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Feasibility of energy generation with biogas at the household level: assessing the impact of anaerobic co-digestion of waste activated sludge and food waste taking a Water-Energy-Food (WEF) Nexus approach

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ABSTRACT

The effects of anaerobic co-digestion at household level with waste activated sludge and food waste as co-substrates were studied in a GD-BMP test with mix ratio volatile solids basis of 20:80, 30:70, 50:50, 70:30 and 80:20 (WAS/OW) respectively. The results obtained were used to assess the feasibility of energy generation and the volume of each waste that can be treated. The highest specific methane yield calculated was of 431.31$mL_{CH4}/g_{VSadded}$ from the 30:70 mix ratio sample with an RSD of 4.68%. It was hypothesized that the benefits of adding food waste will shift the C/N ratio leading to a potential coverage to reduce the energy demand from households by 50%. In addition, the benefits from a house scale SBR with microbubble aeration followed by SCSTR anaerobic co-digestor. Using the 30:70 mix ratio analyzed, a calculation to obtain the electrical energy that can be recovered from a single household resulted in a 30% reduction of energy coming from the grid. This paper reflects that biogas can be used as a replacement of fossil fuels, reducing the carbon dioxide footprint and the strong link to the WEF Nexus cycle, and discusses the implications.

Keywords: anaerobic co-digestion, GD-BMP test, organic waste, waste activated sludge, co-generation, WEF Nexus

1. INTRODUCTION

The world has in the recent past experienced rapid population increase, particularly within the low-income economies [1]. Equally, environmental pollution with wastewater is a frequent phenomenon and a great problem in most metropolitan cities all over the world. At the same time, the amount of organic waste increases hand in hand with the number of inhabitants with huge impacts on the global warming effect. There are various methods that are applicable to sludge treatment and organic waste, both aerobic and anaerobic. The basic mechanism and driving forces through which anaerobic processes function are equal to those for the aerobic systems [2]: firstly, bacteria need substrate for growth and secondly, bacteria need energy for growth, in order to support the functions of cell maintenance and mortality [3].

Sludge and organic waste are a byproduct of human activity but also renewable energy sources. With the new technological advancements in mass communication, people are more aware of the benefits from renewable energy and the need to overcome the fossil fuel era. The renewable energy sector is very new in most countries and this sector can attract a lot of companies to invest in it [4]. Alternative energy sources have become an integral part of the energy portfolio. The objective in using renewable energy sources is to reduce negative environmental effects associated with non-renewable energy sources such as coal, oil and natural gas [5]. The most common renewable technologies nowadays are divided into main sectors such as solar, wind, biogas, geothermal, biomass, hydropower, each promising energy supply for the transformation into electrical energy and reducing the carbon footprint from fossil fuels [5].

A new approach into sustainable living has been addressed by the Water-Energy-Food (WEF) Nexus approach. These three resources are interlinked and are the key to sustainable life. As the demand for these resources increase worldwide, using them wisely has become a critical concern for the citizens of the world [6]. WEF Nexus applications are geared towards addressing

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climate change, environmental concerns, livelihood issues, and population growth to find sustainable answers for future generations [7].

The WEF Nexus approach also advocates that supplying water takes energy, and that water resources are also required to produce energy and food for consumption. The proper planning of these sectors in an integrated loop may enable WEF security for each settlement. A key synergy is achieved by implementing water reclamation with resource recovery. Therefore, bio-energy, organic fertilizers and the reuse of water for different activities can be achieved. However, there are very few examples that have implemented this mechanism [8].

2. STATE-OF-THE-ART

The present study focuses on anaerobic digestion (AD) which helps reduce the concentration of organic matter in sludge. It also seeks to address the feasibility of anaerobic co-digestion of waste activated sludge (WAS) and organic waste (OW) as co-substrates. The aim is to reduce the impact of these wastes on the environment and maximize potential usage for electric and heat transformation. Finally, this paper is addressing the research gap in existing studies concerning the amount of energy that can be generated with the current technology available, as well as pre-treatments and a possible setup system at a household level. The study hypothesizes that a significant reduction of electric energy coming from the grid can be achieved. To achieve this goal, several concepts most be clarified to allocate research gaps.

