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Full length Research

Municipal Wastewater as a Biogas Resource in Multi-Use Systems: The Water-Energy Nexus of Anaerobic Sludge Digestion

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This paper provides a comprehensive background on climate change and the energy–water nexus, articulating the currently pressing demand for global energy and water security. The relevancy of alternative energy generation methods such as anaerobic algae digestion in municipal wastewater to keep up with the 21st century's energy and water demands, while at the same time trying to follow a greenhouse gas reducing path for emissions, will be analyzed. Furthermore, the chemical processes involved and the synthesis of biogas from municipal wastewater sludge will be discussed, together with the question of on-demand energy supply and challenges involved in biogas generation from municipal wastewater and potential solutions. Advances and current initiatives concerning biogas production from municipal wastewater via anaerobic algal digestion was reviewed to contrast the technological advances with reference to a case study from a developing country, Senegal, and a brief overview of wastewater systems in North America will be given.

Keywords: Renewable energy, alternative energy, sustainable development, municipal waste, water-energy nexus, biogas production, anaerobic digestion, algae, municipal wastewater plants

INTRODUCTION

As the climate conference in Paris (COP21) has recently been taking place in December 2015, the challenges and opportunities related to climate change and the need of a concerted, worldwide effort to curb risks of a temperature, are more relevant and urgent than ever before. According to the Stern Review of the Economics of Climate Change, humanities principal aims for the 21st century should consist of the complementary goals of elimination of mass poverty and the risk of catastrophic climate change, together with a serious effort to reduce greenhouse gas emissions on all levels (Stern 2015). Furthermore, Stern argues that an "energy industrial revolution" is within the current young workforce generation's grasp. A potential energy industrial revolution implies that new technological opportunities and advances are highly likely to be given the credit and attention they deserve in terms of funding and pilot implementation. As humanity is approaching an energy industrial revolution, smart solutions in energy generation and storage, energy savings, transport and carbon capture and storage, are expected to be equivalent to the Apollo space program of the 1960s, in terms of research and development in low-carbon energy (Falkner et al 2015).

While human development has progressed substantially in many areas during the last century, it has been unequally distributed and has left a seventh of the world's population behind in terms of access to clean water, basic sanitation and modern sources of energy (Holger 2011). While "the bottom billion" of the world's population is deprived of basic human rights such as a secure water supply, first industrialized economies tend to constantly overexploit natural resources (Tyagi and Lo 2013). Up to now, the overexploitation of resources by developed countries has been somewhat counter balanced by the lack of resources and the resulting low use of energy and water in developing countries. However, steadily rising population growth and an expanding middle class with changing lifestyles and diets across the developing world have resulted in the urgent need to improve water, energy and food security

(Raheem et al. 2015) to evolve as one of the 21st century's most pressing challenges. According to the Stockholm Environment Institute, if developed countries do not alter their consumption and production behaviours significantly, agricultural production will be required to increase by 70% by 2050 and approximately 50 % of directly useable energy will need to be made accessible by 2035 (Akbas et al. 2015).

According to projections by the International Energy Agency (IEA) in 2015, the global energy demand is currently estimated to grow by 40 % until 2030 due to industrial growth in non OECD countries (IEA 2015). China, India and the Middle East are expected to double their energy demand (IEA 2015). Similar projections are also made by other Organizations (OPEC World Oil Outlook, 2015). EXXON Mobil's recently published Energy Outlook for 2040 further confirms the aforementioned claims by IEA and OPEC, by stating that in order to meet the steadily increasing energy demand safely and affordably, while at the same time minimizing risk and environmental impact; advanced technology, expanded trade and investment and, even more importantly: innovation, are paramount (EXXON Outlook 2016). A nexus approach to the highly sensible water-energy relationship is therefore central to mitigate climate change, be more water smart and less energy intensive. The water-energy nexus is an approach that underlines the mutual dependence of climate change and water and energy security, by focussing on the natural resources that underpin that security: water, soil and land (Raheem et al. 2015). The water-energy nexus is based on following three principles: investing to sustain ecosystem services, "creating more with less" and accelerating access by integrating the world's poorest (Holger 2011). There are numerous ways of supporting a region's water and energy security and facilitating its transition to sustainability by reducing trade-offs and generating additional benefits that outweigh potential shortcomings (Akbas et al. 2015). These include, but are not limited to: using waste as a resource in multi-use systems, stimulating development through economic incentives and integrated poverty alleviation by green growth. This paper will focus on how the water-energy nexus approach can be applied to using wastewater as a resource in multi-use systems and how wastewater and its by-products can be converted into a resource for other products and services; in this case, a scheme that converts municipal wastewater sludge from municipal wastewater treatment plants (WWPs) into biogas is going to be analyzed.

Increasing public awareness on the necessity of sustainable energy solutions to fulfill present and future energy requirements has been driven by a combination of factors, such as decreasing fossil fuel reserves, a rising demand for primary energy due to globalization and industrial advancements and rapid development in renewable energy technologies (Tyagi and Lo 2013). Additionally, increasingly strict environmental standards, such as the banning of ocean disposal and strict European landfilling criteria introduced in 2013 (Tyagi and Lo 2013), have lead more and more environmental engineers and scientists to consider nutrient- and energy dense waste water sludge as a viable resource of renewable energy instead of waste. Conventional methods of disposing waste sludge including incineration, landfilling and ocean disposal (Raheem et al. 2015) are being increasingly replaced by alternative methods to re-use wastewater sludge to recover energy and nutrients. The two components in wastewater sludge that have been found to be technically and economically feasible to recover are nitrogen and phosphorus as nutrients and carbon as energy (Tyagi and Lo 2013). While there are several different methods than can be applied to recover energy and nutrients from municipal wastewater, such as, but not limited to: co-digestion, pyrolysis, gasification and supercritical (wet) oxidation (Tyagi and Lo 2013), this paper will focus on the anaerobic digestion of wastewater sludge.

