

REVIEW ARTICLE

A Study on Anaerobic Co-digestion of Sewage Sludge for Bio-gas Production

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Received- 11 December 2016, Revised- 27 February 2017, Accepted- 5 March 2017, Published- 9 March 2017

ABSTRACT

Renewed attention in anaerobic sludge digestion has led to further development in recovery of biogas. This includes studies on various disintegration mechanisms to enhance the digestion efficiency of sludge and food waste by reducing waste activated sludge. Biofuel extension from sludge via biological disintegration tends to be an efficient method because of increase in demand of renewable ecofriendly energy. As the role of extracellular polymeric substances is vital in flocculation, its removal upgrades the pretreatment task throughout. This article intends to provide a general overview of methods in evaluating the proficiency of pretreatment on anaerobic integration and promotion in bioenergy generation. Since higher percentage of biogas extraction remains to be tedious process from collection of waste to generation to utilization, it is thus required a multi-disciplinary strategy to further progress anaerobic co-digestion by resolving all the prevailing unfavorable circumstances.

Keywords: Anaerobic sludge digestion, Waste activated sludge, Extracellular polymeric substances, Flocculation, Biogas recovery.

1. INTRODUCTION

Swift urbanization and population expansion has led to progressive increase in sewage treatment plants, where the resultant sludge is sub-standardly managed. Biodegradation generates biogas and effluent that act as an ecofriendly fertilizer. Waste Activated Sludge (WAS) made up of microbial cells (flocs) prevents biodegradation and is largely obtained due to waste water treatment which is considered to be an environmental problem. These flocs are extended as extracellular polymeric substances (EPS), in which the filamentous bacteria are densely populated. It is vital to locate EPS beforehand in addition to study why it must be pretreated and then it is removed using several techniques. The linkage that exists between the substrate and extracellular matrix is reduced by EPS and therefore it has to be removed so that flocs could be disintegrated and allows enzymes, proteins and carbohydrate to release out so as to hasten the sludge decomposition pace. This process is illustrated in figure 1. At

the same time, it is said that around half of the total sewage treatment cost rests in sludge control. This problem can be resolved by effective anaerobic digestion so that WAS can be stabilized and tuned to produce energy rich biogas. Hydrolysis, acidification (acido/aceto-genesis) and methanogenesis are the phases of anaerobic digestion. Subsequently, once the sludge is anaerobically digested, its recyclable organics are converted into biogas. [1, 2] At first the particulate organic matter is hydrolyzed (liquefied) and converted to low bio-molecular mass. The resultant is converted into volatile fatty acid, which in turn to methane by acetobacter and methogens.

[3] The cost of hydrolysis can be reduced by chemo disperser liquefaction. In this concept, along with a mechanical disperser, sodium tripolyphosphate has been used which is economically viable and cost effective. Among the mechanical, physiochemical, thermal, chemical and biological sludge disintegration strategies, biological processing is found to be pollution

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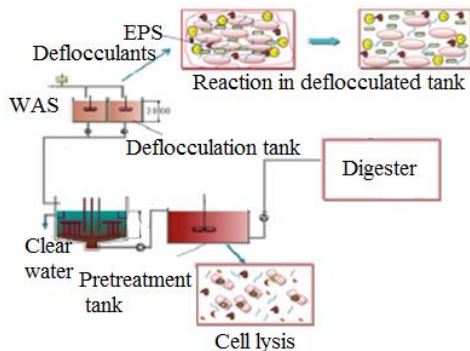
Double blind peer review under responsibility of DJ Publications

<https://dx.doi.org/10.18831/djmicro.org/2017011001>

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free and productive in reducing its organic substances. Even though it does not require extraordinary instruments, pretreatment becomes complicated due to costlier industrial enzymes. Conversely, the other approaches are efficient in terms of its high solubility. A common difference between the biological and other pretreatments is time duration. Comparatively biological process takes more time from hours to days. The features of some of the common methods in practice are,

- Less energy intake of mechanical pretreatment with high maintenance cost.
- In case of physical method, energy consumption is more but the maintenance cost is low.
- Heat energy used up by thermal method is cost effective, which is comparatively better than mechanical and physical methods.
- Chemo pretreatment is costlier and also there arise a need of extra ions. Regarding this, ozone type is preferred as this does not need any ions and make use of only electric charge. Further on, chemical integration must be checked for the incorporation of non-biodegradable particles.
- Biological pretreatment outstands all other methods in organics disintegration, pathogen removal, less energy intake and odor control.