2.1 Sludge

Sludge is a byproduct of the process conducted at wastewater treatment plants (WWTP) and is produced worldwide. It is usually defined as sewage sludge (SS) from the municipal wastewater treatment process [9]. For instance, in Germany an average person consumes around 120 L of water per day[10]. This amount includes drinking water, toilet flushing, shower, and all other household services. The full flow of water will converge in the sewage system to go through various processes and treatments to be consumed once again.

Sludge usually contains hazardous substances which include pathogens, heavy metals as well as other organic contaminants. The characteristics of wastewater, quality and compositions constitute some of the most critical parameters which have influence on the selection of the methods of treatment and treatment design for different facilities. The characteristics or rather constituents of wastewater are majorly dependent on the source from which the water is discharged [12].

Globally, the annual production of sludge has continued to increase because of higher rate of collection, increased efficiency of wastewater treatment and stricter regulations for the quality of effluent in both the developing and developed economies [13]. The annual generation of sludge is approximated to be at around 10 million tons in Europe alone. The wastewater treatment plants (WWTP)s in America generate close to 6.5 million tons of dry solid sludge annually [14].

Such great increase in the amount of sludge makes it important to come up with an effective sludge treatment strategy as it will help to reduce the amount of environmental harm that such sludge is likely to have on nature. Proper sludge treatment is critically essential for environmental sustainability. Additionally, proper management of sludge accounts for close to 50% of all the costs involved in operating the wastewater treatment plant (WWTP) [12]. Therefore, it is very important to reduce the volume of sludge and subsequently recover the energy from the biomass chemically bound in the sludge, so as to help in compensating the operational cost [15]. AD of sludge is usually perceived as an effective and efficient approach in reducing the volume of sludge, stabilizing the amount of sludge, reducing the number of pathogens, and recovering energy in the form of methane, which reduce the costs involved in sludge management.

It is important to note that sludge treatment is usually a very complex process that involves a number of challenges mainly related to low reaction rates and the incomplete decomposition of the organic fraction [16]. Therefore, proper pretreatment is required to accelerate the sludge treatment process by enhancing the rate-limiting hydrolysis and by improving the methane potential. As demonstrated in previous studies, pretreatment is majorly applied to WAS since secondary sludge has a greater amount of extracellular polymeric substances as well as microbial cells that are somehow recalcitrant to the process of biodegradation [17]. Several methods of pretreatment have already been studied, which comprise of chemical, thermal, mechanical, electrical, and lastly biological methods [12]. It is important to highlight the fact that ultrasound has been regarded as a promising alternative to pretreat WAS [18].

2.2 Organic waste and food waste disposal

Food waste (FW) has been recognized as a key problem by the European Union and the international scientific community in the last years. Recent studies estimated that the amount of global food waste and loss is about 1.3 billion tons per year, equivalent to one third of food produced globally for human consumption [25]. For instance, the greenhouse gas (GHG) emissions related to the food wasted during the production phase were close to 2.2 Gt (gigatons) CO_2, while the costs associated with the wastage were around 143 billion Euro per annum in the EU-28 [26].

There are 4 common scenarios discussed nowadays for proper disposal of organic waste. These are mainly landfill, compost, incineration and biogas. Their impacts have been studied and analyzed to identify the most suitable way to proceed [27]. Biogas seems to have the least negative impacts on the environment in terms of OW/FW disposal in comparison with the other two energy-recovery scenarios analyzed. Yet again, AD proves to be a technology where more resources should be focused for research and better results focusing on energy efficiency transformation.

3. MATERIAL AND METHODS

One of the first steps to identify potential biogas yield in anaerobic co-digestion with a semi-continuous stirred tank reactor (SCSTR) is to conduct a Biochemical Methane Potential (BMP) test [50]. There are several methods for this test that are recurrently being updated through a collection of experience and investigations. In order to assess the biodegradability and specific methane production of the co-substrates at hand, the method gas density BMP (GD-BMP) test was found to be the most suitable for the task. It is important to note that this type of test cannot identify synergy or antagonistic effects from the interaction of co-substrates [52, 53]. Its main purpose is to approximate theoretical results in close link to the microbial activity.

