Ref. [129] studied the thermal hydrolysis process in a sludge pilot plant located in a sewage treatment plant in the UK. The results showed that the electrical output increased from 72 kWh/tonnes dry solids (TDS) for conventional anaerobic digestion to 97 kWh/TDS for the traditional thermal-hydrolysis process (THP) and 1070 kWh/TDS for the I-THP (intermediate THP, known as the new THP configuration), and the biogas yield enhanced from 339 $m^3$/TDS (conventional anaerobic digestion) to 454 $m^3$/TDS for the traditional and 503 $m^3$/TDS for the I-THP. The Net opex for conventional AD was −43.16 GBP/TDS, −15.10 GBP/TDS for traditional THP, and 14.14 GBP/TDS for the I-THP. The CapEx for conventional AD was GBP 31 million, GBP 33.36 million for the THP, and almost GBP 35 million for the I-THP, and the NPV was GBP 14.6 million, GBP 20.3 million for the THP, and almost GBP 26.5 million for the I-THP. Ref. [130] investigated the impact of THP applied to fermented primary sludge (FPS) and thickened waste activated sludge (TWAS). The authors conducted an economic analysis based on different scenarios (temperature of 50–90 °C between 30 and 90 min). The overall net savings for the THP applied only to TWAS for 30 min at 50, 70 and 90 °C were AUD 8.88, 21.05 and 27.60 per ton of dry solids, while for the combined FPS and TWAS for 30 min at 50, 70 and 90 °C, the overall net savings were AUD 6.94, 24.93 and 59.33 per ton of dry solids. The net savings calculation included the cost of pre-treatment, the increase in methane production, and the costs of dewatering, transportation, and landfill costs.

### *4.3. Snapshot of the Biogas Production in WWTPs Worldwide*

The quantity and quality of the biogas generated (usually represented by its methane concentration) are primarily related to the composition of the feedstock used, which for

WWTPs is the raw sludge that enters the facility, and the residence time. The higher the concentration of methane in the biogas, the more calorific value it has. In addition, other parameters also influence process efficiency [19]. Biogas volumes from sewage sludge can range from 0.75 to 1.12 $m^3$ per kg VSS (volatile suspended solids), and the methane concentration is around 60% of the biogas composition. If the raw influent is considered, 1 $m^3$ of treated wastewater can produce about 75 litres of biogas [131].

In developing countries, most of the biogas produced comes from small-scale digesters as an alternative energy source for household lighting and cooking, whereas in developed countries, biogas is produced in large-scale plants and used to generate electricity, vehicle fuel, or upgraded to biomethane to be injected into the gas network [132]. In China, from the total of 41.45 billion $m^3$ of biogas generated in 2020, less than 1% of the biogas is generated from sewage sludge in WWTPs; if it is converted into electricity (35% efficiency), the potential would be equivalent to 800 GWh/y or 2.4 TWh/y of heat energy [105]. In India, the national biogas program provides subsidies for building small-scale domestic digesters to generate biogas for cooking and lighting. In 2014, 4.75 million small-scale biogas plants were in operation, and there was a potential to build approximately 12 million plants, which could produce about 10 billion $m^3$ of biogas per annum. In Nepal and Vietnam, the government has promoted small-scale plants to increase biogas production for domestic use. In Nepal, the national program supported more than 300,000 systems over 20 years, and in Vietnam, 183,000 commercial plants were constructed in 11 years [132].

The biogas industry remains emerging, and biogas from WWTPs has great potential. For example, in 2019, these facilities generated more than 50% of the total biogas produced in Germany [20]. Table 5 illustrates the biogas production in WWTPs in some countries around the world [105,123].

