Review on Waste-To-Energy Conversion Through Biochemical Conversion

L.Raja Mohan Reddy[1*],G.V.Ramana[2],B.Purushotham[3], N.B.Sivarami Reddy[1]
[1]*Dept. of Physics, Government Degree College, Rajampeta, Annamayya(Dt),A.P., India-516115*
[2] *Dept. of Physics, SCNR Government Degree College, Proddatur, YSR(Dt), A.P., India-516360*
[3] *Dept. of Zoology, Government Degree College, Rajampeta, Annamayya(Dt), A.P.,India-516115*

Abstract: **Global waste generation is expected to continue to grow due to economic development and population growth. Therefore, sustainable waste management is mandatory if a sustainable world is desired in which the objectives of the circular economy concept are met, where recovery is the last step to be taken when reduce, reuse or recycle have already been carried out. Waste to Energy (WTE) is a very broad term that covers any process that converts waste into energy, or an energy-carrying product, such as a gas or oil. Despite the existence of many different technologies, the aims of all WTE processes are essentially the same, Reduce the volume of waste and hence reduce the volume requiring disposal in landfill; Reduce the biodegradable fraction of waste to zero, and Produce a useful commodity (typically electricity and/or heat) from non-recyclable waste. This review summaries the technological approaches that have been developed, presents some of the basic principles, provides details of some specific processes.**

Keywords: **Waste to Energy, Biochemical conversion, Anaerobic digestion, Fermentation and composting.**

1. INTRODUCTION

Global energy demand has increased rapidly in the last century along with the improvement of living standard, rising fossil fuels consumption and waste generation [1,2]. Waste management has been carried out for a long time from a hygienic point of view, avoiding health problems in society [3]. However, the development of world's population must be environmentally and economically sustainable, addressing climate change immediately [4]. Thus, energy supply and waste management are great current challenges that humanity has to face [2]. The growing inclusion of renewable energies in the energy mix together with a proper treatment and management of waste will be help to a global sustainable development. The 21st century will be the century of the cities. The urban population of the world has grown rapidly since 1950, from 746 million to 3.9 billion in 2014 [5]. According to UN data it is expected to increase up to 9.7 billion by 2050, with nearly 90 per cent of the increase to take place in the urban areas of Africa and Asia. Already today, the global amounts of municipal solid waste are estimated at 2 billion tonnes per year. Unlike world population and urbanization trends, there are no UN forecasts of future waste generation per capita [6]. However, there is a common understanding that waste quantities will substantially increase. The drivers are increased consumption of goods in growing urban populations, changes in lifestyle, and increasing wealth of the rising middle class. Circular economy concept could minimize the waste generation applying the four r's: reduce, reuse, recycle and recover. Recover refers to the last step that should be taken when the previous ones have been undertaken [7]. The recovery of waste as an energy vector or a by-product could contribute to the reduction of waste disposal problems in the future. Besides, the waste-to-energy (WTE) concept could ensure access to energy to all world's population [8].

The potential feedstock for WTE systems can be classified according to its origin: agricultural, industrial and residential [9]. Agricultural sector generates organic vegetable and animal wastes. Industrial sector can produce organic (e.g., by-products from sugar refinery, diary wastes, slaughterhouse animal waste or wastewater) and non-organic wastes (e.g., by-products from pulp and paper industry). The residential wastes are mainly produced in the kitchen, toilets or garden. The kitchen wastes involve municipal solid waste and used cooking oil. The treatment of toilets waste generates sewage sludge that can be recovered. The garden wastes comprehend vegetable wastes.

Organic wastes from agricultural sector (e.g., lignocellulose, livestock manure), industrial wastewater and residential wastes (e.g., waste food, domestic solid waste, sewage sludge) can also be processed biochemically through microorganisms to produce energy as gas or liquid fuel to generate electricity [7]. The most available biochemical processes are anaerobic digestion and fermentation. Both processes may require pre-treatments and perform co-digestion or co-fermentation of different substrates to improve the biodegradability of the waste [10,11]. Although anaerobic digestion is a more widespread process than fermentation, the economic and sustainable feasibility of both biochemical conversion technologies should be assessed in detail.

2. METHODOLOGY

This review study is a result of investigating the articles under the topic of "waste to energy". Data were then collected using the literature, national and international scientific websites such as Google Scholar, PubMed, Elsevier, Scopus, Springer, Magiran and NPTEL.