Adapted from [26]

Figure 1.EPS removal

Apart from anaerobic digestion, other common methods of sludge integration include incineration and landfill. Again, anaerobic disintegration assay is cost effective and potential enough to produce biogas through co-digestion. Anaerobic digestion could be treated as a better way in reducing and stabilizing the organic waste, thereby improving biogas formation. Analyses demonstrate that around

60% of biomass can be transformed to biofuel. The contribution of renewable energy in dropping the toxic gases is widely known, where biogas from sludge also have a part, since it is regarded as a carbon neutral energy. [4] The principal component in biogas is methane and others include CO₂, O₂, sulphide and water vapor. In general case, on treating sewage, it is transformed to sludge or slurry which is then condensed and subjected to digester tank as shown in figure 2 in where microbial process takes place generating methane, CO₂ and hydrogen sulphide (biomethanation). Once this disintegration gets over, the collected biogas is transferred to the gas burner. As a whole, the purposive nature of this process is to reduce digestion timing and thus affording increased biogas production.

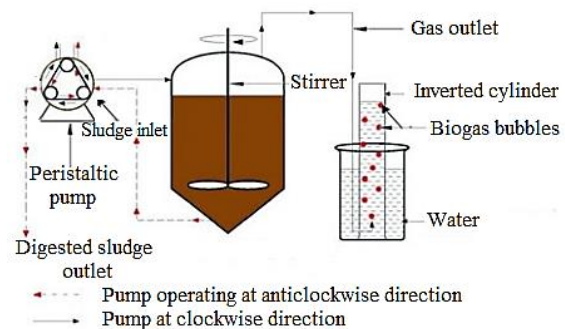


Figure 2.Anaerobic digester

The prospective of pretreated slurry for biogas recovery from anaerobic biodegradation has to be evaluated probably by means of biochemical methane potential assay. In general EPS, pH and temperature are the parameters that influence the bacterial pretreatment and so these factors must be checked.

2. ENHANCEMENT OF ANAEROBIC DEGRADABILITY

Owing to the extended time period of anaerobic digestion and thickened decaying process, waste is pretreated prior to digestion. Certain benefits of pretreatment includes,

- Speedy decomposition and solid reduction
- Improved digester efficiency and biogas recovery
- Increased residual stabilization and settling characteristics
- Reduced specific sludge and foam generation.

In order to enhance the rate of the process in biogas production, the building up

of microbial cell walls in WAS has to be interrupted such that the digestible substances are allowed to release out of the cell walls. Thermal and microwave pretreatment comes under physical methods, which is preferred for stabilization, sludge dewatering and removal of undesirable microbes. [5] Concerning with the chemical methods, the organic matters are destructed using strong acids/alkalis (hydroxyl radicals)/oxidants (ozone), which improves biogas yield and hydrolysis rate. Yet, this cannot be opted for the organics with higher carbohydrate content since it does not suit for methogenesis stage. [6] To enhance degradation and to recover precious products, mechanical pretreatment methods are carried out. [7, 8] In consideration of the biological methods, it is better in increasing hydrolysis pace through catalytic action or microbial cultures. Several of the referred articles preferred biological pretreatment as most of the results were productive in increasing biogas percentage. Rather than focusing on with a single pretreatment system, combinative approach yielded more production. [9] suggested to elevate biogas quantity up to 75% when chemical and mechanical pretreatment methods are adopted in a combined manner. In a similar way, combined sono/alkalization resulted in 80% of biogas generation.

