Sustainability of Waste-to-Energy Nexus: A Paradigm for Environmental Management

Surbhi Sharma¹, Soumen Basu^{1*}, Nagaraj P. Shetti^{2 *}, Pavan Walvekar³, Tejraj M.

Aminabhavi^{3*}

¹School of Chemistry and Biochemistry, Thapar Institute of Engineering and Technology, Patiala-147004, India.

²Center for Electrochemical Science and Materials, Department of Chemistry, K.L.E. Institute of Technology, Hubballi-580 030, Karnataka, India.

³Department of Pharmaceutics, SET's College of Pharmacy, Dharwad 580 002, Karnataka, India.

Abstract

The explosion of global human population, speedy industrialization and urbanization have posed several significant challenges to modern society. Firstly, the rising energy-demand is a serious bottle-neck as non-renewable fossil fuels fail to meet the demands caused by the hike in fuel prices. The realistic estimations state an increase in the energy consumption by 40-50% until 2040. The burning of fossil fuels adds to greenhouse-gases emission resulting in phenomena such as global warming and climate change. Mounting waste-generation is another grievous repercussion of the expanding population growth. It is estimated that about 9.5 billion tons of municipal solid waste per year is projected to be created by 2050. Therefore, waste-to-energy nexus based on the 5R (Reduce, Reuse, Recycle, Refuse and Recover) principle seem to have the paramount importance in solving these Gordian knots. The waste-to-energy approaches have been broadly classified into thermal and biochemical routes. Different wastes can be utilized for creating energy; household waste, agricultural waste, sources from slaughterhouses and effluents

from the sugar mills, dairy, textile and brewery industries. Agricultural waste is produced in a surplus quantities and its utilization for generating energy can solve the problem of crop residue burning. The thermal route includes pyrolysis, gasification and incineration at very high temperatures to obtain char, oil or syngas, but the biochemical route employs the microorganisms for converting waste to energy. The waste requires pretreatment (physical, physicochemical, chemical and biological) prior to the biochemical process to achieve superior yields. The pretreatment of lignocellulosic biomass is crucial to overcome its recalcitrance towards hydrolysis. On the other hand, anaerobic digestion includes the decomposition of waste in the absence of oxygen to biogas, mostly comprising of methane, carbon dioxide and nitrogen. The chief steps in anaerobic digestion include hydrolysis, acidogenesis and methanogenesis. Biogas has been used for heating, cooking, electricity, steam generation and as vehicle fuel. Biodegradable waste is quite apposite to aerobic digestion comprising of MSW (municipal solid waste), agricultural discard, fruit and vegetable wastes. Another widely explored biochemical waste-to-energy technique is fermentation to bioethanol. The feedstock rich in sugar molecules such as sugarcane, agricultural discard and algal biomass is appropriate for bioethanol production. Steps in this process encompass pretreatment, enzymatic hydrolysis, fermentation and ultimately distillation of the fermented broth procuring fuel-grade bioethanol. Hydrogen production by the fermentation has set another important approach in the waste-to-energy nexus, since it is a clean source of energy having high energy-content (~122 kJ/g). Hydrogen can be acquired by individual dark and photo fermentation of wastes by the anaerobic bacteria and photosynthetic bacteria, respectively. However, amassing of organic acids and poor yield are the shortcomings of distinct fermentation processes. Integrating dark and photo fermentation in single or two-stage is an outstanding way out, but more emphasis is required on the economic

viability of these approaches. The waste-to-energy nexus is therefore a paradigm for sustainable development because the linear economy system of “make-use-throw” is replaced with the circular economy system of restoring waste.

Keywords: Waste; Energy; Agricultural; Biochemical; Biogas; Pretreatment.

**Corresponding author:* dr.npshetti@gmail.com (N. P. Shetti); soumen.basu@thapar.edu (Soumen Basu); aminabhavit@gmail.com (T. M. Aminabhavi)

1. Introduction

The global population is continuously growing at an overwhelming speed. The world population is expected to rise from 7.7 billion (as of 2020) to 9.7 billion in 2050 and to a massive figure of 11 billion by the end of the century (Ref). The projection of the rate of population growth by 2050 in various regions of the world is displayed in Fig. 1. Of these, the population of sub-Saharan Africa is estimated to get over to reach two-fold by 2050, while India is predicted to become the most populated country in the world by 2030 (United Nations, Department of Economic and Social Affairs (UNDESA), 2019). Over-population, urbanization and industrialization can be considered the fundamental reasons behind most of the problems encountered by the world. A substantial upsurge in global energy demand and solid-waste generation are two chief issues that we will focus our discussion on in this timely review.