4. RESULTS

For the BMP method conducted, the determination of VS% for inoculum and substrates is crucial to plan the amount of mass needed for each of the 27 bottles. Table 4.1 shows the values obtained after performing the gravimetrical method and consequent calculations. A standard deviation for the triplicates adds a statistical significance to values reported.

Table 4.1. TS%, VS% values for substrates, inoculum and microcrystalline cellulose

Description	TS%	SD	VS%	SD
Cellulose	94.27	0.11	94.27	0.11
Inoculum	2.32	0.17	1.47	0.11
WAS	4.95	0.16	3.24	0.10
OW	92.63	0.12	82.58	0.09

Calculation of the total volume of each flask is essential to determine the working volume and thus, the headspace available for biogas to accumulate. Table 4.1 contains all values obtained by filling up each bottle with water and assuming a water density of 1 g/mL. For the headspace volume, a rule of thumb of 1/3 of the total volume was recommended. A simplification was made after observing that all bottles would have on average a working volume of approx. 750mL. Therefore, this volume was set and the headspace for each bottle calculated.

Following the guidelines from the Standard BMP methods collection [57] and using OBA^{TM} "BMP plan tool", an ISR of 2 was procured for all mix ratios, inoculum only and substrates bottles. Table 4.2 contains the mass weighed that was added to each bottle and the pertinent ISR and organic load (OL) for each mix bottle. The incubation temperature was preset to 38 $^{\circ}$C (mesophilic temperature) and monitored for 5 days prior to the start of the test. Fluctuations of ±2 $^{\circ}$C were observed and found not relevant as to the impact of temperature on biogas production since the average temperature was steady for intervals of 30min.

There are two algorithms that can be used for GD-BMP calculations, the difference between them is essentially in the way mass loss is calculated. The general and recommended approach from the standard BMP method collection is the GD_t, where t stands for total. The second method is the GD_v and should be used only when bottle leakage is significant. After 28 days of sampling, data obtained was analyzed thoroughly without discarding any bottle.

4.1 GD_t BMP algorithm

For GD_t, mass loss for each individual bottle (Δm_b) is taken as the sum of mass loss across all individual incubation intervals, which is exactly identical to the difference between initial and final mass [57]. As stated before, this algorithm is recommended in general but only when bottle leakage is under the limit of detection (LOD).

As shown in Figure 4.1, the cumulative leak during the test for the mass loss and biogas volume confirm that the GD_t algorithm cannot be applied and GD_v would be the most suitable for calculations. The variability present in these parameters was mainly due to the lack of experience during the early stage of the method. Venting the biogas was found to be challenging and therefore the higher headspace pressure the easier mistakes can be made.