3. WASTE-TO-ENERGY (WTE) TECHNOLOGY

There are several waste to energy technologies available based on the type, quantity and characteristics of raw material, the required method of the energy, economic conditions, environmental standards and specific factors [12]. The most commonly used waste to energy technologies are thermo-chemical, bio-chemical, chemical and physical conversion technologies [13]. The thermal treatment includes cineration, pyrolysis, gasification and refused derived fuel (RDF) The biological treatment includes anaerobic digestion (AD) and fermentation. The chemical conversion includes hydrolysis, solvent extraction and transesterification. The physical conversion includes mechanical extraction, briquetting of Biomass and distillation.

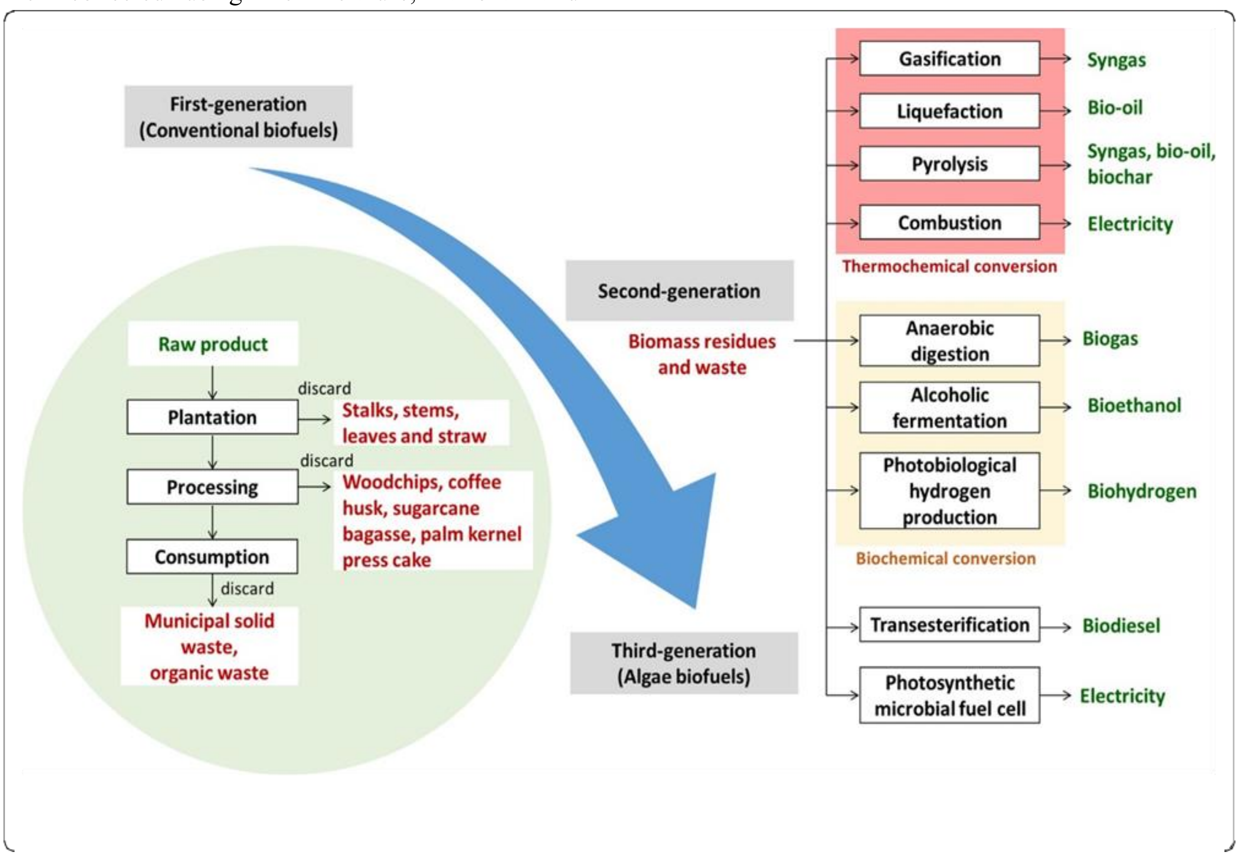

Fig. 1. Diagram of the development of biofuel generation with highlights on the second generation biofuels produced by biomass residues andwaste and their conversion pathways to produce a wide variety of bioenergy

3.1. Biochemical conversion

Biochemical conversion entails breaking down biomassto make the carbohydrates available for processing into sugars, which can then be converted into biofuels and bioproducts through the use of microorganisms and catalysts. Potential fuel blend stocks and other bioproductsinclude the following:

- Renewable gasoline
- Ethanol and other alcohols
- Renewable chemical products
- Renewable diesel

Biochemical conversion include the considerable cost and difficulty involved in breaking down the tough, complex structures of the cell walls in cellulosic biomass. The Bioenergy Technologies Office is exploring more efficient and cost-effective ways to gain access to theseuseful sugars for conversion processing.