MODEL

The anaerobic digestion (AD) process converts organic solids that are found in wastewater sludge to biogas, which mainly consists of a mixture of methane (CH_4), carbon dioxide (CO_2) and traces of several other gases, such as carbon monoxide (CO) and higher hydrocarbons (Raheem et al. 2015). The general reaction of this conversion can be seen below:

$C_cH_hO_oN_nS_s + y\ H_2O \rightarrow x\ CH_4 + n\ NH_3 + x\ H_2S + (c-x)\ CO_2$

where $x = 1/8\ (4c + h - 2o - 3n - 2s)$,

and $y = ¼\ (4c + h + 2o + 3n + 3s)$

Biogas that is produced via anaerobic digestion of sewage sludge has been found to be composed of 60 – 70 % methane, 30 – 40% carbon dioxide and small amounts of nitrogen, hydrogen, hydrogen sulfide, and water vapor (Tyagi and Lo 2013). Table 1 outlines the typical composition of biogas generated from anaerobic digesters.

The anaerobic conversion process of wastewater sludge to biogas consists of the following four major biochemical reactions: hydrolysis, acidogenesis, acetogenesis and methanogenesis (Raheem et al. 2015). During the first step of anaerobic conversion, sedimentation and filtration are used to facilitate the reduction of solid content in the wastewater (Uribe et al. 2015). More specifically, the wastewater sludge's organic compounds, which mainly consist of polysaccharides, proteins and fat, are hydrolyzed with the help of extracellular enzymes (Tyagi and Lo 2013). The secondary step can vary widely depending on the wastewater treatment plants (WWTPs) and its main objective is to remove organic matter and nutrients (Uribe et al. 2015). In many WWTPs that utilize anaerobic digestion, the hydrolysis products from the

Table 1: Typical composition of biogas generated from anaerobic digestion of wastewater sludge

Parameter	Unit	Values
Methane	vol%	50-75
Higher hydrocarbons	vol%	0
Hydrogen	vol%	<1
Carbon monoxide	vol%	<0.3
Carbon dioxide	vol%	25-45
Nitrogen	vol%	<2
Oxygen	vol%	<2
Hydrogen sulphide	mg/L	<1000 (0-10^4)
Ammonia	mg/L	<100
Total chlorine (as Cl^-)	mg/N m^3	0-5

Source: Tyagi, Vinay Kumar and Lo, Shang-Lien. “Sludge: A Waste or Renewable Source for Energy and Resources Recovery?” *Renewable and Sustainable Energy Reviews* 25 (2013): 708 – 728. Print. Table 3.

first step are transformed into hydrogen, formate, acetate and higher molecular-weight volatile acids (VFA) via acidogenesis (Tyagi and Lo 2013). Following acidogenesis, short-chain organic acids and alcohols that were produced during the second step of the conversion process are being exposed to acetate-forming bacteria in order to produce acetic acid, carbon dioxide and hydrogen (Tyagi and Lo 2013). During methanogenesis, the final step of the anaerobic conversion process, biogas is produced in form of a mixture of methane and carbon dioxide from hydrogen, formate, and acetate (Tyagi and Lo 2013).

The high percentage of methane gas that is produced in the anaerobic digestion of sewage sludge can also be used as the main energy source for the operation of municipal wastewater treatment plants (WWTPs), involving powering gas engines and producing electrical and thermal energy (Raheem et al. 2015). This is a valuable advantage, as the electricity costs associated with operating WWTPs are fairly high and, by using the methane gas that has been produced during anaerobic digestion, the costs can approximately be halved (Tyagi and Lo 2013). In addition to substantially minimizing operational costs through providing electricity, the anaerobic digestion of wastewater has far-reaching environmental benefits. The conventional disposal of sewage sludge into landfills causes methane to be directly released into the atmosphere (Tyagi and Lo 2013) and results in substantial environmental harm, as methane gas has been found to be more efficient at trapping radiation than CO_2, resulting in a 25 times greater impact on climate change compared to CO_2, over a 100 year period (USEPA 2010). Anaerobic digestion, however, allows for efficient capturing of methane and, given the methane is utilized for the generation of electricity and not for the production of fossil fuels, decreases the CO_2 generation associated with energy-use of a wastewater plant (Tyagi and Lo 2013). Therefore, anaerobic digestion of sewage sludge is an ideal source of renewable energy in form of biogas and can be used for a large number of applications, such as production of heat and steam, electricity generation, vehicle fuel and the production of chemicals (Raheem et al. 2015).

The promising advantages biogas offers in terms of electricity production can be visualized by a study conducted by the U.S. combined heat and power (CHP) partnership. According to the CHP partnership, if the methane produced by anaerobic digestion was used as electricity source at all 544 wastewater treatment facilities in the U.S., approximately 340 MW of electricity could be generated, which would be sufficient to power 261 000 homes (Tyagi and Lo 2013). Furthermore, according to an official statement released by the United States Environmental Protection Agency (USEPA) in 2013, 2.3 metric tons of carbon dioxide emissions, which is estimated to be equivalent to the average annual emissions of 430 000 cars, could be eliminated annually through the installation of energy recovery facilities in all existing WWTPs in the U.S. that employ anaerobic digestion (Tyagi and Lo 2013). Therefore, it can be said that anaerobic digestion of sewage sludge is not only an ideal source of renewable energy in theory, but also delivers tangible results when directly implemented in the industry.