**Table 5.** Biogas production in WWTPs in some countries.

| Country | Number of Biogas Plants | | Generation Potential (GWh/Year) | | Year |
|---|---|---|---|---|---|
| | WWTPs | Total * | WWTPs | Total * | |
| Australia | 52 | 242 | 381 | 1587 | 2020 |
| Brazil | 57 ** | 638 | 8590 ** | 11,700 | 2021 |
| Canada | 31 | 150 | na *** | na *** | 2019 |
| Denmark | 51 | 172 | 308 | 3723 | 2018 |
| Finland | 16 | 96 | 221 | 877 | 2020 |
| France | 88 | 687 | 442 | 3527 | 2017 |
| Germany | 1271 | 10,551 | 4000 | 54,100 | 2020 |
| Ireland | 15 | 59 | na *** | 752 | 2019 |
| Republic of Korea | 36 | 119 | 630 | 2815 | 2017 |
| Netherlands | 80 | 262 | 640 | 3465 | 2018 |
| Norway | 27 | 162 | 305 | 782 | 2019 |
| Sweden | 134 | 282 | 721 | 2161 | 2020 |
| Switzerland | 271 | 434 | 638 | 1519 | 2019 |
| UK | 163 | 994 | 1280 | 8317 | 2018 |

* Total number of biogas plants, including agricultural, industrial, bio-waste, sewage sludge, and landfill; ** including landfill plants; *** na: data not available.

### *4.4. Biogas Opportunities in WWTPs*

The opportunities for biogas in WWTPs may come from two directions: reducing on-site operating costs or generating extra revenue. Biogas can be used on-site (see Figure 4) to maintain the temperature of the anaerobic digestors, dewatered sludge, or steam processes (i.e., the Rankine cycle, thermal pre-treatment, and chemical absorbent in the biogas upgrading system). Boilers are the simplest and most common option for biogas, especially due to their high heat efficiency (75–85%) and their capacity to operate with low-quality biogas. In many biogas plants, the primary source of heating is the heat recovery system of a combined heat and power (CHP) unit when generating electricity. If the heating demand is not met by the CHP's thermal power, biogas can be used in boilers to produce the necessary heat to meet the required thermal demand. In addition, heat can also be generated from biogas upgrading technologies [133]. Biogas can be used to produce electricity using fuel cells (FC), gas turbines (GT), and internal combustion engines (ICE). Table 6 shows a comparison of the characteristics of FC, GT, and ICE [133,134]. Hydrogen can also be generated from biogas via steam methane reforming or from water electrolysis (i.e., biogas is used to generate electricity in CHP units, which then powers the electrolysers) [135,136]. Another option is to also flare the biogas, which is not used to meet the carbon emission requirements [36]. Some WWTPs only use anaerobic digestion for sludge treatment without energy recovery. Biogas flaring is the dominant method of converting the methane in the biogas to carbon dioxide. No energy is recovered from waste gas burners, and they require low capital and operating costs [25,133,137].

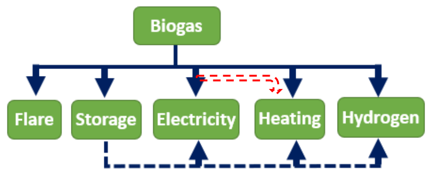


**Figure 4.** Biogas utilisation in WWTPs.

**Table 6.** Characteristics of biogas power generation technologies.

| | **FC** | **GT** | **ICE** | **Micro GT** |
|---|---|---|---|---|
| Size | Small | Large | Small/Medium | Small |
| Capacity (kW) | 300–1500 | 3500–15,000 | 110–3000 | 30–300 |
| Electrical/Thermal/Overall Efficiency (%) | 40–45/30–40/75–80 | 40–45/30–40/75–80 | 30–40/40–50/70–80 | 40–45/30–40/75–80 |
| $CH_4$ minimum level (%) | 85 | 30 | 60 | 40 |
| Emissions $NO_x$ | Extremely low | Low | Medium/High | Very low |
| Capital costs (GBP/kW) | 3000~4000 | 400~1100 | 900~1500 | 600~1200 |
| O&M costs (GBP/kWh) | 0.003~0.01 | 0.01~0.02 | 0.005~0.01 | 0.008~0.015 |