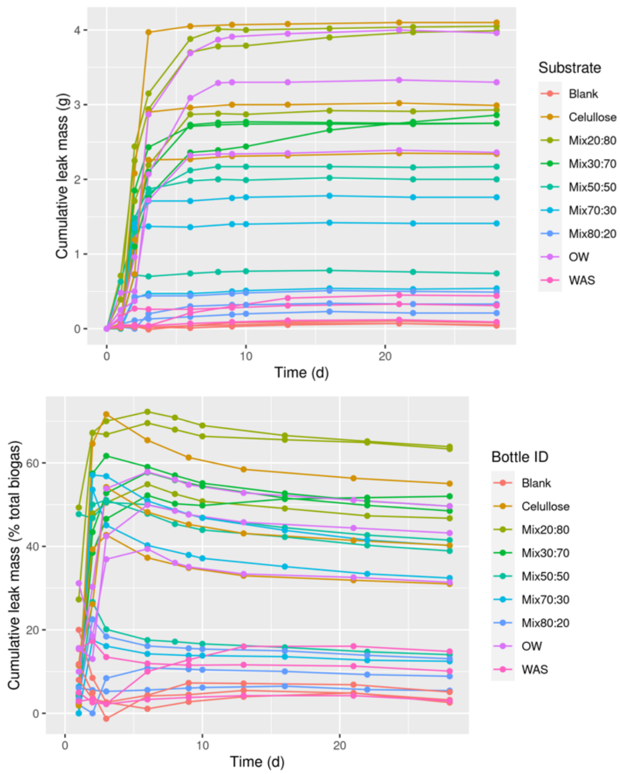

Figure 4.1. Cumulative leak mass and % total biogas leak respectively

Although the data suggests following the next algorithm, calculations and plots were performed so as to visually understand and observe the behavior of the graphs and compare results with the theoretical methane yield expected. Figure B6 provides a view of fluctuations between triplicates, resulting in massive biogas leakage and falling into high standard deviation. Both algorithms were calculated manually with Excel worksheet as well as the R package software tool provided from OBA™[54].

4.2 GD$_v$ BMP algorithm

With GD$_v$, Δm_b is taken as the sum of the difference between pre- and post-venting mass over the entire BMP test.

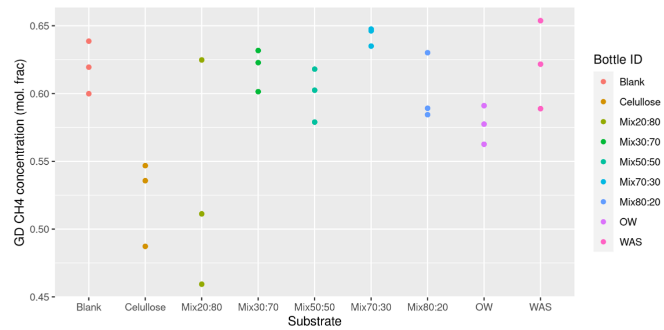

Figure 4.2. Concentration of methane (mole fraction) for all triplicates investigated.

At a first glance after calculations were finished, with the first plot of xCH_4 shown in Figure 4.2, a discrepancy was found for a mix ratio 20:80. The low performance can be attributed to mainly a poor flushing of the oxygen leading to inhibition. Another factor was gas leakage at the early stage of the trial due to the lack of skill to perform biogas venting. At the same time, the headspace pressure for the early stage of the method was overwhelming to the septa, incurring in biogas venting errors. The unsuccessful planification of sampling events is a factor to take into account for further application of the method.

A second plot describes the specific methane potential curve during the time of the trial (see Figure 4.3). The graphs have been generated separately and grouped on a grid to detect the difference between them. Focusing on the plateau trend for each triplicate, the trial was stopped the moment the 1% net methane yield was achieved as suggested [56, 57]. This is done by subtracting the methane yield produced by the inoculum from the substrate or mixture. A scrutinous visual inspection confirms the findings from Figure 4.2 and the variability for each triplicate. The shape of the curves looks reasonably parabolic even with the high SD calculated for some mix.

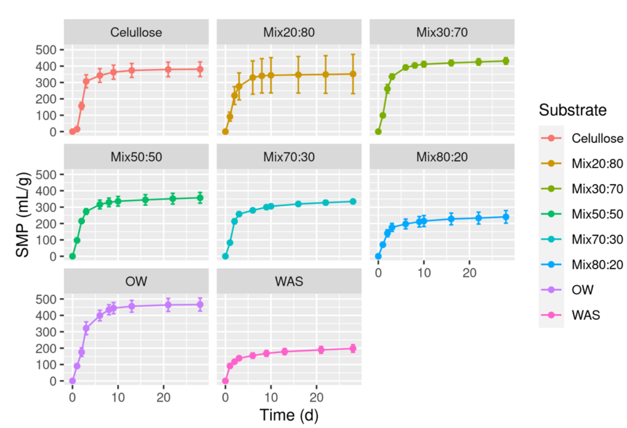

Figure 4.3. Specific methane potential for each mix ratio, validation and substrates

Regarding the validation from the inoculum activity, the trial was found 6.71% out of range permissible for RSD criteria in cellulose bottles (5% max for cellulose bottles [56]). The possibility to discard the lowest bottle would incur an RSD below 5%. For scientific purposes, the full trial should be repeated under same conditions as to replicate all data and confirm the veracity of the results at hand. Despite of this deviation, the validation trial had a mean BMP of 381.08 $mL_{CH4}/g_{VSadded}$. This value lands in a range between 352 and 415 $NmL_{CH4}/g_{VSadded}$ corroborating the quality of the inoculum [52]. As for the rest of the triplicates investigated, Table 4.2 lists the final results obtained with their pertinent RSD%. According to Holliger et al. [56] for inhomogeneous substrate like WAS, the limit was set to an RSD of 10%.