Biochemical Conversion Step by Step

Biochemical conversion uses biocatalysts, such as enzymes, in addition to heat and other chemicals, to convert the carbohydrate portion of the biomass (hemicellulose and cellulose) into an intermediate sugar stream. These sugars are intermediatebuilding blocks that can then be fermented or chemically catalyzed into a range of advanced biofuels and value-added chemicals. The overall process can be broken into thefollowing essential steps:

A. Feedstock Supply: Feedstocksfor biochemical processes are selected for optimum composition, quality, and size. Feedstock handling systems tailored to biochemical processing are essential to cost- effective, high-yield operations.

B. Pretreatment: Biomass is heated(often combined with an acid or base) to break the tough, fibrous cell walls down and make the cellulose and hemicellulose easierto hydrolyze (see next step).

C. Hydrolysis: Enzymes (or other catalysts) enable the sugars withincellulose and hemicellulose in the pretreated material to be separated and released over aperiod of several days.

D1. Biological Conversion: Microorganisms are added, which then use the sugars to generate other molecules suitable for use as fuels or building-block chemicals.

D2. Chemical Conversion: Alternatively, the sugars can beconverted to fuels or an entire suite of other useful products using chemical catalysis.

E. Product Recovery: Products are separated from water, solvents, and any residual solids.

F. Product Distribution: Fuels are transported to blending facilities, while other products and intermediates may be sent to traditional refineries or processing facilities for use in a diverse slate of consumer products.

G. Heat & Power: Theremaining solids arecomposed primarilyof lignin, which canbe burned for heat and power.

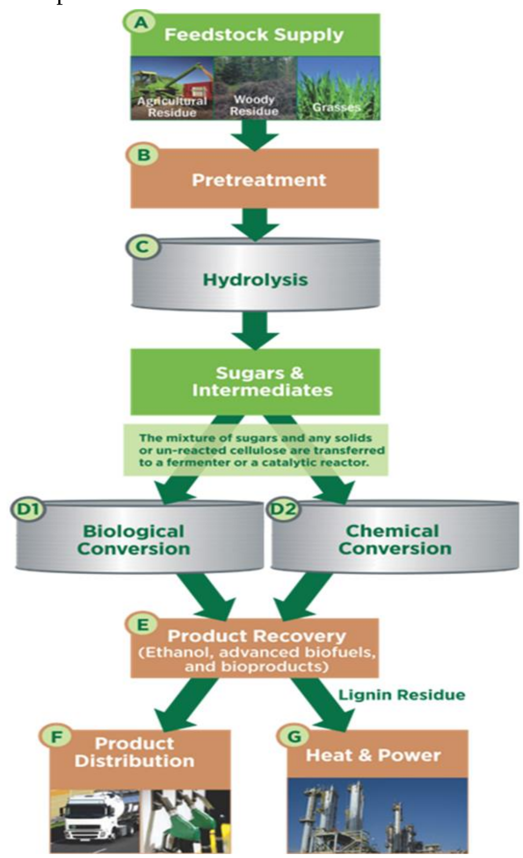

Fig.2.Biochemical ConversionStep by Step

3.1.1.*Anaerobic digestion*

Organic wastes can be efficiently processed through anaerobic digestion; a significant circular economy technology to mitigate the GHG emissions and to convert waste into biogas (50–70% CH_4) and organic fertilizers [14]. The most common organic raw waste materials used for biogas production are biodegradable organic fraction of municipal solid waste (OFMSW), sewage sludge, organic industrial wastes, food wastes and manure from livestock [15]. Depending on the moisture of raw material, wet or dry anaerobic digestion will be more suitable to process the organic waste. Wet AD is used to treat the organic matter with water content over 80% and conventionally higher than 90%, making it especially attractive for wastes as livestock manure or industrial & agriculture wastes. Continuous and batch dry AD is typically used to process materials with high solids content, between 20% and 40% [16], which is more suitable for the treatment of the organic fraction of municipal solid waste and agricultural wastes. Wet AD leads to methane yields of 0.1–0.150 m3/kg of waste while dry AD presents methane yields between 0.2 and 0.6 m3/kg of volatile solids. Dry AD has increased its interest and capacity in the last decade, but the lack of knowledge compared to well-established wet AD technology makes it still less preferred and represents only a 35% of anaerobic digestion facilities [17]. Besides total solids content of feedstock, other significant differences between wet and dry AD include: (i) not requirement of internal mixing in dry AD digestors, (ii) dry AD can be continuous or batch process, being batch with percolate recirculation the preferred configuration or (iii) the requirement of water is scarce or none in dry AD. The most relevant aspects for the efficiency and productivity of this process has been identified as: feedstock composition, co-digestion of substrates, temperature, pH, C/N, organic load and hydraulic retention time [15]. The composition of substrate strongly varies the methane production; between 0, 33 and 450 Nm^3 biogas/ton VS (volatile solids) depending on the use of lignocellulosic wastes or sugar and starch crops [18]. Co-digestion of complementary substrates provides an enhanced equilibrium of macro and micronutrients which improves biogas production by increasing the biodegradable components, providing a wider range of digesting microbial species and increasing the concentrations of active biomass[19].