As already previously mentioned, there are several different ways to recover energy and nutrients from wastewater sludge, which include: co-digestion, pyrolisis, gasification, supercritial (wet) oxidation and anaerobic digestion (Tyagi and Lo 2013). While a brief background to the general reactions and mechanisms involved in treating wastewater sludge by anaerobic digestion was given in the previous paragraphs, this paper will specifically focus on micro-algae based anaerobic wastewater treatment systems. As Akbas et al. point out, domestic sewage can be treated via anaerobic digesters that treat wastewater and produce biogas as a clean energy source from anaerobic biodegradation of biomass in the absence of oxygen and the presence of micro-organisms (Akbas et al. 2015). According to Uribe et al.’s “Advanced Technologies for Water Treatment and Reuse”, new regulations and energy prices coupled with an increasing environmental awareness, has led to increasing support of and interest

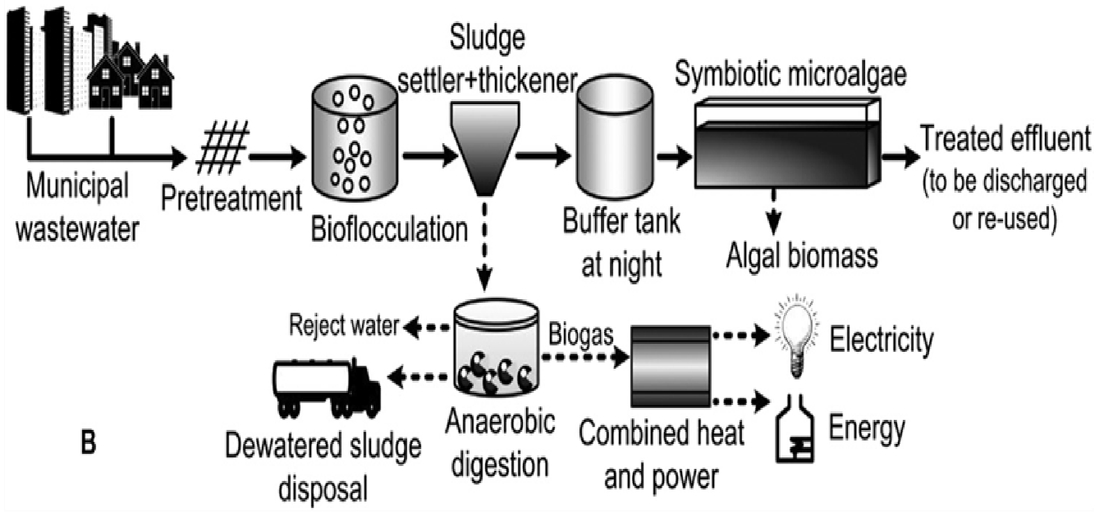

Figure 1: Schematic representation of a municipal wastewater treatment plant
Source: Khiewwijit, Rungnapha et al. “Energy and Nutrient Recovery for Municipal Wastewater Treatment: How to Design a feasible Plant Layout?” *Environmental Modeling and Software Journal 68* (2015): 156 – 165. Print. Figure 2b.

in new, innovative wastewater treatment technologies (Uribe et al. 2015). Wastewater treatment plants based on high rate algal ponds (HRAPs) have been a popular field of study since the 1950s, because of their potential to be a cost-effective alternative to conventional wastewater treatment systems (Passos et al. 2015). Benefits of algae-based anaerobic wastewater treatment systems include low energy demand and a simple operation (Passos et al. 2015). However, according to Passos et al., who monitored microalgae production and bio energy generation through anaerobic digestion in a microalgae-based WWTP over a one-year period, despite numerous benefits of algae-based anaerobic wastewater treatment systems, several steps involved in biogas production through microalgae still need to be further optimized in order to allow for full-scale applications. Wieczorek et al. mention that biogas produced from algae-based wastewater treatments is not yet feasible for commercial scale application due to high economic and energy costs resulting from the cultivation of microalgae (Wieczorek et al. 2015). However, Wieczorek et al. also acknowledge that wastewater provides a particularly suitable environment for growing microalgae due to its rich ammonia, phosphate and essential nutrient content (Wieczorek et al. 2015).

The following two, simultaneously occurring mechanisms are involved in the preliminary treatment and pollutant removal, defined as “algae-bacteria symbiosis”, of the incoming municipal wastewater: (i) direct/ indirect transformation of pollutants by microalgae and (ii) enhancement of bacterial biodegradation by oxygen generated through microalgae photosynthesis (Passos et al. 2015). A general, schematic representation of a municipal wastewater treatment plant utilizing symbiotic algae can be seen in figure 1.

The proportionally low energy demand for microalgae-based wastewater treatment systems compared to conventional systems can be explained by the fact that in conventional wastewater treatment systems, the oxygen required for the removal of organic matter is supplied by mechanical aeration (Passos et al. 2015). However, in microalgae-based wastewater treatment systems there is no need for mechanical aeration, because the oxygen required for organic matter removal is already provided by microalgae photosynthesis (Passos et al. 2015). The fact that no additional oxygen source is needed for microalgae-based wastewater treatment systems due to naturally occurring photosynthesis is a substantial advantage, as it saves energy and money by replacing the most energy intensive process in wastewater sludge treatment systems. Mechanical aeration in conventional activated sludge systems is reported to use up 60% to 80% of the total energy needed to operate the wastewater treatment plant (Passos et al. 2015). Wieczorek et al. also confirms the advantages of microalgae-based wastewater systems, by underlining the fact that microalgae is produced without external oxygen and carbon dioxide supplements, while at the same time producing biomass and decreasing CO_2 emissions (Wieczorek et al. 2015). What makes micro-algae based systems especially interesting to study, is the fact that they not only produce biomass that can be used for multiple purposes, such as biofuel in form of biogas, but also can be used as a low-energy wastewater treatment application (Passos et al. 2015). As Uribe et al. also mention, there is a rising interest in and need of innovative technologies that not only serve the sole purpose of removing coarse constituents from wastewater, but at the same time also can serve functions such as recovering energy and other valuable products and purify water for alternative use (Uribe et al. 2015).