[10] A 3-phase CH_4 fermentation model to treat food waste was structured analyzing temperature effect. Chemical O_2 Demand (COD) solubilization and biogas yield were optimized under thermophilic condition rather than mesophilic one. [11] Photo-Fenton process proves to be an efficient technique in the reduction of biomass sludge. Response surface method was used to evaluate pH, ferrous ion conc. and H_2O_2 . Solar photo Fenton process enhanced solubilization of chemical oxygen demand and it is recorded to be 5% at four hour contact period. This method is economic, ecofriendly and inexpensive. [12] This sort of Fenton treatment can be improved by the addition of citric acid for the removal of EPS. While this strategy could even reduce slurry disposal cost from 297 USD to 61 USD per sludge tons. [13] Contaminated organics from industrial discharge must be treated before letting to pass through public sewers. Here ferric chloride is added to remove 44% of color reduction and incorporating Fenton process into this enhances color and COD removal up to 90%. It reports that the

suspended solids (SS) and insoluble matter reduction can be performed by the former method whereas to treat soluble organics, Fenton process needs to be carried out along with the above process. Mono digestion is preferred when the amount of materials to be treated is low. Co-digestion is advantageous to mono digestion as it results in higher biogas yield and efficient removal of volatile solids. It suggests that vegetable and cattle waste is a better option in such treatment.

2.1. Surfactant-dispersion mechanism

[14] examined the impact of surfactant-dispersion mechanism over dairy waste activated sludge (WAS) minimization. The analysis included Sodium Dodecyl Sulfate (SDS) as surfactant and disperser. This pretreatment enhanced the efficiency of semi-continuous anaerobic digesters. [15] Surfactant mediated bacterial pretreatment was carried out which promoted lysis. [16, 17] SDS was used to remove extracellular polymeric substance from WAS which is then pretreated to enhance anaerobic biodegrading ability. As a result, the suspended solid was reduced by 26% and a conclusion was drawn as, when pretreated, the anaerobic biodegradability was enhanced. In this experimental study, WAS was initially collected and concentrated. Protease and amylase produced from the bacillus strains used in the process enhanced sludge integration. The cultured cells were obtained by mass cultivation which is then applied for solubilization of waste activated sludge. Extracellular polymeric material was removed by optimizing sodium dodecyl sulfate. Bacterial pretreatment and developing mode of inoculated strains were carried out which is then followed by biochemical methane potential assay development to determine the generation of biogas. [18] focused on the impact of sodium dodecyl sulfate surfactant in EPS, where the resultant was bacterially pretreated. The COD solubilization and SS minimization were determined as 24% and 27% respectively.

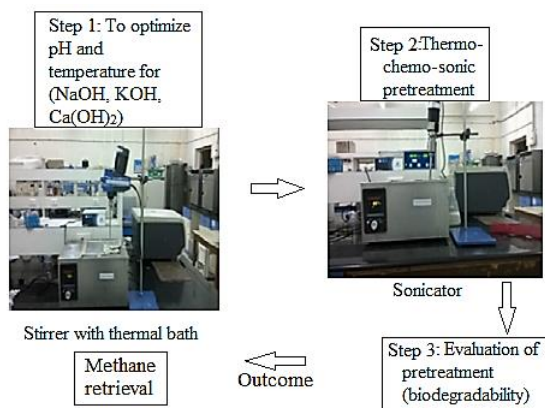
2.2. Combined mechanism

[19] Here the collected WAS was thermo-chemically hydrolyzed and then subjected to thermochemical and disperser pretreatment. This method is optimum for effective hydrolysis since the volatile fatty acids produced is high. Based on fermentation

analysis, the usage of this proposed strategy on hydrolysis and acidification of waste activated sludge was examined. Biogas recovery by thermo chemical disperser (combined) pretreatment is 0.5(L/g VS) which is greater than thermo chemical (simple) pretreatment process. The effects of thermo chemical treatment are,

- As temperature increases, SCOD (Soluble Chemical Oxygen Demand) tends to increase.
- Desorption of extracellular biomolecules due to electrostatic repulsion extension.
- Since at pH 8 and 9, SCOD is found to be ineffective, both these pH values are ignored, whereas the next two pH values are concentrated on.
- Ideal temperature and pH is noted as 80°C and 10 respectively and at this specifications, the resulted COD solubilization is 21%.
- In relation with specific energy, solubilization of chemical oxygen demand and minimization of suspended solids enhance as specific energy increases.
- Inexpensive
- Results in 90% energy saving.

[20] Thermo-chemo-sonic decomposition strategy as illustrated in figure 3 has been proposed using three alkalis namely, NaOH, KOH and Ca(OH)₂. It results in minimization of maximum suspended solids and COD solubilization. It also states that there is no significant difference in output in reference with all the three alkalis.