Pretreatments remove unwanted compounds and enhance biodegradability of the waste. Lately, several pretreatments were explored to improve biogas production between 20 and 33% [20]. They include physical (grinding/milling, irradiation), physico-chemical (steam explosion, liquid hot water), chemical (alkali, acid, oxidizing agents, organic solvent) or biological (ammonia fibre explosion, ionic liquids or fungal).

Domestic solid waste production rate is rapidly increasing worldwide with food and green waste contents between 32 and 56% depending on the GDP of the country [17]. Dry anaerobic digestion has received increasing attention as a potential technology to reduce the GHG emissions of this waste and it has been shown that the rate-limiting step is the hydrolysis phase. Future research in this line should explore some of the different pretreatment options presented above to enhance hydrolisis through the increase of biodegradability of these wastes keeping in mind the cost-effectiveness of the process. The trend in developed and developing countries is to move towards intensive livestock farming leading to higher specific concentrations of livestock manure with strong environmental impact when not properly managed. The main limitations of manure as feedstock for anaerobic digestion are the low C/N ratio (given its high nitrogen content), the low percentage of volatile solids and the high proportion of components with low degradability potential. Research should focus on innovative biological, chemical, thermal and physical pretreatments for livestock manure to further enhance methane production [21].

Sewage sludge represents a major issue in wastewater treatment plants and anaerobic digestion appears as a well-known and suitable technology to process it [22]. Urban wastewater_treatment facilities supply a large share of the current worldwide produced biogas also presenting a great potential for future exploitation[23]. This process makes use of primary and secondary sludge converting about near 50% of organic matter in the sludge into biogas.

Lignocellulose is an interesting substrate for second-generation biofuel production given its low cost and wide availability. However, it also presents a complex structure which limits its biological degradation [24]. Physical, physical-chemical, chemical and biological pretreatments are used to modify this structure increasing its biodegradability. Codigestion of lignocellulosic residues with high C/N ratio is commonly carried out. Low yields of biogas associated to lignocellulose wastes can also be improved through the application of o physical and physico-chemical pretreatments.

Waste food represents one third of food production, around 1.6 Gt/year, and anaerobic digestion appears as an adequate technology to efficiently dispose fruit or vegetable given their high moisture and high biodegradability [25]. Their easy hydrolysis generates acidification which inhibites methane production reducing final efficiency. Acidification can be solved by means of different pretreatments, co-digestion, adjustment of the inoculum concentration and monitoring of the operation conditions [26].
Traditionally, the application of anaerobic digestion is limited to industrial_wastewater with COD of 3000–40,000 mg/L such as vegetable and fruit, starch, sugar and alcoholic beverages industrial sectors. In the last years, wastewater with lower COD (1500–3000 mg/L) has also been successfully processed by specific anaerobic digestors [27].

Photosynthetic eukaryotic and prokaryotes microalgae comprise over 20,000 species whose composition contains carbohydrates, proteins and lipids with varying content of volatile solids. The main drawback of anaerobic digestion of microalgae is the low biodegradability of unprocessed microalgae. This problem is solved through the application of pretreatments which break down the cell walls of the microalgae, increasing biomass biodegradability and methane yields [28]. A second limitation is the low C/N ratio and/or ammonia inhibition, which can be counterbalanced through the addition of high carbon substrates [29].

Anaerobic digestion of organic waste is considered a reliable process and has become an attractive technology from a policy-making point of view which will play a major role [30]. Also standardization process should be promoted by governments to boost the utilization of low carbon biogas for energy generation [31]. Finally, economic feasibility of this technology should be carefully assessed given the large investments required. Further research should focus on the finding additional revenues of the process from the chemical products.