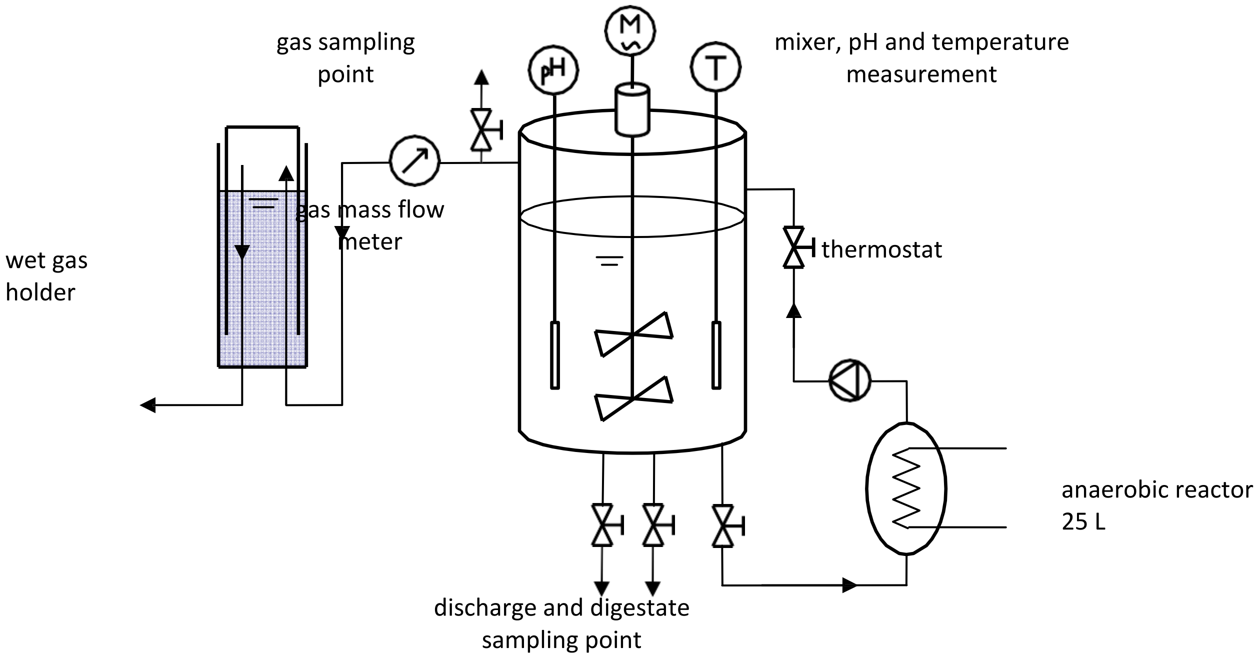

Figure 2: Schematic representation of an anaerobic digestion pilot plant as used in the laboratory
Source: Stritesky, Lubos et al. "Biogas Production from Algal Biomass from Municipal Wastewater Treatment". *Symbiosis International Conference* (2014): 1 – 6. Print. Figure 1.

DATA AND DESCRIPTIVE STATISTICS

Stritetsky et al. from the Brno University of Technology in the Czech Republic have extensively studied micro-algal biofuel production and conducted a simulation of biogas production from algal biomass utilizing wastewater in the laboratory environment. Stritetsky et al. point out that microalgae's ability to fix CO_2, nutrients and store solar energy in their cells through photosynthesis make them particularly interesting and worthwhile to study not only as an alternative energy source in the form of biogas, but also for wastewater treatment (Stritesky et al. 2014). The set-up, which Stritesky et al. utilized to carry out the anaerobic digestion in the laboratory environment, consisted of following components: an enclosed anaerobic digester, a mixer, a thermostatic tank with recirculation pump, a wet gas holder, a pH and temperature logger and a gas mass flow meter (Stritetsky et al. 2014). A schematic diagram of the anaerobic pilot plant set-up that was used in the laboratory can be seen in figure 2.

In the schematic representation of the anaerobic digestion plant that was used in the laboratory simulation for Stritetsky et al.'s study, the anaerobic digester with a volume of 25 L (of which 22 L were usable), the thermally isolated shell, the mixer, the valves for gas, digestate and discharge sampling, a wet gas holder and a connection to the thermostatic tank can be seen. Throughout the experiment, the pH and temperature were monitored and the volume of biogas that was produced was measured via the mass flow meter situated on the inflow route to the wet gas holder (Stritetsky et al. 2014). In order to achieve accurate and realistic results, the wastewater sludge that was used during the experiment, was retrieved from a municipal wastewater treatment plant situated in Brno-Modrice, Czech Republic (Stritetsky et al 2014). For the experiment, Stritetsky et al. utilized two differently composed types of microalgae and bacteria biomass (MaB), which were added to wastewater sludge: MaB 1, which consisted of living micro-algal cells and MaB 2, which consisted of bacteria and dead micro-algal cells. In total, four batches containing different combinations of two different types of wastewater sludge (Inoculum and Primary Sludge) and two different types of MaB (MaB1 and MaB2) were analyzed in digesters A, B, C and D. Table 2 outlines the exact compositions of each digester.

Stritetsky et al. reported that throughout their study, the internal temperature of all digesters remained at the constant value of 36˚C (Stritesky et al. 2013). However, the pH values of the mixtures in the each digester have been reported to differ due to the different wastewater

Table 2: Compositions of dry and organic matter in wastewater sludge and bacteria mixtures in digesters A, B, C and D

Component	Digester				Dry matter [%]	Organic matter [%]
	A	B	C	D		
Inoculum (IN)[1]	1	2	1	2	3.08 % ± 0.05	54.65 ± 0.51
Primary Sludge (PS)[2]	0	1	0	1	7.79 % ± 0.02	59.82 ± 0.43
MaB 1	1	1	0	0	0.64 % ± 0.01	52.04 ± 0.85
MaB 2	0	0	1	1	0.58 % ± 0.02	73.16 ± 0.60

[1]Inoculum (IN) represents an untreated sample of wastewater sludge; [2] Primary Sludge (PS) represents a wastewater sludge sample from the same source that has undergone primary treatment, i.e. organic matter has been removed to some extent.

Source: Stritesky, Lubos et al. "Biogas Production from Algal Biomass from Municipal Wastewater Treatment". *Symbiosis International Conference* (2014): 1 – 6. Print. Table 1.