Raw biogas from sewage treatment plants has an average lower heating value between 21.5 and 23.3 MJ/Nm$^3$, and it is composed mainly of methane (60–65%) and carbon dioxide (35–40%), but with also traces of other elements, including nitrogen (<1–2%), oxygen (<0.05–0.70%), hydrogen sulphide (<0.5–6800 ppm), ammonia (<1–7 ppm), and siloxanes (<1–400 mg/m$^3$) [133]. Methane is the main component of biogas due to its high calorific value (around 42 MJ/kg). However, the presence of other gases not only decreases the economic value and energy potential of the biogas but also can cause equipment damage, including an increase in maintenance frequency and costs, a reduction in the equipment's lifespan, and a reduction in system efficiency [20]. The level of biogas treatment depends on the biogas utilisation. For example, for electricity generation, biogas used in microturbines can have a concentration of hydrogen sulphide up to 1000 ppm, whereas fuel cells do not accept a level higher than 5.5 ppm [20,138]. The most common elements that are removed from biogas are water vapour, hydrogen sulphide, ammonia, siloxanes, halogenated hydrocarbons, and carbon dioxide. Depending on the technology type of the power generation system, biogas upgrading may be required, especially if it is an FC system. Improving methane concentration to levels greater than 95% is referred to as biogas upgrading.

Alternatively, biogas can generate extra revenues for a WWTP by exporting the electricity generated on-site to the grid or by injecting biogas into the gas grid. In the latter case, the biogas must be upgraded. Upgrading biogas aims to not only remove carbon dioxide but also reduce the concentration of other elements, such as hydrogen sulphide, ammonia, and siloxanes. The main objective of biogas upgrading is to generate a high-value fuel that can be used in transportation or injected into the natural gas grid (compression between 4 and 80 bar may be required), improve the methane concentration in the biogas, and reduce gas volume [25,133]. Table 7 summarises the biogas utilisation in some countries [105,123].

**Table 7.** Biogas utilisation in some countries from landfills, WWTPs, agricultural, industrial, and bio-waste plants.

| Country | Electricity | Heat | CHP | Biomethane | Flare | Others | Year |
|---|---|---|---|---|---|---|---|
| Australia * | 33.3 | 26.2 | 21.4 | - | 19 | - | 2020 |
| Brazil | 73 | 8.2 | - | 18.4 | - | 0.4 | 2021 |
| Canada | 50 | 10 | 25 | 5 | - | 10 | 2019 |
| Denmark | 17 | 29 | - | 54 | <1 | - | 2018 |
| Finland | 21 | 32 | - | 13 | 17 | 17 | 2020 |
| France | 47 | 43 | - | 10 | - | - | 2017 |
| Germany | 62.7 | 35.6 | - | 1.7 | - | - | 2020 |
| Republic of Korea | 39.5 | 23.7 | - | 4.2 | 11.3 | 21.3 | 2017 |
| Netherlands | 32.4 | 65 | - | 2.6 | - | - | 2018 |
| Norway | 5 | 25 | - | 51 | 14 | 5 | 2019 |
| Sweden | 2 | 19 | - | 65 | 11 | 3 | 2020 |
| Switzerland | 25 | 23 | - | 26 | 13 | 13 | 2018 |
| UK | 66.70 | 0.05 | - | 33.25 | - | - | 2018 |

* including only WWTPs.