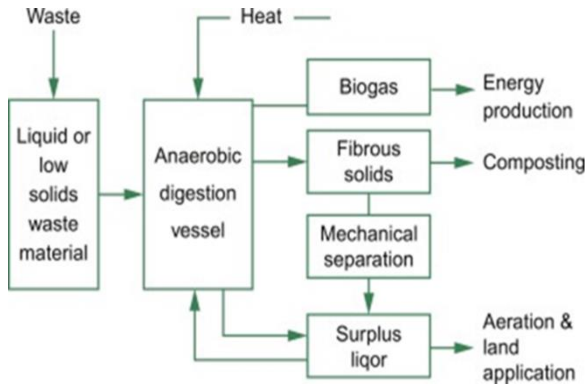

Fig. 3. Process involved in the typical anaerobic process

3.1.2. Fermentation
Fermentation is a biological process that is commonly facilitated by secretion of enzymes sourced from microorganisms which converts simple sugars to low molecular weight structures such as alcohols and acids. The fermentation of two most common sugars follow the two reactions below:

Glucose : $C_6 H_{12}0_6 \rightarrow 2C_2 H_6 O + 2CO_2$ (1)

Xylose : $3C_5 H_{10} O_5 \rightarrow 5C_2 H_6 O + 5CO_2$ (2)

During fermentation, biomass could be converted into alcohols through biochemical pathways. These pathways involved several schemes in which hydrolysis and fermentation process are carried out either concurrently in the same reactor Conversion of biomass feedstocks through fermentation process is a vital issue because it allows for the production of wide range of substances under mild conditions. The extent of fermentation on organic substances largely depends on composition and structure of the biomass feedstock. Only feedstocks that are not competing with the food items in terms of demand should be selected for biofuel production. Consequently, residues and waste materials from agriculture and forestry were considered as the most interesting sources of biomass.
High hydrolysis ratio is also an important requirement for the effective utilization of monosugars present in lignocellulosic structures. From biochemical perspective, organic substances present in the hydrolyzed solution can be categorized into several groups such as simple and complex carbohydrates, lipids, proteins, and heteropolymers. The potentials for biogas and biohydrogen generation from lignocellulosic biomass is huge due to utilization of different microorganisms in the conversion of

cellulose and hemicellulosic fractions of the agricultural and forestry residues [32]. However, a major setback is usually encountered during biofuels production which is the conversion ratio of the polymeric substances into fermentable sugars like hexoses and pentoses due to production of inhibitors along with the desired products. To minimize such inhibitors and maximize hexoses and pentoses production, microbial metabolism in the degradation and saccharification of the biomass cell wall were considered [33, 34].