Fig.1. Estimation of the percent population growth rate in various regions by 2050 (United Nations, Department of Economic and Social Affairs (UNDESA), 2019).

Non-renewable traditional fossil fuels such as coal, petroleum and natural gas have been exploited profusely to meet the ongoing energy requirements (Mehta et al., 2019; Mishra et al., 2019c, 2019b). The shortage of energy supply, in turn, may cause a hike in fuel price leading to fiscal concerns. The energy consumption is dependent on the population, which is projected to escalate by 50% by 2035 (UNDESA, 2018). Among the developing countries, India is reported to consume ~9% of the total energy of the world and stands third in the category of highest energy consumers after China (23%) and USA (17%) (Wang et al., 2020), while China is also the world's top-most energy producer (Gielen et al., 2019).

Due to the burning of fossil fuels, our planet is inundated with grievous environmental issues such as acid rain, global warming, ozone layer depletion and climate change. The

unrestrained CO₂ emission has accentuated the global warming and the level is projected to touch 500 ppmv (parts per million volume) by 2050 if the same scenario persists. The focus has, therefore, shifted to alternative sources of sustainable energies to combat these challenges and to reduce the negative impact on the mother earth. Green and renewable energy sources such as hydro, wind, solar, biomass, geothermal and hydrogen are mostly reasonable and environmentally friendly alternatives to meet the sustainable development goals (Mishra et al., 2020, 2018; Sharma et al., 2020).

Escalating the generation of solid waste is a consequence of socio-economic development. Solid wastes are generally hardly-biodegradable and take more time to be transformed into the natural compounds (Pan et al., 2015). Municipal solid waste (MSW) comprises of domestic, commercial or industrial wastes such as organic matter, plastic, metal, glass, textiles, wood, rubber, leather and paper (Samarasiri et al., 2017). Economic conditions and living standards have affected the rate of waste generation in various countries all over the world. The remarkable growth in MSW from 0.5 to 1.7 kg per person indicates the gravity of the situation quite well (Ramayah et al., 2012). In fact, the waste volumes across the globe are mounting more rapid than the speed of suburbanization. The overall annual MSW generation levels at present are nearly 1.3 billion tons which is almost 1.2 kg/person/day. By the end of 2025, this level is anticipated to reach 2.2 billion tons i.e., 1.42 kg/capita/day (Negi et al., 2019). Around 9.5 billion tons MSW per year is estimated to be generated by 2050 (Chen, 2016). The growth rate of MSW generation in a developing countries like India is 1.3% per year pointing towards the enlargement in socio-economic standards of the general public. In India, approximately 90 million tons of MSW is generated per year presently (Ghosh et al., 2019), while per capita waste generation is estimated to be 0.37 kg/day (Thapa et al., 2019). In addition,

roughly 94% of waste out of which around 70-75% is organic matter that is normally thrown out of perilously in the unrestrained open dumps with no segregation (Ghosh et al., 2019; Ramachandra et al., 2018; Shah and Shah, 2019). World's most populous country, viz., China produced 234 million tons of MSW in 2016 (J. Liu et al., 2019). The rate of MSW generation in the UK, USA, South Africa, Ghana and Nigeria is accounted to be around 1.34, 2.13, 2.00, 0.09 and 0.58 kg/capita/day, respectively (Ibikunle et al., 2019).

The percent composition of MSW basically depends on the economic growth, culture, income-status climate and is variable in different regions accordingly. In low- and middle-income nations, approximately 40% to 85% of organic matter, while in high-income and affluent countries, MSW primarily contains inorganic materials (Negi et al., 2019). Food waste (FW) includes resources consumed by the people that are afterwards discharged, lost, contaminated or degraded. FW in the developing nations is generally correlated with the lifestyle, earnings, education, awareness, ethical values and infrastructures apart from the governmental policies to regulate such activities (Loizia et al., 2019). Apparently, MSW comprises of approximately 25-60% of the food waste (Nghiem et al., 2017). Around 1.3 billion tons of food waste is generated annually, which is roughly one-third of the overall food produced for the humans (Yaixin Zhang et al., 2019). In around 70 Asian countries, the amount of urban food waste might increase to 416 million tons by about 2025 (Uçkun Kiran et al., 2014). Almost 0.5-0.8 kg per day food is wasted in Malaysia (Kasavan et al., 2019). It is accounted that about 88 million food is wasted in the European Union per year. Around 53% of the food waste comes from the households, while ~12% from the retails and foodservices (Schanes and Stagl, 2019). Such a mounting waste generation at an alarming rate is a bottleneck for the municipalities to appropriately collect, dispose and manage the