Adapted from [20]

Figure 3. Thermo-chemo-sonic disintegration

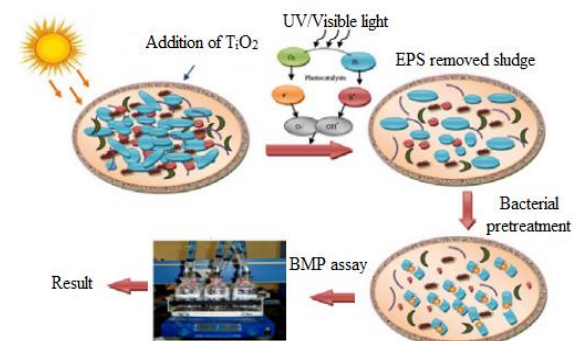
[21] EPS removal from waste activated sludge has been manifested using citric acid which also included ultrasonic pretreatment. COD solubilization, SS

minimization and biogas production of deflocculated slurry were greater than flocculated one. Altogether chemo-sonic mechanism can be chosen to enhance biodegradability and thereby improve biogas yield. The experimental procedure has been done by considering dairy industry into account. Statistical and cost analyses were carried out analytically with respect to standard approaches, UV-vis spectrometry, Lowry's principle, anthrone H₂SO₄ and Diphenylamine colorimetric system.

[22] Ultrasonic induced bacterial defragmentation has been employed to enhance aerobic biodegradation. The by-products are usually heat, moisture and CO₂ whereas anaerobic digestion suits for biogas generation and for disintegration of massive quantity of waste.

2.3. Reaction with chemical compounds

[23] Biogas generation has been influenced by NaCl with respect to disintegration and biodegradability of waste activated sludge. In this context, the solubilization was obtained as 23%. NaCl is used to get rid of extracellular polymeric substance. It states that floc removal with 0.03 g/g suspended solids of NaCl and the organic matter decomposition with bacteria can be preferred since it adds benefits to the biodegradability mechanism. [24] The impact of titanium dioxide in the presence of solar radiation as shown in figure 4 in removing EPS has been investigated in sludge processing. The obtained results prove that the extracellular polymeric substance free, bacterially pretreated slurry resulted in 23% of suspended solid reduction and COD solubilization and the methane content produced was 0.5(gCOD/gVSS).

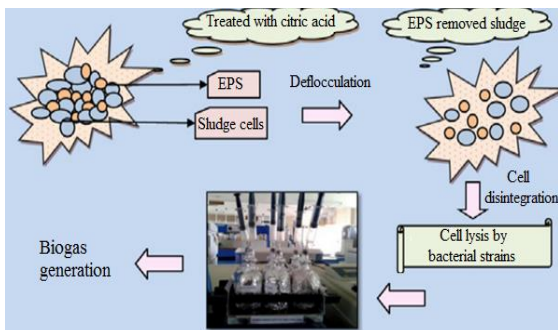


Adapted from [24]

Figure 4. Chemical disintegration using solar effect

2.4. Effect of citric acid

[25, 26] A protease secreting microbe has been employed in pretreating sludge that enhances aerobic digestion. Usage of citric acid helps in removal of EPS, thus in turn takes away flocs of the sewage waste. For the sake of optimization, response surface methodology has been adopted. Comparative analysis of microbial pretreatment represents that the sludge when treated with and without citric acid results in 18 and 10% reduction of suspended particles accordingly. Upon consideration of solubility, sludge with and without EPS has been found to be 11 and 7% respectively and in both the previous cases, when raw sludge is considered, its usage with citric acid and solubility accounts for 5.3 and 4.8%. The suspended particle shrinkage with reference to aerobic and controlled reaction leads to 52 and 15% respectively. It is suggested that using protease secreting bacteria after the elimination of EPS is favorable. Yet optimization in achieving biogas yield is low with aerobic digestion. [27] Extracellular polymeric substance from WAS can be reduced by using citric acid concentrated at 0.05g/g with lytic bacterial strains, where the suspended particle minimization and COD solubilization was determined to be 21% and 16% accordingly with respect to deflocculated and biologically pretreated slurry. In this, anaerobic biodegradability assay analysis is deduced by 0.45 L/(g VS) of biofuel yield for the sludge that were undergone with de-flocculation and bacterial pretreatment. Biogas production for flocculated sludge is lower and was assessed to be 0.34 L/(g VS). The typical diagram relating this concept is shown in figure 5.