Biomethane (upgraded biogas) has been widely used in several countries in Europe for transportation, as an alternative to natural gas, and also to generate electricity. To inject biogas into gas networks, there are requirements and standards that should be met. The standards required for biomethane injection into the gas grid can vary from country to country; for example, France and the Netherlands require a minimum concentration of methane of 86% and 85%, respectively, whereas Austria, Germany, and Switzerland require a minimum level of 96%, and Sweden even higher, at 97%. The maximum concentration of carbon dioxide allowed is 2.5% in France, 3% in Sweden and Austria, and 6% in the Netherlands. In addition, the maximum level permitted of hydrogen sulphide for all those countries is 5 mg/Nm$^3$, except in Sweden (it is 10 mg/Nm$^3$) [139]. In addition, in the U.S. (California), the minimum level of $CH_4$ concentration ranges from 93~96%, depending on the network gas provider [33]. In Australia, the natural gas quality limits determined by the system operator, AEMO, are the minimum and maximum higher heating values of 37 MJ/m$^3$ and 42.3 MJ/m$^3$, respectively, which give a methane concentration of around 93%. Moreover, the maximum levels of hydrogen sulphide, water content, and sulphur are equal to 5.2 mg/m$^3$, 73 mg/m$^3$, and 50 mg/m$^3$, respectively [140,141]. In Korea, the level of methane concentration in biomethane is at least 95%. For water and sulphur, the maximum allowed concentrations are 32 and 10 mg/m$^3$, respectively [142].

Generally, the decision of utilising biogas on-site or exporting it will vary from plant to plant and can be related to some parameters and variables, including biogas production rate, power generation capacity, biogas system capabilities (i.e., upgrade system, storage, treatment), and feed-in tariff (gas and electricity) [20,137]. From a technical perspective, the injection of biomethane into natural gas networks is well-established and technically feasible. The main issues related to biogas upgrading and natural gas injection can be related to the economic feasibility of the biogas plant and the standards and requirements of the gas system operator [133]. It should be highlighted that WWTPs must meet some requirements regarding the purity of their biogas, and to inject power back into the grid, the plants also need to have the technical capability.

The economic feasibility of a biogas upgrading system can be very challenging. The selection of the most suitable biogas upgrading technology requires an analysis of capital and operating costs. The operating and maintenance costs for these methods are associated with energy consumption, labour, and resources (water and/or chemicals used). Other factors to consider for technology selection include site-specific details, such as biogas production, regulations, and end-use purposes. The lowest-cost technology may not always be the most appropriate solution [143]. Examples of upgrading technologies include absorption (including chemical absorption, high-pressure water scrubbing, and organic physical scrubbing—also known as physical absorption), cryogenic separation, pressure swing adsorption, and membrane separation [144,145]. Table 8 summarizes the most common technologies for biogas upgrading [123].

**Table 8.** Biogas upgrading technologies' characteristics.

| Method | Energy Required ($kWh/m^3$) | CH4 Recovery Rate (%) | Capital Cost (GBP/kWh) | Op. Cost (GBP/kWh) | Number of Plants * | Benefits | Drawbacks |
|---|---|---|---|---|---|---|---|
| CA | 0.06–0.17 | 99.9 | 264–438 | 1.15–1.92 | 104 | • Provide the highest biomethane purity<br>• No need for pressurized biogas<br>• No need for $H_2S$ treatment | • Prior $H_2S$ treatment is needed<br>• Heat, water, and chemical is required<br>• Higher energy consumption<br>• Problems with corrosion and precipitation |
| CS | 0.18–0.25 | 98–99.9 | 394–960 | 4.80–7.10 | 9 | • No water and chemicals required<br>• High biomethane purity | • Biogas treatment is required<br>• Not mature technology<br>• High investment and O&M<br>• Prior $H_2S$ treatment is needed |
| PSA | 0.16–0.35 | 90–98.5 | 255–831 | 0.92–6.50 | 81 | • Low energy consumption<br>• Compact technology<br>• No water and chemicals required<br>• Widely used in small-scale sites | • Lower biomethane purity compared with others<br>• Prior $H_2S$ treatment is needed<br>• High energy consumption and strict process control |
| WS | 0.20–0.30 | 98–99.5 | 357–731 | 0.47–0.94 | 175 | • Low energy consumption<br>• Simple, flexible, and low O&M costs<br>• Remove $NH_3$ and $H_2S$ • Most used type | • Dried process is needed<br>• More strict process control<br>• Chemicals may be required<br>• High water demand is needed |
| OPS | 0.23–0.33 | 96–99 | 510–969 | 0.92–1.05 | 19 | • Remove $NH_3$, $H_2S$ and other compounds<br>• High biomethane purity | • High investment and O&M<br>• Higher energy consumption<br>• Heat and chemicals may be required |
| MS | 0.18–0.35 | 85–99 | 205–367 | 0.79–5.50 | 148 | • Simple, flexible, and low O&M costs<br>• Compact and reliable technology<br>• No chemicals, water, or heat required | • Require multiple stages<br>• High investment costs (membranes)<br>• Not mature technology<br>• Can be inefficient<br>• Not recommended for biogas composed of many impurities |

