A COMPREHENSIVE OVERVIEW ON ANAEROBIC DIGESTION OF SOLID WASTE COMPRISING OF FOOD WASTE: A REVIEW

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ABSTRACT
Increase in human population, urbanisation, improvement and changes in life style have led to an exponential growth in food waste generation. Apart from environmental pollution due to excessive organic loading on the receiving natural systems, emissions of Green House Gases, scarcity of land and rising cost of waste disposal, increase in the wastage of food and its continuous deposition are the recent and crucial challenge. While, life style corrections and better management practices are required to reduce the generation of food waste; proper collection, treatment and disposal is also a must to reduce the burden on the already overstretched natural resources. A review of different techniques with particular reference to the traits of nutrient production, eco-friendliness and fulfilment of energy requirements, are discussed. Conversion of food waste to biogas through anaerobic digestion provides a sustainable high calorific value energy source in the form of methane and also nutrient rich compost for soil and plants. Methane, being a non-conventional form of energy, reduces the green house emission potential by twelve times when used as a fuel. The anaerobic bio-digestion of the food waste with review of the important parameters and various techniques affecting the digestion performance has been presented.

KEYWORDS: *Anaerobic Digestion, methane, Bio digester, Green house emission, calorific value.*

I. INTRODUCTION

With the worldwide economic development and population growth, changing urban lifestyle; households, canteens, restaurants, hotels, and cafeterias are generating enormous amount of food waste (FW). FW has a significant contribution to the greenhouse gas (GHG) emissions - about 3.3 billion tonnes of CO_2 is released to the atmosphere per year due to the food waste [1]. FW, as a special category of municipal solid waste, typically has higher moisture, salinity, organic matter, and oil content, which requires treatment methods different than that applicable to common municipal solid waste[2]. Common treatment methods for management of the FW include anaerobic digestion, landfill, incineration, composting, and heat moisture reaction[3]. Anaerobic Digestion imparts the most useful product, methane and the residual by-product may be used as fertilizers ,while the lacunas of the technology include high installation cost, strict start-up condition and long time for fermentation[4][5][6][7].A conventional method of Landfill has several disadvantages such as requirements of large area of land with possibility of soil, surface and sub-surface water contamination, and great amount of greenhouse gas emissions. The volume of waste is greatly reduced by the process of thermal energy production called incineration but is energy intensive and costly process[8].Globally consumer food waste amounts to roughly 900-1000 Metric tonnes per year which equates to about 400-500 kg per person [9].

Table 1 Highlights of Food loss across the entire globe

Geographical area	Annual food waste (kg/person)	Annual Food waste GHG foot print (kg CO_2 equivalent /person)	References
USA,Canada, Australia, New Zealand	100-120	350-400	[10][11]
Europe	80-100	300-350	[12]
China, Japan and Korea	80-90	250-300	[13]
North Africa, West and Central Asia	20-40	100-150	[14]
Latin America	30-40	100-130	[15]
South and South east Asia	10-20	50-100	[16]
Sub Saharan Africa	5-10	30-50	[17]

II. CONVERSION TECHNIQUES OF FW

According to the variability in food consumption habits, the Food Waste constitution and structure differs. Due to the high moisture content (MC) (70 to 80%), FW is recyclable substrate. Disposal of FW without any effective treatment measure has led to a threat of environmental pollution in many countries[18]. The traditional approaches for FW disposal comprises of landfill, incineration and aerobic composting [13]. Incineration of food waste consisting of high moisture content leads to the release of dioxins which enormously reduce the economic value of the substrate. The recovery of nutrients and valuable chemical compounds from the incinerated substrate therefore becomes too difficult. Land filling of FW is completely prohibited in many countries; due to land, water, and air pollution. Both the approaches, being environmentally unfriendly, are being gradually discarded. Composting is a common alternative to land filling, an aerobic process that decomposes organic material into a nutrient-rich soil amendment [19]. Barriers to composting include lack of on-site storage space, the cost to separate food waste from its packaging, and transportation constraints along with odour issues. FW can’t be used as animal feed as it invites the chances of enhanced contamination and a lot of diseases. [18]. Laws are hence increasingly becoming more severe with respect to protection of environment and also to ensure food safety. The alternative methods for Food Waste disposal are required for the proper management of food waste[2]. Anaerobic digestion can be a feasible option to strengthen world’s energy security by employing food waste to generate biogas which can fulfil the issue of waste management and nutrient recycling.