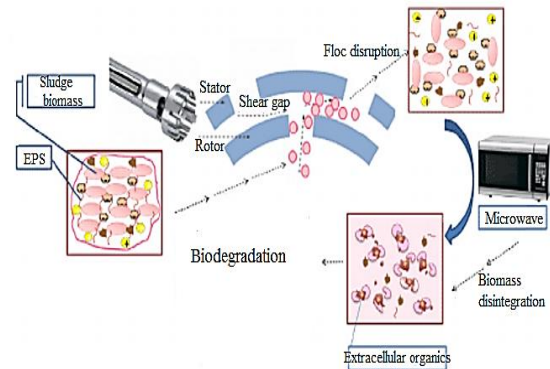
Adapted from [27]
Figure 5. Citric acid and bacterial pretreatment

[28] 50mM/L of citric acid was utilized to bacterially pretreat (*Bacillus*

licheniformis) WAS for the production of biogas. The reduction of suspended solids (SS) and volatile acid and COD solubilization were found to be 43%, 48% and 40% accordingly.

2.5. Microwave and ozone pretreatment

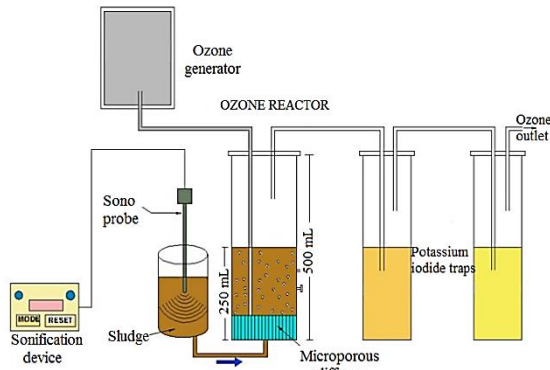
[29] examined the microwave pretreatment to determine biodegradation. At first the flocs are disintegrated by means of disperser and then they undergo microwave pretreatment. The obtained values are 17% and 22% for disperser induced, which is higher than the one without disperser, where its readings are found to be 9% and 16%. This is a profitable approach comparatively. The block diagram depicting this function is given in figure 6.



Adapted from [29]
Figure 6. Disperser induced microwave pretreatment

[30] deflocculated slurry by ultra-sonication and disintegrated cells by ozone. In this case, limited ultrasonic specific energy and ozone is enough for the enhancement of anaerobic biodegradability. The experiment has been carried out aiming at the removal of polluted odor and yielding biogas from dairies that is rich in organics. In order to quantify loosely and tightly bound extra polymeric substance, heat extraction strategy has been implemented. Lowry and Anthrone mechanism were done to determine the concentration of protein and carbohydrates accordingly.

In figure 7, ozone generator produces ozone from O₂ and the micro-porous diffuser distributed the produced ozone to the sludge. Two potassium iodide traps are utilized such that ozone remains can be absorbed. Then biochemical methane potential assay is done to assess biodegradability using advanced Gompertz model and Polymath software package.



Adapted from [30]
Figure 7. Experimental setup of ultrasonication and ozone decomposition