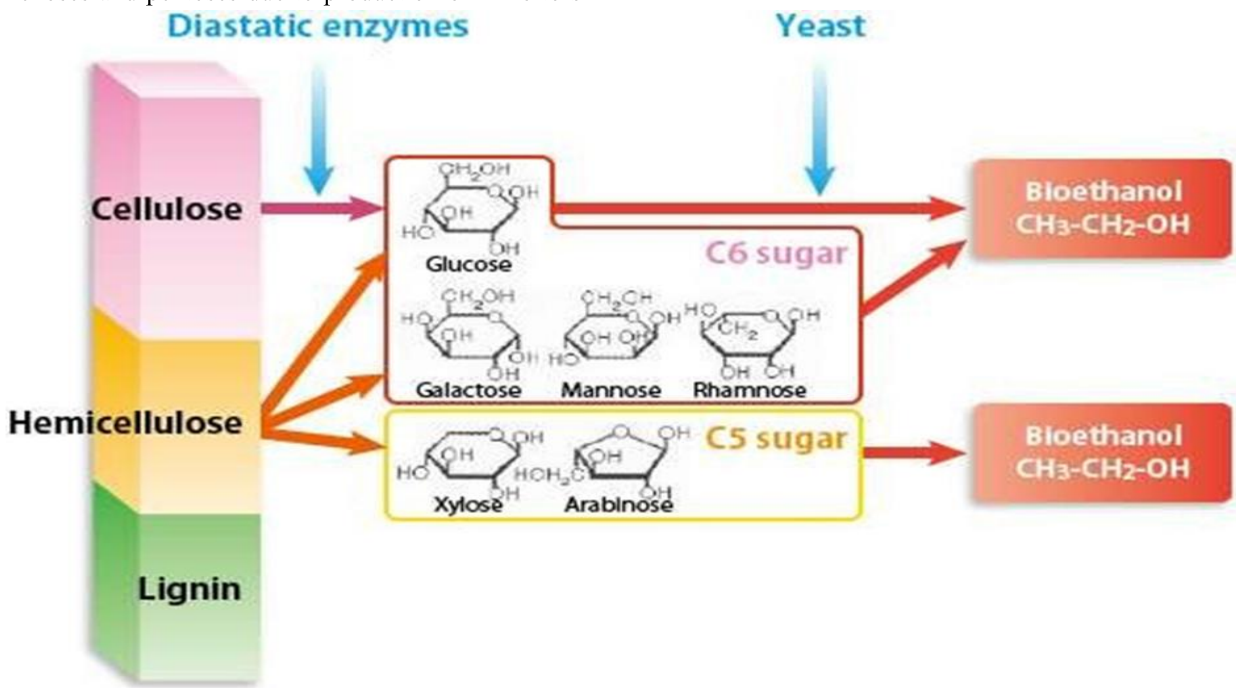

Fig.4. Bioethanol production process

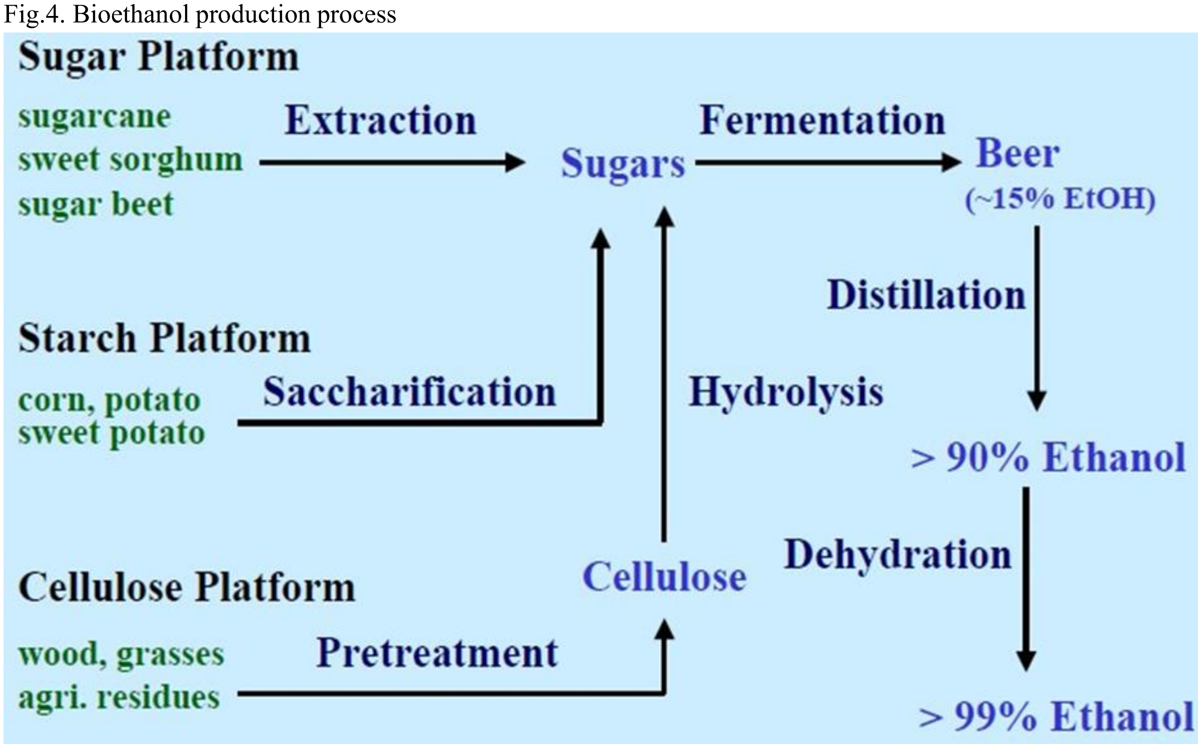

Fig.5. Bioethanol production flow diagram

4. CONCLUSION

With the ever-increasing demand for energy in a rapidly growing economy like India, cheap and sustainable energy is the need of the hour. Waste to Energy conversion remains a major untapped energy resource in the Indian context. Biomass residues and waste can be converted into transportation fuels and bioelectricity using transesterification, thermochemical and biochemical pathways. The choice of process technology depends on the end product desired and the feedstocks. In general, thermochemical technology that employs thermal heat might not be sensitive to the biomass waste composition when compared to the biochemical strategies for the production of biofuels. Nevertheless, the production of biofuels from biomass waste is still considered more robust in material handling, transportation, and conversion technology, when compared to traditional editable food crops-based biofuels. Still, on-going research studies are devoted to fill up the inadequacies of the existing technologies and improve the efficiency and economics of the production technologies employed.