Table 2 . Techniques which are applied for conversion of food waste.

Techniques	Description	Benefits	lacunas	Reference
Aerobic digestion	Aerobic digestion uses micro-organisms in the presence of oxygen to oxidize and decompose organics	Complete oxidation of organics take place	Energy intensive process; large amount of sludge is generated which is difficult to handle	[20]
Gasification	Gasification converts organic material into carbon mono oxide,hydrogen,carbon and carbon dioxide, by reacting the materials at high temperature(> 700°C) by a controlled supply of oxygen	The end products as fuel gases can be used in engines or fuel cells and synthetic gases generated can be used for methanol, ethanol or other chemical production.	Harmful pollutants emission as polycyclic Aromatic hydrocarbons, Polycylic Aromatic Benzene etc. and fly ash produced which is difficult to dispose.	[5] [21]
Pyrolysis	Pyrolysis is the heating of an organic material without the presence of oxygen, resulting in the decomposition of	Hazardous air emissions are rarely produced.	Dioxins, oxides of nitrogen, oxides of sulphur and particulate matter sometimes produced.	[5]

	organic material into gases and charcoal			
Briquetting	This process forms processed waste into chunks of renewable fuel which can be fed into boilers used for industrial cogeneration.	High Volumetric energy density and lower water content in the fuel, hence greater storage stability.	Degree of biodegradation is less	[20][22][7] [23]
Anaerobic digestion	The process uses microbes to break down the organics in an oxygen free environment	Biogas produced and the digestate material can be used as fertilizer.	Chances of process failure since it is a complex process	[4][5]

III. ANAEROBIC DIGESTION PHASES

To get a Glimpse of Anaerobic Degradation Process, it was thoroughly studied that the anaerobic biological degradation of organic waste to methane is governed by symbiotic association existing amongst different groups of bacteria in which the microbial populations linked by their individual substrate and product specificities in order to maintain equilibrium between substrate concentration and bacterial number [20]. The anaerobic digestion being a complex process, involves a number of biochemical reactions that occur under anoxic conditions [24] **.**The complex macromolecules of organic matter which are present in food waste, for its transformation into biogas require multidisciplinary microorganisms. There are multiple steps that are required for the anaerobic digestion of proteins, carbohydrates, and lipids. Four major distinguishable phases are considered in the overall conversion process of organic matter to biogas: hydrolysis, acidogenesis, Acetogenesis, and methanogenesis [24] [25] [26]**.**

3.1 Hydrolysis

The first and foremost step in anaerobic digestion process which involves the enzymatic media conversion of insoluble organic materials and higher molecular mass compounds into soluble organic materials is hydrolysis. These compounds are suitable to be used as a energy source and carbon of cell .Step carrying forwarders are anaerobes as Bacteroides, clostridia and facultative bacteria[18]**.** The decomposition rate is totally dependent on the nature of the substrate [27]**.** The hydrolysis step is considered to be the rate-limiting for complex organic substrate [28][29][30][31][32][33][1]**.** The end products comprising of toxic by-products (complex heterocyclic compounds) or non-desirable volatile fatty acids (VFA) produced during this step[25] [34]**.**

3.2 Acidogenesis

The short chain organic acids are the major end products that are formed when the monomers produced in the former phase are utilized by facultative and obligatory anaerobic bacteria. During this phase, simple sugars, fatty acids and amino acids are converted into organic acids and alcohols[24].