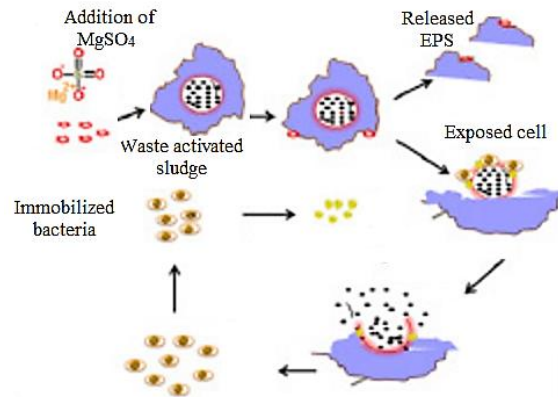
2.6. Analytical approach

As most of fruits and vegetables cultivated seasonally were easily perishable, managing them tends to be an environmental threat because of remains. One such example is orange peel in which anaerobic digestion would possibly treat organic effluent. In predicting the efficiency of digesters and optimizing the anaerobic process, kinetics are useful. Non-biodegradable matters could be easily removed by the adsorption systems. Analytical model and sensitive analysis of acetic and volatile fatty acid, inorganic carbon, CO₂ and CH₄ were evaluated by means of slope of concentration. This is helpful in optimizing industrial biofuel generation. [31] has tried hands in disintegrating WAS with possibly minimal cost. Magnesium sulfate has been added to decompose EPS where the disintegration rate was obtained to be 92% and then the composite was subjected to bacterial post treatment. Kinetic analysis was performed through nonlinear regression criteria in order to determine biodegradability. Both solubilization and methane production was found to be greater in case of deflocculated slurry. A simple illustration of this experiment is shown in figure 8.

3. MONO-DIGESTION VERSUS CO-DIGESTION

[32] performed mono-digestion demonstrations with the slaughterhouse waste, where methane production of 280 Nm³/t COD was calculated. [33] In this, the river bank grass was anaerobically mono-digested and considerable methane generation was observed. [34] On comparison with anaerobic mono and co-digestion, it is proved that co-digestion is effective in improving biogas

quantity because of efficient methane yield and in relation with microenvironment. Furthermore, in co-digestion, there are no dynamic alterations of prokaryotic structure to a greater extent and metabolic attributes are well organized. [35, 36] Biomass contents are mono and co-digested, where the results favored for co-digestion based on methane production.



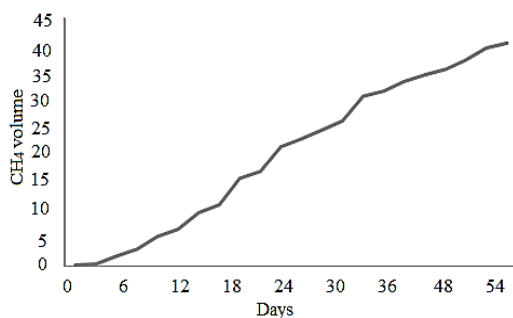
Adapted from [31]
Figure 8. MgSO₄ pretreatment

Here, vegetable remains and grass and animal manure are subjected to mono digestion and co-digestion under thermophilic states. In addition, the total methane to carbon dioxide ratio was higher during co-digestion. [37] conducted mono and co-digestion with corn stalk and animal manure. Kinetic results show that co-digestion is superior to mono digestion, where it promoted for sustainable microenvironment. It is also extended to prove the stability of the microbial communities. [38] Co digestion of municipal solid waste and food remains reveals the production of maximum biogas and methane with 1:3 ratio of solid and food waste. Co-digestion analysis shows that the average rise in methane was 140% and 44% in case of solid and food waste correspondingly where the rate of volatile solids reduction was found to be 55%. [39] Computational fluid dynamic systems were structured for mono and co-digestion. Flow field and power intake was considerably altered during co-digestion. [40] When compared with anaerobic mono digestion, co-digestion tends to be instable since it is operated at increased organics and subjected to huge changes in substrate matrix. Co-digestion modeling seemed to be complex as it requires pH changes and inhibitory intermediate deposition like organic acids. [41]

Investigation was made with respect to mono and co-digestion of potato pulp waste. As potato pulp is rich in proteins and lipids, it is considered to be ideal medium for methane yield. On contrary, deposition of fatty acids and ammonia nitrogen creates imbalance and these problems have to be curbed. The released free ammonia prevented mono digestion and so it is the co-digestion that improved stability and methane generation and it was found to be around $700 \text{ dm}^3/\text{kg VS}_{\text{fed}}$. [42] Biogas and methane production from spoiled milk were calculated to be 0.2 and $0.4 \text{ Nm}^3/\text{kgVS}$ respectively during anaerobic disintegration. In most of the referred case co-digestion is preferred to mono digestion as it increased the bio methane yield.