Table 3: Compositions of produced biogas for different wastewater sludge/micro-algae composition

	CH_4		CO_2		O_2		N_2	
	236 h	496 h	236 h	496 h	236 h	496 h	236 h	496 h
A	73.0 ± 0.5	71.9 ± 0.3	15.5 ± 0.4	18.8 ± 0.4	0.5 ± 0.0	0.5 ± 0.0	10.6 ± 0.2	9.3 ± 0.1
B	71.6 ± 3.9	62.7 ± 0.7	20.9 ± 4.5	27.0 ± 0.4	1.3 ± 0.4	1.3 ± 0.0	7.4 ± 1.4	8.2 ± 0.1
C	60.3 ± 0.0	61.5 ± 0.3	28.6 ± 0.7	29.5 ± 0.2	0.9 ± 0.2	0.7 ± 0.1	9.4 ± 0.4	8.0 ± 0.1
D	67.5 ± 0.8	68.3 ± 0.5	21.6 ± 0.8	27.2 ± 0.3	1.5 ± 0.0	0.7 ± 0.0	7.9 ± 0.2	3.4 ± 0.1

Source: Stritesky, Lubos et al. "Biogas Production from Algal Biomass from Municipal Wastewater Treatment". *Symbiosis International Conference* (2014): 1 – 6. Print. Table 3.

sludge/ micro-algal bacteria compositions. The difference in pH values is natural, given that MaB 2 biomass has an extremely low pH of approximately 3.5 and MaB 1 biomass had a neutral pH of approximately 7.5 (Stritesky et al. 2013). The biogas composition that resulted from the anaerobic digestion of algal biomass was measured by two distinct samples for each digester. In other words, for each one out of four distinct mixtures of wastewater sludge and micro-algal bacteria, one sample was exposed to 236 hours and a second sample was exposed to 469 hours. The final compositions of each wastewater mixtures can be seen in table 3.

In theory, it has been reported that microalgae biomass has the potential to produce up to 550 L kg^{-1} OM, assuming perfect efficiency and that all organic matter is decomposed. The results of this study lead to the general conclusion that digesters B and C yielded a higher biogas production than digesters A and D. In terms of liters of biogas per kilogram of substrate, digester C had the highest biogas production; yielding 330 liters per kilogram of organic matter (L kg^{-1} OM) and digester D had the lowest specific biogas production, yielding 64 L kg^{-1} OM (Stritesky et al. 2013). Digesters A and B produced a similar, median range volume of biogas of approximately 169 L kg^{-1} (Stritesky et al. 2013). The difference in volume of biogas produced for each digester, confirms that the composition of biomass, i.e. MaB 1 or MaB 2, plays a decisive role. At the same time, however, it has been observed that the type of wastewater sludge, i.e. Inoculum or Primary sludge, did not make a tangible difference and it might therefore be an energy-saving option to use unprocessed sludge directly. While Stritesky et al. reported that they have not been able to determine which composition of biomass (MaB 1 or MaB 2) yields higher volumes of biogas, this study and its straightforward experimental set up can be a valuable starting point for anyone who wishes to investigate biogas production from micro-algal biomass and wastewater in a more detailed manner.

The fact that biogas production via anaerobic digestion of algae in municipal WWTPs serves dual application for the purpose of producing biomass and treating the wastewater makes this scheme particularly promising for developing countries. Developing countries desperately require water and energy to fuel their gradual advance out of poverty and while those two resources come at a high price, supporting partially self-sustaining, reduced-energy and multi-application systems, such as micro-algae based wastewater treatment schemes, can make a difference. As can be seen from the schematic representation in figure 3, two highly valuable resources can be produced by minimal input: the "input" being waste water and naturally

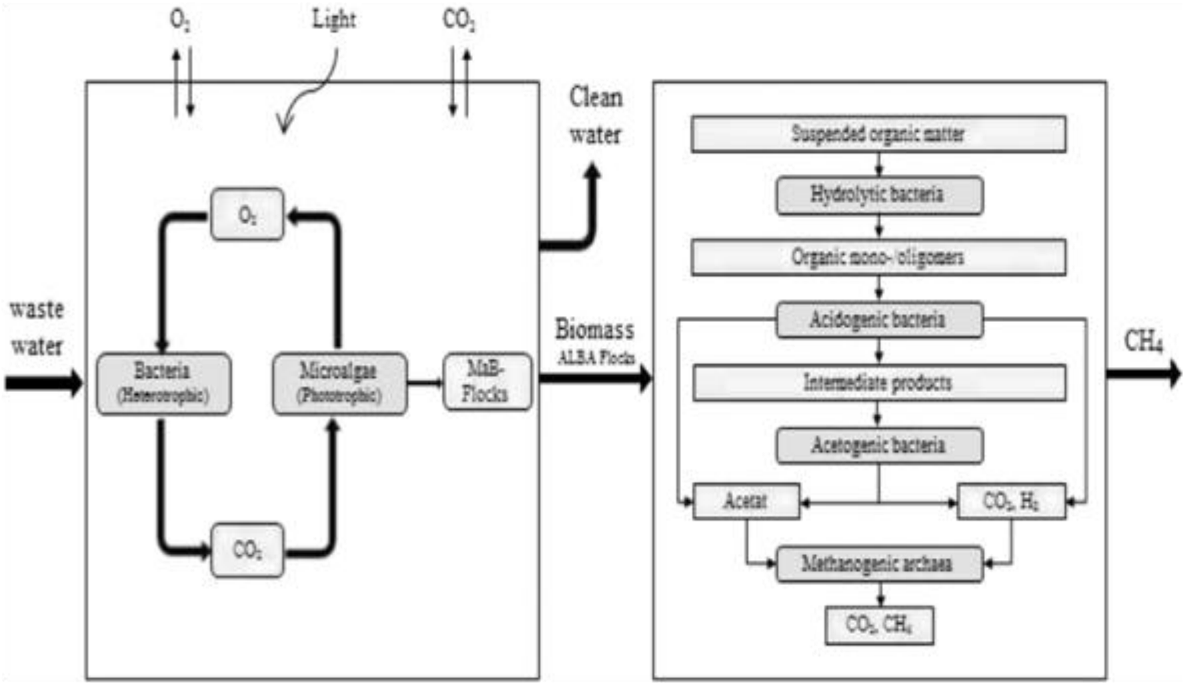

Figure 3: Microalga-bacterial wastewater treatment and the biogas production process
Source: Wieczorek, Nils, Mehmet Ali Kucuker and Kerstin Kuchta. "Microalgae-Bacteria Flocs (MaB-Flocs) as a Substrate for Fermentative Biogas Production." *Bioresource Technology Journal* 194 (2015): 130 – 136. Print. Figure 3.