REFERENCES

[1] S. Sharma, S. Basu, N.P. Shetti, T.M. Aminabha vi Waste-to-energy nexus for circular economy and environmental protection: recent trends in hydrogen energy. Sci. Total Environ., 713 (2020), 10.1016/j.scitotenv.2020.136633

[2] N.B. Klinghoffer, N.J. Themelis, M.J. Castaldi Waste to energy (WTE): an introduction Waste to Energy Convers. Technol., Elsevier (2013), pp.3-14, 10.1533/9780857096364.1.3

[3] P.H. Brunner, H. Rechberger Waste to energy - key element for sustainable waste management Waste Manag., 37 (2015), pp. 3-12, 10.1016/j. wasman.2014.02.003

[4] P. Wienchol, A. Szlęk, M. Ditaranto Waste-to-energy technology integrated with carbon capture – challenges and opportunities Energy, 198 (2020), 10.1016/j.energy.2020.117352

[5] United Nations, Department of Economic and Social Affairs, Population Division, "World Urbanization Prospects: The 2014 Revision, Highlights," United Nations, New York, 2014.

[6] D. C. Wilson, L. Rodic, P. Modak, R. Soos, A. Carpintero, C. Velis, M. Iyer and O. Simonett, "Global Waste Management Outlook," United Nations, Environment Program and International SolidWaste Association, Osaka and Wien, 2015.

[7] I. Khan, Z. Kabir Waste-to-energy generation technologies and the developing economies: a multi-criteria analysis for sustainability assessment Renew. Energy, 150 (2020), pp. 320-333, 10.1016/j.renene.2019.12.132

[8] R.E. dos Santos, I.F.S. dos antos, R.M. Barros, A.P. Bernal, G.L. Tiago Filho, F. das G.B. da Silva Generating electrical energy through urban solid waste in Brazil: an economic and energy comparative analysis J. Environ. Manag., 231 (2019), pp. 198-206, 10.1016/j.jenvman. 2018. 10.015

[9] R. Kothari, V.V. Tyagi, A. Pathak Waste-to-energy: a way from renewable energy sources to sustainable development Renew. Sustain. Energy Rev., 14 (2010), pp. 3164-3170, 10.1016/ j.rser. 2010.05.005

[10] V.K. Tyagi, L.A.Fdez-Güelfo, Y. Zhou, C.J. Álvarez-Gallego, L.I.R. Garcia, W.J. Ng Anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW): progress and challenges Renew. Sustain. Energy Rev., 93 (2018), pp. 380-399, 10.1016/j.rser.2018.05.051

[11] C. Liu, W. Wang, S. O-Thong, Z. Yang, S. Zhang, G. Liu, G. Luo Microbial insights of enhanced anaerobic conversion of syngas into volatile fatty acids by co-fermentation with carbohydrate-rich synthetic wastewater, Biotechnol. Biofuels, 13 (2020), p. 53, 10.1186/ s13068-020-01694-z

[12] Kalyani KA, Pandey KK, 2014, Waste to energy status in India: A short review, Renewable and Sustainable Energy Reviews, 31, 113-120. http://doi.org/10.1016/ j.rser.2013.11.020.

[13] Chinwan D, Pant S, 2014, Waste to energy in India and its management, Journal of Basic and Applied Engineering Research, 1(10), 89-94.

[14] F. Tessele, J. van Lier Anaerobic digestion and the circular economy Water E J., 5(2020), pp.1-5.

[15] R. Curry, M.N. PérezCamacho, R. Brennan, S. G ilkinson, T. Cromie, P. Foster, B. Smyth, A. Oro zco, E. Groom, S. Murray, J.A. Hanna, M. Kelly, M. Burke, A. Black, C. Irvine, D. Rooney, S. Gl over, G. McCullough, A. Foley, G. Ellis

Quantification of anaerobic digestion feedstocks for a regional bioeconomy Proc. Inst. Civ. Eng. - Waste Resour. Manag., 171 (2018), pp. 94-103, 10.1680/jwarm.17.00014.

[16] J. Guendouz, P. Buffière, J. Cacho, M. Carrère, J .-.P. Delgenes Dry anaerobic digestion in batch mode: design and operation of a laboratory-scale, completely mixed reactor Waste Manag., 30 (2010), pp. 1768-1771, 10.1016/j.wasman. 2009. 12.024

[17] D.P. Van, T. Fujiwara, B. Leu Tho, P.P. Song Toan, G. Hoang Minh A review of anaerobic digestion systems for biodegradable waste: configurations, operating parameters, and current trends Environ. Eng. Res., 25 (2019), pp. 1-17, 10.4491/eer.2018.334.