3.3 Acetogenesis

Microorganisms consume the products of former phase as substrates which were active in the acidogenic phase in which anaerobic oxidation are performed [35]**.** Products are converted into methanogenic substrates, volatile fatty acids and alcohols (VFA) which are further oxidized into acetate, hydrogen and carbon dioxide, VFA with carbon chains longer than one unit are oxidized into acetate and hydrogen [4]**.**

3.4 Methanogenesis

In the methanogenic phase, the production of methane and carbon dioxide occurs. [35]. Methanogenesis ,being the critical step of anaerobic digestion process imparted as the slowest biochemical reaction of the process[4].

IV. SUBSTRATE AND ITS IMPORTANCE FOR ANAEROBIC DIGESTION PROCESS

Any substrate that can be converted to methane by anaerobic bacteria is termed as feedstock[10]. The substrate for anaerobic digestion process includes a wide variety of components necessary for the activity of microbial enzymes systems such as trace elements and vitamins [35]. Substrate composition either enhances or degrades digestion residue (digestate) quality, outcome of the process, energy output and the quality of bio fertilizer. Food waste is considered to be a suitable substrate for AD owing to its high moisture content and high organic content which imparts it the potential of being converted to biogas. Various literatures justify the same.

Table 3 Biomethanation Potential of food waste for anaerobic Digestion

Type of Substrate	Digester type	Volatile solids Reduction	Methane yield (mL/gVS)	References
Fruit and vegetable wastes	Two stages	95.1%	530	[29][30][31]
Food Waste	5-L continuous digester	70%	440	[36][37]
54 different types of food	Not mentioned	Not mentioned	180 to 732	[38]
Korean food Waste	Not mentioned	86%	472	[13]
Canteen food waste mixed with straw in the ratio of 5: 1.	Not mentioned	Not mentioned	0.392 m^3 CH_4/kg-VS	[39][40]
Kitchen wastes	Two stages	63%	338.7ml(g/COD)	[41][35]
Canning factory waste	Not mentioned	80%	300-580	[38] [42]

V. KEY PARAMETERS AFFECTING AD PROCESS

In an anaerobic digestion process, the microbial consortia enhance the process efficiency if grows syntrophically or may lower the efficiency of the process if allowed to grow antagonistically [43]. To prevent the process failure the parameters are required to be studied thoroughly.

Table 4 . Parameters with their importance

Key Parameters	Range	Effects	References
Temperature	Psychrophilic (10°C to 30°C)	No gas production	[32]
	Mesophilic (30°C to 40°C)	Inhibition of Ammonia is observed Insulation of digester is required	[32] [33] [1][44][45]
	Thermophilic (50°C to 60°C)	Higher metabolic rate Higher specific growth rate Higher rates of destruction of pathogens Biogas production was more than twice the production in Psychrophilic range	[46] [7] [40] [47] [35] [48] [49] [50] [51]
pH	6.5-7.5	Ideal pH is neutral at 7.0. Methanogens unlikely to grow with pH < 6.5	[31] [48] [49]
Alkalinity	around 2000mg/L	Bicarbonates of Sodium and calcium required for buffering of reactor	[6][46] [7][31] [48] [49][52]
Volatile Fatty Acids (VFA)	200 mg/L - 300 mg/L	Higher concentrations will inhibit acetate and biogas production	[52][20]