occurring sunlight and the "output" being clean water and CH_4 (biogas) produced from the system's biomass.

Analysis of Data Issues and Potential Solutions

Despite the numerous advantages associated with micro-algae based wastewater treatment systems, there are several drawbacks and disadvantages involved that need to be considered as well. One of the main disadvantages involved is the fact that algal ponds require large surface areas and therefore also a large power supply for effective mixing of the algal mass is required (Uribe et al. 2015). A further disadvantage of microalgae based wastewater treatment systems is the fact that microalgae is difficult to separate and cannot be achieved without the additional help of reagents (Uribe et al. 2015). The resulting sludge is extremely high in volume and is not easily biodegradable, unless it is directly converted into biogas, ethanol or biodiesel as is shown in figure 3 above. In reality, the second disadvantage does not necessarily have to be a drawback and depends entirely on how the WWTP is operated. A higher volume of sludge that is difficult to biodegrade upon being released into water streams directly is only a negative attribute if the biomass was going to be disposed immediately after the separation of microalgae.

However, since in this case a wastewater treatment model that aims to valorize the remaining biomass "waste" for biogas synthesis is being proposed, the high volume of sludge is an advantage as it directly converts into an increased volume of biogas output. In order to outweigh the previously mentioned disadvantages related to micro-algal wastewater treatment, two requirements need to be met: the biomass resulting from micro-algal wastewater treatment needs to be valorized by conversion to biogas and should not be directly disposed of. The second requirement for a feasible micro-algal wastewater treatment scheme is that the biogas that is being produced from micro-algal wastewater treatment should be used to cover up to 50% of the WWTP's total energy requirement. If these two requirements can be satisfied, both economic and energy cost restraints mentioned earlier by Wieczorek et al. and Passos et al., can be outweighed and optimization for full-scale application can be achieved.

As is the case with all non-conventional and renewable energy sources, biogas produced via anaerobic algal digestion from municipal wastewater needs to be able to address the issue of energy storage and on-demand usage effectively in order to allow for full-scale applications. Aichinger et al. at the University of Innsbruck in Austria conducted a study on the

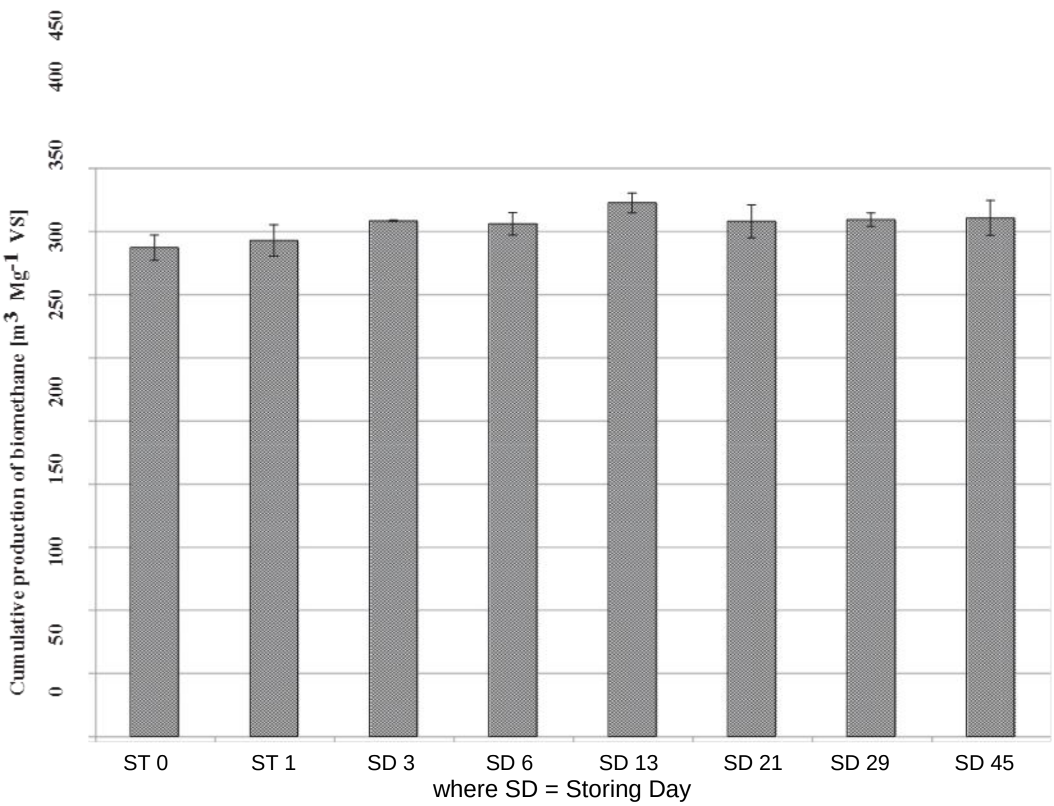

Figure 4: Biomethane yield produced from bio-waste stored over a period of 0-45 days
Source: Aichinger, Peter et al. "Demand-driven Energy Supply from Stored Biowaste for Biomethanisation." *Biosource Technology Journal* 194 (2015): 389 – 393. Print. Figure.