CA: Chemical Absorption, CS: Cryogenic Separation, MS: Membrane Separation, OPS: Organic Physical Scrubber, PSA: Pressure Swing Adsorption, WS—Water Scrubbing. * Total number of plants using upgrading technologies in some countries, including Germany, UK, Sweden, France, Switzerland, Denmark, the Netherlands, Austria, Finland, Canada, South Korea, Brazil, Estonia, and Ireland [123].

The Malabar biomethane project at the Sydney Water Malabar WWTP in Sydney, Australia, is the first commercial-scale biogas upgrading facility in Australia. The project is a partnership with the NSW gas network (Jemena), Sydney Water, and the Australian Renewable Energy Agency. The project cost is AUD 14 million, the technology used is membrane separation, and it will have the capacity to process over 200 TJ/year. The plant will save around 5000 tonnes of $CO_2$ eq. [105].

*4.5. Incentives and Subsidies*

The financial viability of industrial biogas plants typically relies on incentives and financial support. Therefore, many governments and/or system operators provide incentives in some countries [105]. For example, in Australia, some projects received government support: (i) the Jandakot Bioenergy Plant received a total of AUD 3.8 million (a total investment of AUD 8–10 million), (ii) the Goulburn Bioenergy Project received AUD 2.1 million (a total investment of AUD 5.75 million), and (iii) the Malabar Biomethane Project received AUD 5.9 million (a total investment of AUD 14 million). Although many financial support schemes were provided, the biogas industry is still facing some challenges due to a lack of industry experience and too few policies and supporting mechanisms for long-term planning [105,124].