		Only the unionized volatile acids in the concentration range of 30 - 60 mg/L are toxic.	
Ammonia	Around 650 mg/L	Excess of free ammonia can inhibit methane synthesizing enzymes It might create proton imbalances and potassium deficiency, causing cell lysis.	[39] [42] [30] [33] [49]
Carbon to Nitrogen Ratio	20:1 to 30:1	Higher C:N ratios result in methanogens consuming nitrogen; lowering biogas production	[36] [39]
Organic Loading Rate	3-5 kg of Volatile Solids per cubic meter of digester volume per day	Microbes are generally inhibited if loading rate exceeds 6.4 kg/m^3 day	[53][43][36][32]
Hydraulic Retention Time	Minimum is 2-4 days , Maximum is 40-60 days (India) 100 days(colder climate)	Varies widely based on feedstock, temperature, and system design	[36][39][32]
Nutrients	Hydrogen. Carbon, oxygen, nitrogen, Sulphur and phosphorus are the major ones.	Optimum N/P ratio can be considered to be 7. The theoretical minimum COD/N – ratio is considered to be 350/7.	[36][54]
Inhibitors/Toxicity	Volatile acids	Least toxic is acetate; most toxic is propionate Unionized part of acids penetrates cell membrane of microbes and disrupts them thereby causing digestion failure	[6][44][20]
	Ammonia – Nitrogen	Rapid production of VFAs Buffering capacity of the system may not compensate for the decrease in pH and alkalinity.	[44][54]
	Sulphide	Sulphide concentration in excess of 200 mg/L in a digester at 35 °C, leads to cessation of gas production	[54]
Additives	Metals,pectin,charcoal,vermiculite,pebbles,glass marbles, plastic mesh	For enzymatic activity of microbes molybdenum, selenium, tungsten and nickel are necessary Pectin, an enzyme, increased methane production by 10-20% Decreases residence time	[32] [55] [54]
Agitation/stirring/mixing	Gas production increases by 3 times	Intimate contact amongst the microbes is maintained. Violent agitation retards the digestion.	[36] [32]

VI. REACTOR CONFIGURATIONS

The performance of anaerobic digestion is highly dependent on Feedstock characteristics and process configuration [56]. An efficient anaerobic system should be capable of providing an optimum environment for the growth of the anaerobic microorganisms [43]. Certain criteria are essential for the optimum environment such as high retention of the active biomass (microorganisms) inside the bioreactor, sufficient contact between the biomass and the substrate, high reaction rates and elimination of the limiting transport phenomena, suitable environment for the adaptation of the

biomass to various types of feedstock and suitable environment for all organisms under the operating conditions[57][58].
In single stage anaerobic digestion, owing to the fact that all the 4 digestion phases are completed in a single reactor with added advantages of smaller investment cost and lesser technical problems encountered, usually it is preferred [58] where as in the case of two stage anaerobic digestion, production of hydrogen and volatile fatty acids (VFA) by acidogens and hydrogen producing microbes takes place in first stage in a separate reactor followed by conversion of VFAs to methane and carbon dioxide employing acetogens and methanogens in the second reactor permitting higher organic loading rate and higher methane generation[41][35][59]
Packed bed reactors (PBR) or fixed bed systems have been developed in order to attain high loading, immobilize microbial consortia and stabilize methanogenesis [27].
The efficiency of digestion could be improved by co-digesting different wastes, trace element addition, and using active inoculum as start-up seed.

Table 5. Operational and Performance data for various types of reactor configurations used in Food waste study

Type of Reactor and volume	Temperature	OLR (kg VS m^{-1} $days^{-1}$)	HRT (Days)	Efficiency (%)	CH_4 yield (m^3 kg^{-1}VS added)	Biogas yield (kg^{-1}VS)	%CH_4	Researcher
Batch system	50	Not Reported	10,28	81	0.348,0.435	Not Reported	73	[18][13] [60][41][35]
3 stage semi continuous	50	Not Reported	12.4	Not Reported	Not Reported	Not Reported	67.4	[40] [47]
Batch (1.1 litre)	55	Not Reported	90	74	0.18, 0.05	Not Reported	68.7	[58]
Floating Dome type (200 l)	33	40	20	65	Not Reported	0.98	50	[41][35]
Batch scale (5 litres)	36-55	0.12-5.32	21-60	Not Reported	0.84	0.2-1.4	60-65	[18] [13][61][62] [63][60]
Batch (2 l)	35-55	8	12	78	3.3	5.60	58.9	[40][47]
Batch and continuous (18 and 20 l)	35,50	0.5,1.0	28	80–97, 78–91	0.25–0.55, 0.35–0.78	0.53–0.83, 0.60–1.10	47–68, 48–74	[47]
2 stage UASB (8 L)	Not Reported	1.04	Not Reported	90	0.277-0.482	Not Reported	Not Reported	[19]

VII. PRE-TREATMENTS REQUIRED

In order to enhance anaerobic digestion process, so that one can get the maximum output certain pre-treatment methods have been suggested. These treatment methods improve the solubility of food waste when they are applied under optimized conditions [57]