"demand-driven energy supply from stored bio-waste for biomethanisation" and tested the hypothesis that energetic potential of bio-waste does not decrease upon storage (Aichinger et al. 2015). Aichinger et al. acknowledge that demand-driven energy production and its storage require optimization and at the same time point out that other alternative energy sources, such as wind and solar power, are inefficient in supplying reliable energy on demand due to being weather dependent (Aichinger et al. 2015). The fact that energy in the form of biogas can be stored in tanks and can be directly injected into the compressed natural gas (CNG) grid (Aichinger et al. 2015) without the external effects such as wind and sun seasonality, makes biogas production and storage a promising alternative energy source. Furthermore, Aichinger et al. mention that the efficiency of biogas production and use in self-sufficient WWTPs can be maximized by deliberately shifting energy production to periods of high energy demand in order to avoid following two scenarios: high-cost energy purchases (during high energy demand) and low-cost energy sales and gas flaring (when biogas production exceeds on-site demand).

While biogas production is a fairly rapid process, as it has been reported that methane production starts only a few hours after biomass has been added to a running biogas plant (Aichinger et al. 2015), there has been concern about the relationship between the energetic value of biogas and the time of storage (i.e. it has been suggested that methane's energetic value might decline together with prolonged storage periods). In this study, bio methane production was performed in a laboratory environment with bio-waste that was stored in increments of 1, 2, 3, 6, 13, 21, 29, 37 and 45 days and subsequently the amount of biogas produced for each sample was measured. A sample of approximately 12 kg of bio-waste was collected from a waste treatment plant in Tyrol, Austria and underwent primary treatment before being stored in sealed, temperature controlled containers with an internal temperature of 19.2 ˚C. A graph outlining the cumulative production of biogas versus the storing time of the bio-waste can be seen in figure 4.

As can be seen from the graph above, the main findings of Aichinger et al.'s study are that biogas production from bio-waste is largely unaffected by the storage period of bio-waste, as after 45 days the volume of biogas was almost identical to the first day. Aichinger et al. have suggested that a prolonged storage period of waste is likely to even favor hydrolysis of the waste via acidification and might result in a slightly increased yield. Therefore, it has been concluded that bio-waste can be

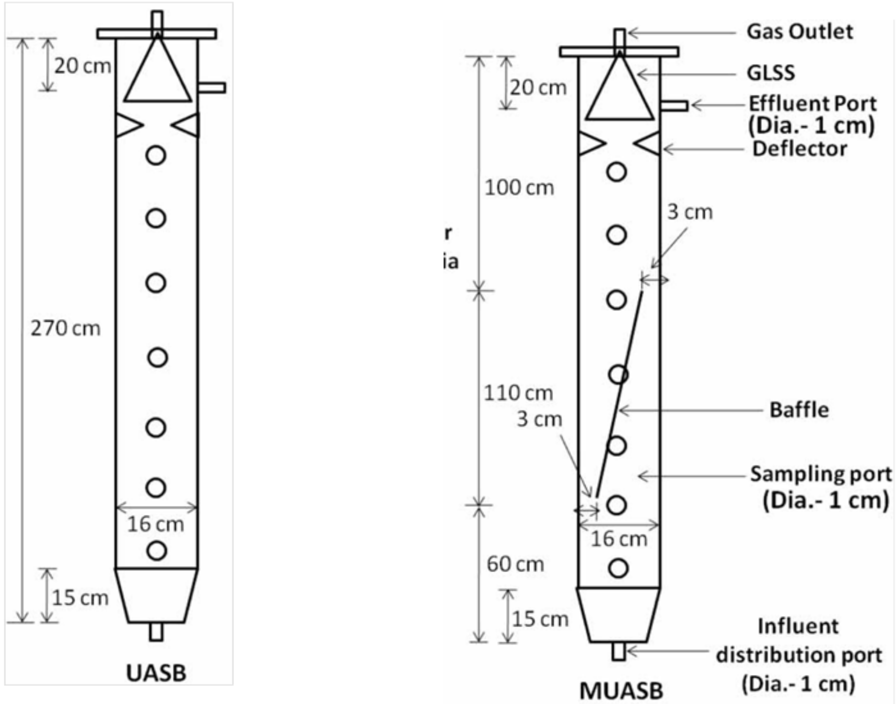

Figure 5: Schematic representation of UASB and MUASB reactors
Source: Das, Suprotim and Chaudhari, Sanjeev. "Effect of Reactor Configuration on Performance during Anaerobic Treatment of low strength Wastewater." *Environmental Technology Journal* 36:18 (2015): 2312 – 2318. Print. Figure 1.

stored for prolonged periods of time of up to 45 days in order to produce bioenergy on-demand, thus maximizing both the financial and energy efficiency of WWTPs by allowing adjustment to power grid fluctuations and WWTP operation peak times.

Although there are many advantages of treating municipal wastewater via anaerobic algal digestion, there are several factors that affect the efficiency and general success of biogas production via anaerobic algal digestion in WWTPs. According to Akbaş et al., in 2013 a volume of 1500 km^3 of biodegradable wastewater per day has been generated worldwide, but 80% of it was not collected or treated (Akbaş et al. 2015). In order to increase the use and valorization of such a readily available resource, wastewater treatment methods such as algal anaerobic treatment need to be optimized and enhanced in terms of efficiency. Apart from the previously mentioned investments in terms of finance and energy, factors that play a decisive role in the performance of anaerobic treatment of wastewater for biogas production are also strongly related to the way WWTPs are engineered. For instance, the configuration and geometry of wastewater reactors play a decisive role in biogas production. Das and Chaudhari from the Indian Institute of Technology in Bombay, India have studied the effect of two different reactor configurations upon the efficiency of anaerobic wastewater treatment systems. The study included one conventional up-flow anaerobic sludge blanket reactor (UASB), which has been reported to exhibit low efficiency in biogas production due to poor mixing of the wastewater sludge, and a modified reactor (MUASB). As the primary reason for a low biogas yield in UASB has been suspected to be inefficient mixing of the wastewater sludge, the MUASB reactor configuration has been modified to include a vertical baffle along the height of the reactor in order to facilitate better mixing (Das and Chaudhari 2015). Both UASB and MUASB reactors were monitored for 375 days under constant conditions in the Indian Institute of Technology laboratory facilities and were evaluated in terms of chemical oxygen demand (COD) removal efficiency. A schematic representation of a UASB and MUASB can be seen figure 5.