In Austria, the "Green Electricity Law" supports the electricity production from biogas, and the feed-in tariffs in 2019 were 189.7 GBP/MWh and 161 GBP/MWh if using biomethane. Biogas plants were able to receive subsidies for up to 20 years, and, for new plants, the investment grants were set at up to GBP 10 million a year. In Brazil, there are no defined subsidies for supporting the use of biogas specifically. At the time of writing, in Finland, feed-in tariffs for electricity generation in large-scale plants and fuel tax exemptions for biomethane use in vehicles exist. In addition, three main supports for biogas plants are provided, including support for large-scale industrial plants, own energy generation, and the agricultural sector. Biogas plants from the agricultural sector can receive up to 40% of the investment costs of the power generation system and up to 30% if they decide to produce vehicle fuel or utilise their biogas on-site. In Germany, existing and new facilities, after March 2021, could get 184 GBP/MWh and 164 GBP/MWh. An additional 5 GBP/MWh can be granted for small-scale plants (<0.5 MW) [105]. In Ireland, support for biogas plants with CHP was 139.07 GBP/MWh for plants over 0.5 MW capacity and 160.47 GBP/MWh for plants less than 0.5 MW capacity in 2020. For non-CHP plants, the tariffs were 106.98 GBP/MWh for plants over 0.5 MW and 117.67 GBP/MWh for plants lower than 0.5 MW. In addition, there is a Renewable Heat support scheme to incentivize the use of biogas instead of fossil fuel heating. The gas tariff is 295 GBP/MWh for the first 1 GWh/year and 5 GBP/MWh for the next 1 to 2.4 GWh/year. In Norway, financial support is given to biogas plants that convert biogas to vehicle fuel, which can also be used in the agricultural industry. Plants that generate at least 1 GWh may apply for subsidies. In 2019, the Norwegian government provided support for around 45% of large-scale plants and 50% of small-to-medium facilities. Enhancing biogas production has been the Norwegian government's objective in order to reduce greenhouse gas emissions for more than 10 years. Subsidies are focused primarily on biomethane for vehicle fuel in Sweden. Some of the current policies include: (i) no taxes on carbon dioxide and energy relating to biogas utilisation for heating until 2030, whereas the tax on natural gas is approximately 29 GBP/MWh; (ii) no carbon dioxide or energy tax on biomethane for vehicle fuel until 2030, whereas the tax on petrol for carbon dioxide and energy taxes is 44 GBP/MWh and 27 GBP/MWh, respectively; (iii) and renewable energy certificates (for electricity), where the generator acquires one certificate for every MWh produced (price in 2014/15 was around 13~18 GBP/MWh). In Switzerland, the goal is to reach up to 30% (equivalent to 12 TWh) of renewable gases in the network by 2030 (in 2019, this contribution was 1.05 TWh). However, industrial plants are usually not economically feasible without support. Therefore, the Swiss government has proposed feed-in premium tariffs, including support for plant planning and operation, and provided carbon tax and energy tax exemptions to promote the renewable gas industry. In the UK, the government's priority is to produce biomethane for injection into the natural gas grid based on the Green Gas Support Scheme (GGSS). The GGSS promotes a fixed tariff rate for 15 years of 5.51 pence/kWh for the first 60 GWh, 3.53 pence/kWh for the next 40 GWh, and 1.56 pence /kWh for the extra injection. In addition, Green Gas Certificates provide extra subsidies for the injection of biomethane into the gas networks [105].

In Canada, there are three main funding programs that support biogas projects: the Ontario Biogas Systems Financial Assistance Program, Alberta's Bioenergy Infrastructure Development Fund, and Quebec's Program for Processing Organic Matter using Biomethanation and Composting. Additionally, feed-in tariff programs guarantee security for biogas generators over 15~20-year agreements. In Ontario, feed-in tariff rates are 165~258 CAD/MWh for electricity generated from biogas, whereas Quebec and British Columbia pay around 15 and 30 CAD/GJ for renewable natural gas. In Denmark, a feed-in tariff of 56 GBP/MWh is required for biogas used in CHP units or injected into the grid, and 37 GBP/MWh is required for utilisation in transport or industry. Financial support is also provided for upgraded biogas plants (in 2013, this subsidy was 14.95 GBP/GJ). In addition, biogas support is granted, including 10.6 GBP/GJ for CHP units, upgrades, and distribution through the natural gas network, and 5.2 GBP/GJ for transport and industrial utilisation. After 2020, no new biogas plant will be subsidized, and existing plants (built before 2020) are eligible for the feed-in tariff until 2032. In France, feed-in tariffs for electricity and biomethane are provided. Electricity rates could range from 150 to 225 GBP/MWh in 2016, and for biomethane, the rates in 2018 were 48~101 GBP/MWh for landfills, 55~142 GBP/MWh for WWTPs, and 73~133 GBP/MWh for other anaerobic digestion plants. In Korea, there are no tariffs or subsidies for biogas, but a total budget of USD 74 million for 7-year research (2013–2020) was granted. However, different policies, research, and initiatives directly and indirectly support this sector. In the Netherlands, incentives based on feed-in tariffs and renewable energy subsidies are offered. The scheme concept works as a market competition among renewable plants, and the tariffs guarantee a minimum rate. In 2018, a total budget of GBP 12 billion was granted for the renewable energy sector [123].