Table 4.2. BMP obtained for each mix, substrates and validation after 28 days of trail and their relative standard deviation

Description	time (days)	BMP ($NmL_{CH4}/g_{VSadded}$)	RSD%
Celullose[1]	28	381.08	11.71
Mix20:80	28	351.81	34.06
Mix30:70	28	431.32	4.69
Mix50:50	28	357.05	9.21
Mix70:30	28	334.37	3.80
Mix80:20	28	240.48	16.00
OW	28	466.15	8.56
WAS	28	197.93	11.81

[1]Validation triplicate result with microcrystalline cellulose

As expected, the mix 20:80 (WAS/OW) with a BMP of 351.81 $mL_{CH4}/g_{VSadded}$ had an RSD of 34.06% which rejects the triplicate. Although it could also mean an overload of organic matter can affect the system. On the other hand, mix 30:70 (WAS/OW) shows the highest value with 431.32 $mL_{CH4}/g_{VSadded}$ with an RSD of 4.69. This value represents the main target of the BMP test for the hypothesis formulated. A decrease on the BMP values on the following mix ratios 50:50 and 70:30 with acceptable RSD and BMP values of 357.05 and 334.37 $NmL_{CH4}/g_{VSadded}$ respectively, can be observed. The last mix ratio investigated must be rejected with a BMP of 240.48 $NmL_{CH4}/g_{VSadded}$ and an RSD of 16%.

To verify the result obtained in the OW triplicate with the method, the OBA™ tool was used to compare the accuracy of the trial. The result from the GD-BMP is 466.15 $NmL_{CH4}/g_{VSadded}$ with an RSD of 8.56% and OBA™ estimation value was 428 standardized $mL_{CH4}/g_{VSadded}$ with a mole fraction CH_4 of 56%. This mole fraction compared to the one reported on Figure 4.1 is found slightly above the value recommended by OBA™ "Theoretical Biogas" tool and a 38.15 $mLCH_4/g_{VSadded}$ difference between the methods. Finally, for the WAS triplicate, the value of 197.93 $NmL_{CH4}/g_{VSadded}$ with an RSD of 11.81% should be discarded.

5. DISCUSSION

The inconsistencies reflected in the trial are mainly due to the lack of experience with the method applied. A second trial should be conducted to compare and verify all results obtained. Every error during the process was noted as well as possible solutions for different challenges that may present in the future. Although the RSD% of 4 of the triplicates were rejected, the trail was a success in terms of the mix substrates analyzed. A mix ratio VS based of 30:70 will be set as a main parameter to discuss the extents of this finding. This means that for every 1 kg of WAS, 90g of OW could be added to a SCSTR anaerobic digestor to achieve the highest specific methane yield at mesophilic temperature. It is important to clarify that a BMP test cannot be utilized to assess long-term effects since the high share of inoculum marks the difference to the share present on a semi-continuous process [53]. For instance, the mix ratio found will be used as a starting point for proving the hypothesis formulated assuming this mix provides the highest anaerobic biodegradability of the substrates mix based on results observed.

In comparison with other studies [61], an improvement with a BMP test of C/N ratio was reported from 6.16 to 14.14 as the portion of OW in the mixture increased. As for biodegradability, an enhancement from 36.6 to 82.6% was observed. The optimum results on this particular study were obtained with a mix of 50:50 VS basis enhancement on VS removal, biogas production and SMP on a single-stage anaerobic digester (SSAD) at 35 ˚C were reported. Due to time constraints and the COVID-19 outbreak, these results [61] could not be directly replicated for comparison but leaves the question to an optimal mix ratio to prove the hypothesis. Perhaps more sensitive mix ratios could be tested to set a start point for future testing in a pilot plant.