[18] R. Iglesias, R. Muñoz, M. Polanco, I. Díaz, A. S usmozas, A.D. Moreno, M. Guirado, N. Carreras , M. Ballesteros Biogas from anaerobic digestion as an energy vector: current upgrading development Energies, 14 (2021), pp. 1-30, 10.3390/en14102742

[19] V.K. Tyagi, L.A. Fdez-Güelfo, Y. Zhou, C.J. Álvarez Gallego, L.I.R. Garcia, W.J. Ng Anaerobic co-digestion of organic fraction of municipal solid waste (OFMSW): progress and challenges Renew. Sustain. Energy Rev., 93 (2018), pp. 380-399, 10.1016/j.rser.2018.05.051

[20] E. Naran, U.A. Toor, D.-.J. Kim Effect of pretreatment and anaerobic co-digestion of food waste and waste activated sludge on stabilization and methane production Int. Biodeterior. Biodegrad., 113 (2016), pp. 17-21, 10.1016/j. ibiod.2016.04.011

[21] M.Q. Orlando, V.M. Borja Pretreatment of animal manure biomass to improve biogas production: a review Energies, 13 (2020), p.3573, 10.3390/en13143573

[22] M.P. Caporgno, R. Trobajo, N. Caiola, C. Ibáñez, A. Fabregat, C. Bengoa Biogas production from sewage sludge and microalgae co-digestion under mesophilic and thermophilic conditions Renew. Energy., 75 (2015), pp. 374-380

[23] N. Bachmann, Sustainable Biogas Production in Municipal Wastewater Treatment Plants, Paris, France (2015)

[24] C. Sawatdeenarunat, D. Nguyen, K.C. Surendra, S. Shrestha, K. Rajendran, H. Oechsner, L. Xie, S.K. Khanal, Anaerobic biorefinery: current status, challenges, and opportunities, Bioresour. Technol., 215 (2016), pp. 304-313, 10.1016/j.biortech.2016.03.074

[25] P.C. Slorach, H.K. Jeswani, R. Cuéllar-Franca, A. Azapagic, Environmental sustainability of anaerobic digestion of household food waste, J. Environ. Manag., 236 (2019), pp. 798-814, 10.1016/j.jenvman.2019.02.001

[26] B. Ruggeri, A.C. Luongo Malave, M. Bernardi, D. Fino, Energy efficacy used to score organic refuse pretreatment processes for hydrogen anaerobic production, Waste Manag., 33 (2013), pp. 2225-2233, 10.1016/j.wasman.2013.06.024

[27] C.-.H. Lay, T.-.P. Vo, P.-.Y. Lin, P.M. Abdul, C.-.M. Liu, C.-.Y. Lin, Anaerobic hydrogen and methane production from low-strength beverage wastewater, Int. J. Hydrogen Energy, 44(2019), pp.14351-14361,10.1016/j.ijhydene.2019.03.16 5

[28] P. Ayala-Parra, Y. Liu, J.A. Field, R. Sierra-Alvarez, Nutrient recovery and biogas generation from the anaerobic digestion of waste biomass from algal biofuel production, Renew. Energy., 108 (2017), pp. 410-416, 10.1016/j.renene. 2017. 02.085

[29] W. Zhong, Z. Zhang, Y. Luo, W. Qiao, M. Xiao, M. Zhang, Biogas productivity by co-digesting Taihu blue algae with corn straw as an external carbon source, Bioresour. Technol., 114 (2012), pp. 281-286, 10.1016/j.biortech.2012.02.111

[30] C.A. Sevillano, A.A. Pesantes, E. Peña Carpio, E.J. Martínez, X. Gómez, Anaerobic digestion for producing renewable energy—the evolution of this technology in a new uncertain scenario, Entropy, 23 (2021), p. 145, 10.3390/ e23020145

[31] M.N. Uddin, S.Y.A. Siddiki, M. Mofijur, F. Djav anroodi, M.A. Hazrat, P.L. Show, S.F. Ahmed, Y. M. Chu, Prospects of bioenergy production from organic waste using anaerobic digestion technology: a mini review, Front. Energy Res., 9 (2021), 10.3389/fenrg.2021.627093.

[32] Abo BO, Gao M, Wang Y, Wu C, Ma H, Wang Q. Lignocellulosic biomass for bioethanol: An overview on pretreatment, hydrolysis and fermentation processes. Reviews on Environmental Health. 2019;34(1):57-68

[33] Zhang CM et al. Effective ethanol production by reutilizing waste distillage anaerobic digestion

effluent in an integrated fermentation process coupled with both ethanol and methane fermentations. Bioprocess and Biosystems Engineering. 2010;33(9):1067-1075.

[34] Cheng X-Y, Li Q, Liu C-Z. Coproduction of hydrogen and methane via anaerobic fermentation of cornstalk waste in continuous stirred tank reactor integrated with up-flow anaerobic sludge bed. Bioresource Technology. 2012; 114:327-333.