## 5. Conclusions

WWTPs play an important role in society by treating wastewater generated by the population. As the price of electricity increases along with the efficiency goals of those plants, alternative approaches to increasing the WWTPs' energy efficiency are urgently needed. The use of the biogas generated as a by-product of the sewage treatment process is a promising alternative that can increase energy self-sufficiency in WWTPs. This scoping review gathered works that focused on the use of four techniques to improve biogas production, including co-digestion, pre-treatment techniques, biological hydrogen methanation, and optimisation of anaerobic digestion performance. Based on the PRISMA methodology, a total of 77 papers and industry/government reports were analysed in this scoping review.

Increasing biogas production from sewage sludge using co-digestion and pre-treatment techniques were the most common alternatives in terms of efficiency, costs, and implementation. Based on different studies, co-digestion showed better efficiency in increasing methane concentration and biogas production compared with pre-treatment techniques. However, the main disadvantage of co-digestion is the increase in sludge production and, consequently, more costs with biosolids disposal and digested sludge dewatering, as well as the additional operational and maintenance costs required for cleaning up the components of the anaerobic digestion system. Among different feedstocks, fat, oil, and grease, as well as food waste and slaughterhouse waste, were promising substrates that, combined with sewage sludge, showed great potential for improving biogas production. Alternatively, pre-treatment techniques showed great potential in improving the biodegradability of sewage sludge, which further helps to reduce the costs of dewatering the digested sludge and the costs of biosolids disposal, and they also showed potential in improving biogas production. The main drawbacks of the pre-treatment technique are the high energy requirements and, therefore, the high operating costs. Among them, thermal hydrolysis appears to be the most mature method, which can be found in full-scale WWTPs. In addition, microwave and ultrasound have shown great potential in lab-scale experiments.

No study on the utilisation of biological methanation hydrogen in WWTP has been found in the literature. BHM can become a great alternative for generating methane in a WWTP, especially if this facility has biogas upgrading systems. In the ex situ method, the carbon dioxide generated in the biogas upgrading process can be combined with hydrogen in a reactor to generate methane. However, due to the lack of data validation, technology maturity, and process economic feasibility data, it is very hard to evaluate if this technology can be feasible or not in a WWTP. The last alternative, anaerobic digestion performance optimization, relies mostly on models and the experience of WWTP's operators and engineers. It is very hard to replicate and validate the results from a model based on a full-scale WWTP, especially due to the complexity of modelling the anaerobic digestion process. Because of that, not many studies have lately investigated this alternative. Modelling the anaerobic digestion process is an important way to understand the sludge treatment performance and identify the system's performance in the daily operation of the facility. At the same time, optimising the anaerobic digestion process may not contribute much to improving biogas production in a real-world scenario.

It was also found that few papers have investigated the techno-economic feasibility and viability of co-digestion and pre-treatment techniques in WWTPs. It is clear that co-digestion and pre-treatment techniques can increase biogas production and reduce the operating costs of sludge treatment, but the cost-benefit analysis should be more comprehensive and include different operational aspects. Therefore, further research is necessary to propose a detailed methodology that can be used to assess the economic feasibility of those alternatives in WWTPs. Additionally, not many papers have investigated the optimal utilisation of biogas in WWTPs.

The government can help WWTPs increase biogas production and contribute more towards sustainability. The governments of several countries in Europe have developed long-term plans for increasing the market share of biogas. For developing countries, the government also provides incentives, but they are more focused on the construction of small-scale domestic plants. With these subsidies and incentives, biogas generation from industrial plants can become more cost-competitive compared with the prices of natural gas, petrol (in the case of biomethane utilisation as vehicle fuel), and electricity.

Finally, we can expect more research on improving energy efficiency and sustainability in WWTPs. Treating sludge is one of the main concerns of a WWTP; however, at the same time, operating these plants in an efficient, sustainable, and more sustainable way can be achieved through the optimal configuration of different technologies.

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