An interesting review and compilation of recent studies for the year 2020 in regard of operating factors suggest that optimal mixing ratio of sewage sludge (SS) and OFMSW were observed at a 46:54 VS basis. They report an 59% improvement of methane yield and 94% on VS removal at mesophilic temperature with an OL rate of 1.9 $g_{VS}L^{-1}d^{-1}$ and a hydraulic retention time (HRT) of 10 days for CSTR mode [62]. Although this study was conducted with SS and OFMSW, the range of C/N ratio for SS and OFMSW are similar to WAS and OW values who can be observed in Table 4.1. Therefore, assuming a 30:70 VS basis mix ratio would suffice for the current investigation. As a result, from previous studies, the second BMP trail should include additional triplicates that can address the sensibility of mix ratio ranging between 30:70 and 50:50 VS basis.

6. CONCLUSIONS

Man-made methanogenic reactors have the capacity to produce, store, and use CH_4 in a controlled way. Methane is a powerful greenhouse gas that can heat the planet 23 times more for every kilogram than CO_2 in a time span of 100 years. CH_4 formation and CH_4 oxidation are essential parts of the global carbon cycle. As a matter of fact, one can address several environmental issues: Divert waste from landfill, reduce GHG emissions, energy positive process and digested residue can be used as a fertilizer or soil conditioner. This contributes to the positive WEF Nexus cycle. Anaerobic co-digestion of these two types of waste consolidates the aim of the WEF Nexus and approach that underlines the importance of keeping a balance between these resources.

On the one hand, proper education of the population in terms of separation of organic and inorganic waste is needed in order to procure the efficiency of the process and keep inhibition and possible undesired heavy metals or other waste solids inside the reactor. Keep in mind that not all countries are using electric stoves and electric boilers. The biogas can be used directly as an alternative for water heating systems and for kitchen purpose.

Another possible approach to fulfill the goal of this research could have been achieved by adding the electrical power coming from solar panels. Therefore, a higher coverage of electricity from the grid can be successfully reached. Nonetheless, the aim of any environmental research is to diminish the impact of anthropogenic effects that are harming the environment. For this particular case the carbon emissions are kept low with the technology applied and a significant reduction of the carbon footprint could be achieved if the system can be proven to work at acceptable efficiency.

The dimensions of a biogas biodigester is a challenge for implementing the technology at a household level. The noise coming from the CHP unit can be addressed by placing the unit in a machinery room with proper ventilation. Security issues might be another concern to users, this is a job that safety engineers can assess and minimize by establishing security standard requirements. Further research should be conducted by operating a pilot scale plant with different mix ratios and sourcing suitable pre-treatments and post treatments.

To enhance the reduction of waste and transformation to energy from these two challenging wastes that urban areas produce is a goal that needs to be achieved. Assessing the thermodynamic capabilities of the flue gas in terms of heat transfer and proper flows is also a research gap that should be addressed. The technology is still under development, new operation systems, pretreatments and post treatments are being researched nowadays. The possibility of a CO_2 free process is tangible and can be achieved. Methanation of the CO_2 captured from flue gas and the hydrogen that can be obtained from other renewable energies available opens a promising enhancement to the process.

Finally, the difference between a centralized and a decentralized process could be key to the success expected from the technology. The advantages and disadvantages were not addressed in this document for household and neighborhood scale. The cost-benefit analysis at household level was not calculated and should be addressed to assess the feasibility of the project. The need for an automated software system is another challenge since the technology requires trained engineers for operation.

The benefits of anaerobic co-digestion can be a future in both developing and developed economies. The application of the WEF Nexus principles and the future advantages from it, go hand to hand with renewable energies towards a path to sustainable living. This project can be seen as a start up in the field of anaerobic digestion for household-usage. It has the purpose to show the potential it could have in future and attract more research and development for CO_2-free energy production. Anaerobic co-digestion is a promising green technology that reduces the carbon footprint from anthropogenic activity and addresses the global warming effect that concerns the future of the planet.

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