3.1. Co-digestion of plant and animal waste

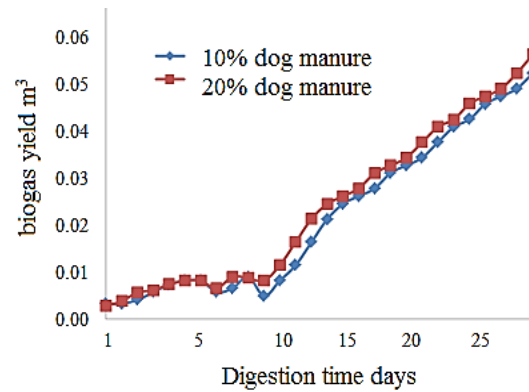
[43] Results show that co-digestion of food and animal waste improved methane generation from 100 to 250 mL methane/gram. But the vegetable remains when added with poultry waste, methane quantity decreased from previous results, whereas increase in rate of volatile solid reduction was observed. [44] On analyzing cattle waste and remains from olive oil processing, the results obtained are shown in figure 9. According to figure methane yield has reached 41 at 55th day when the cumulative organic manure was 94%. Likewise the production of biogas too constantly increased, where methane covered 64 % in the total biogas recovered.



Adapted from [44]

Figure 9. Total volume of CH₄

[45] Animal (dog and cattle) and vegetable (especially cabbage) waste produced sufficient biogas yield and it further increased with the rise of dog manure as depicted in figure 10.



Adapted from [45]

Figure 10. Biogas yield versus increase in dog manure concentration

[46] The quantity of methane obtained due to the anaerobic digestion of chicken and grass waste was 65%. It is advantageous in terms of maintaining stability too. Neither of these two produced maximum yield when used as a single substance. C to N proportion of chicken and grass waste was 8 and 39 respectively, where the ratio of chicken waste does not suit for disintegration due to excess N that would prevent bacterial growth and at the same time grass is not suitable due to its instable nature. Therefore it is concluded that when both of them combined together in the production of biogas, this approach is considerable. [47] With an aim to enhance mesophilic anaerobic disintegration, blue green photosynthetic organism has been used and feasibility study has been done in co-digesting seafood and glycerol remains. It is found out that anaerobic co-digestion of all these contributed in biofuel production qualitatively and quantitatively. It resulted in methane yield of 3430 ml at 94% of seafood waste, 1% of glycerol waste and remaining percentage of algae. It is to be noted that further increase in algae content could reduce the outcome.

3.2. Co-digestion of sludge with food waste

[48] came to a conclusion that combined sludge and cookery waste result in increased production of biogas other than using each separately. pH, chemical oxygen demand, and volatile solids, biogas yield were assessed by pH-3CpH meter, and fast airtight catalytic, burning and drainage collection process accordingly. The findings are drawn as,

- Higher percentage of biogas generation from cookery waste than from sludge

- The total biogas yield from kitchen waste is 26050 ml
- Production of biogas is found to be 4060 ml
- As the ratio of cookery waste rises, biofuel quantity gets increased.

[49] Results show that higher the proportion of total solids, the more bioenergy it resulted. Modified Gompertz relation has been used in modeling biogas yield. The experiment results are as follows,

- Biogas yield per day is 0.9 l
- Total generation after 13 days is 7 l, of which, 73% concentration is methane and remaining 24% is carbon dioxide
- Waste activated sludge added with cow manure lead to be an efficient approach in producing biofuel.

4. CONCLUSION AND FUTURE DEVELOPMENTS

Based on several reviews it is found out that biogas recovery is enhanced due to deflocculated and bacterial pretreatment of sludge. Co-digestion attributes to effective process of anaerobic disintegration as several streams of sludge could be digested simultaneously in a single system. The use of citric acid as a deflocculating agent is a promising method to remove extra polymeric substance from waste activated sludge, where this could be adopted with other methods also as a combine mechanism in order to improve biodegradation and quantify biogas yield. Utmost care should be given in choosing the chemicals in case of chemical pretreatment as it inhibits biological process due to the possibility of metabolic reactions. Certain problems such as absence of operation experience and feasible choice for biogas utilization, food remains collection and management and effect of disintegration on bio-solid re-usage have to be addressed to develop co-digestion. An appropriate ecofriendly quantification strategy must be put forth by considering all non-positive aspects.

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