It has been observed that the treatment of municipal sewage has been more effective with the use of the MUASB configuration depicted above. While the measured COD removal efficiency over a monitored four hour period has been observed to be 72.7 % for a MUASB configured reactor, the conventional UASB reactor has yielded a COD removal efficiency of only 53.7% (Das and Chaudhari 2015). While the study conducted by Das and Chaudhari represents only one out of many experimental methods that can be utilized to investigate modifications for an increased biogas output in anaerobic wastewater treatment systems, it is a noteworthy example of a low-cost intervention with tangible outcomes.

Case Studies: A developing country (Senegal) versus two developed countries (US and Canada)

Another factor that is essential to spreading awareness and increasing the application of micro-algal anaerobic waste treatment systems especially in less developed economies is an adequate understanding of the global initiatives related to biogas and clean water production from municipal wastewater. Recently it has been reported that the fast growth of the Senegalese capital Dakar has caused sanitation issues and has resulted in a difficult-to-manage situation due to the sanitation problem being coupled with the already existent, chronic power deficit of the West African country (Reuters 2015). According to the International Renewable Energy Agency (IRENA), Senegal's power is almost five times more expensive than in other developing countries, as the price is 0.22 USD/ kWh compared to 0.04 USD in South Asia (Reuters 2015). As the uncontrolled expansion of Dakar in recent years has caused a rapid increase in slum dwellers and the formation of low income "suburbs", nearly half of Dakar's population has been reported to either have no toilet at all or being unable to afford the mechanized removal of waste (Reuters 2015). A recently introduced cooperation between the *Innovation for Poverty* Action and the *Gates* Foundation gave rise to a scheme which includes the installation of a conventional flush toilet in every home, together with an initiative where residents can dial into a call centres that gives trucking companies an hour to submit "bids to empty tanks, before selecting a winner based on price and proximity" (Reuters 2015). According to a Gates foundation representative, the ultimate goal is to feed the households' sludge to a power plant for conversion into drinking water and grid electricity in the form of biogas. Dakar's population is projected to grow 50% by 2025 and timely interventions are absolutely necessary for a sustainable future not only in Senegal, but in all less developed countries. The Dakar initiative is an example of an industrialized economy's organization providing an initial investment in the form of expertise, initiative and financial support to build a scheme that provides much needed drinking water and electricity, with the ultimate goal being a self-sustaining and locally operated scheme addressing the needs of a less developed country's environment.

Lackey et al. from Queens University, Canada conducted a study to investigate the current knowledge of biogas production and its use in municipal wastewater treatment plants across North America (US and Canada). Biogas usage trends in urban areas larger than 150 000 in the US and 50 000 in Canada were studied and, while it was found that 66% of all WWTPs in the US and Canada employed anaerobic wastewater digestion techniques, only 35% were reported to recover or directly use that energy in the wastewater facility. Lackey et al.'s study concluded that there was a significant difference in the relationship between sludge input and biogas production in winter (December, January, February) and that a CH_4 variability between 61% and 98% was observed when compared to the other seasons for central North America (Lackey et al. 2015). Whereas no extensive overall popularity of biogas generated via anaerobic digestion of wastewater has been identified in North America in general, it has been observed that anaerobic digestion systems for wastewater and biogas-to-energy use are slightly more prevalent in the west coast states of Washington, Oregon and California (Lackey et al. 2015). Among larger North American states, in the eastern US merely 20% of the anaerobic wastewater digester systems were reported close the "waste-to-energy" loop. However, it was reported that California had 55% of all biogas-to-energy systems and 73% of anaerobic digesters among the US's larger states. According to Lackey et al., California's high number of waste-to-energy system installations is likely to be due to the state's green legislation including the California Climate Action Reserve and California Global Warming solutions act (Lackey et al. 2015). Overall, it can be said that biogas production via anaerobic digestion of wastewater is not yet popular and widespread in North America and it might be questionable if such systems would be viable, given the cold climate over extensive periods of time which do not favor the anaerobic digestion of wastewater sludge. California, on the contrary, can be used as a positive example for the warmer US states both in terms of energy-to-waste policy, but also in terms of legislations and bylaws protecting the environment and slowing down climate change.

CONCLUSION

In conclusion, it is worth to mention that a micro-algal wastewater treatment scheme that aims for maximum valorization of all products, i.e. the high scale production of clean water and biomass that is to be further converted into biogas, adheres to all three of the fundamental principles of sustainable development mentioned previously. The proposed wastewater scheme discussed throughout this paper invests in (i) sustaining ecosystem services, by not disrupting the natural cycle of micro-algae formation and a photosynthesis process exclusively functioning with naturally occurring sunlight. At the same time, the second principle of sustainability, (ii) "creating more with less", is applied by making use of wastewater and sunlight to create clean water and biogas in return. The final principle of sustainability, (iii) accelerating access by integrating the world's poorest, is made more realistic as micro-algal wastewater treatment utilizes up to 70% less energy than conventional anaerobic wastewater sludge treatment and up to 50% of the WWTP's total energy requirements can be satisfied by the already produced biogas. Overall it can be said that, while financial and technical constraints naturally always accompany any energy scheme, wastewater treatment through micro-algal anaerobic digestion that yields both clean water and energy is certainly a promising renewable energy solution, especially for less developed countries, and has the potential to support the rapidly growing global south economies in an inclusive and sustainable manner.

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