Table 6: Various pre-treatment methods employed for food waste

Type of pre-treatment	Subtype	Effects and consequences	References
Mechanical	Milling and grinding	Size reduction of food waste which results in increase in the surface area thereby increasing the biogas yield by 18-32% Increase in the CH_4 yield	[64][18]
Thermal	Microwave or higher temperatures	Disintegrates the cell membrane and enhances the solubilisation of COD which increases biogas production	[18] [65]

		Shortens the retention time in the digester Removes pathogens When food waste was pretreated at 120°C, an increase of 24% was observed in bio methane production	
Chemical	Acids, alkalis or oxidants	Enhances the hydrolysis rate and biogas production Not preferred for substrates containing high amounts of carbohydrates	[66]
Biological	Enzymes such as amylases, proteases, lipases	Improves the solubility of the biomass without producing any inhibitory compounds Improves the hydrolysis of food waste if composting or micro-aeration done prior to digestion.	[59][57] [63]
Ultrasonic	Cavitations at low frequencies; chemical reaction at high frequencies	Reduces the retention time and increases the methane production	[52]
Ozonation	Not applicable for food wastes	Readily degradable organic wastes, hence not required	[52]

VIII. Co-Digestion and Other Factors

The digestion of two or more organic waste feedstock or substrates together or simultaneously is termed as co digestion. Co- digestion of multiple substrates improves the yields of anaerobic digestion of feedstock which leads to establishment of positive synergisms in the digestion medium and the supply of missing nutrients [67]. Nutrient imbalance in the form of C:N ratio adversely affects the activity of microbes. Carbon rich substrates should be mixed with Nitrogen rich substrates to improve the process stability [68][69].Co-digestion helps to overcome the disadvantages of monodigestion as it provides buffering capacity and increased organic loading [52] [68] [55]. As compared to monodigestion, co digestion can enhance methane production from 25-400%[68] [55].

Table 7: Substrates with different C/N ratios

Substrates	C/N ratio	References
Food waste	3-17	[68]
Mixed food waste	15-32	[52]
Cow dung	16-25	[55] [70][62]
Kitchen waste	25-29	[55][10]
Waste cereals	16-40	[29][71] [31]
Potatoes	35-60	[29][71] [31]
Sugar beet	35-40	[29] [71] [31]
Rice straw	51-67	[1]
Wheat straw	50-150	[1]
Fallen leaves	50-53	[68]

Table 8: Co-digestion of various feed stocks for improving performance of Anaerobic Digestion

Feedstock	**Action of Co-digestion**	**Influencing Factor**	**References**
Food Waste + Cow Manure	Improve methane yield enhanced and helps in achieving system stability Improves biogas production Reduces green house gas emissions	High buffering capacity from ammonia, nutrient balance and trace elements supplement.	[18] [63] [70] [10] [72]
Food Waste + livestock waste	Improve methane yield and Volatile Solids reduction	Higher buffering capacity	[63] [1][55]
Food Waste + dewatered sludge	system stability increases	Sodium inhibition is reduced	[63] [1] [55]

Food Waste + sewage sludge	High organic loading rate is exerted	Buffering capacity from ammonia is enhanced	[63] [1][55]
Food Waste + green waste	Improve Volatile Solids reduction	Carbon/Nitrogen ratio	[63][73] [68]

IX. CONCLUSION

On reviewing the various parameters and aspects governing the ample utilization of food waste to convert it into resourceful end product, attention has been drawn on the fact that apart from being rich source of energy, conversion technique applied for food waste also satisfies the criteria of being economically viable and practically feasible due to the availability of the feedstock at the local level itself. Research data emphasizes that the anaerobic digestion at mesophilic temperature can produce up to 125 m^3 of biogas having a methane content of 60% approximately if the quantity of feedstock used is nearly one ton[74].

Dissemination of know-how of the practices promoting anaerobic digestion technology and further research is required at molecular and microbiological level that could provide a better insight to the process leading to reduction in capital and management costs[57] [49].

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