solid waste. Further, the agricultural waste is known to be a substantial source for deriving energy. It consists of discard produced in farming fields, animal discard, and effluent from agro-industries. It is reported that over three billion tons of agricultural waste was produced globally while in India over 600 million tons of agricultural residue is produced per year. The crop wastes consists of energy-rich elements that are suitable for energy derivation (Nazimudheen et al., 2020; Yilmaz et al., 2018). The improper waste disposal (domestic/agricultural/industrial) and inefficient management have caused the release of contaminants into the air, water and land all of which are jeopardizing the environment and the mankind (Kamali et al., 2019a; C. V. Reddy et al., 2020a; Sharma and Basu, 2020; Singh, 2019; Singh et al., 2019; Tavangar et al., 2020).

Utilizing the waste for generating energy is therefore an interesting and stimulating approach for waste management besides sustainable development (Klinghoffer and Castaldi, 2013; Srivastava et al., 2020). This would aid to vacate the landfills occupied by the waste to save substantial space (Negi et al., 2019).

Different types of wastes (either solids or liquids) can be used for waste-to-energy conversion such as household wastes, agricultural or lignocellulosic wastes, discard from the slaughterhouses and the effluents from industries such as sugar, dairy and brewery, and pulp and paper mills (Kamali et al., 2019b; Kothari et al., 2010). The 5R's of sustainable development principals are therefore: Reduce, Reuse, Recycle, Recovery, and Reclamation, as demonstrated in Fig. 2. The 5R's have the pivotal role in moving from the quintessential linear model of economy towards a much effective circular model. The linear model is about "make-use-throw" where disproportionate use of energy and excessive waste

generation causes degradation of the ecosystem and loss of resources. On the other hand, circular model is based on the notion of restoration, using renewable sources and eradicating waste by means of better infrastructure and designing the superior products (Michelini et al., 2017) as displayed in Fig. 3. The foundation for circular economy is therefore laid by the “waste-energy” nexus. For better sustainability, waste recycling and energy-generation should be linked in an industrial system. Waste-energy nexus has therefore gathered attention for its ability to tackle several pressing environmental problems in the modern society simultaneously i.e., waste management, energy generation and reducing the environmental pollution (Sharma et al., 2020).

Fig. 2. The 5R principle for sustainable development.

The discussion to transform waste into useful forms of energy has become ubiquitous. In developed nations, utilization of waste for producing energy, heat and fuel is more prominent than the developing nations where collection, transportation and proper

disposal of wastes are still the Gordian knots (Moya et al., 2017). This review discusses the recently published reports on the emerging trends of waste-to-energy nexus circular economy considering the main pillars of sustainability including technical, environmental, social and economic considerations (Kamali, 2020). To this end, The published reports of the ten-year period 2010-2020 are critically evaluated on future developments as well as recommendations in this rapidly growing area are covered and critically discussed.

Fig. 3. The conceptual arrangement of circular economy model.

2. Waste-to-energy conversion techniques

The techniques to convert waste-to-energy can be broadly classified into thermal and biochemical (Fig. 4).

2.1. Thermal route

Thermal methods of waste-treatment involve the decomposition of organic matter at elevated temperatures. The major thermal techniques include pyrolysis, incineration and gasification. Reports on the products obtained by the thermal processing of wastes are summarized in Table 1.

2.1.1. Pyrolysis

Thermal disintegration of solid materials under almost anaerobic conditions occurs at high temperatures ranging from 300 to 1300 °C, which depends on the waste materials being used. However, pyrolysis is the primary phase of incineration and gasification (Song et al., 2018). The pretreatment of wastes is a must prerequisite; the mechanical separation of glass, metals and inert materials is quite essential in this step (Moya et al., 2017). The pyrolysis method is a quite appealing approach because of its tendency to produce the recyclable products i.e., biochar, wax, oil, or biofuels and combustible gases along with some ash residues. The merit of pyrolysis is that less quantities of harmful gases like nitrogen oxides (NO_x), sulphur oxides (SO_2) and dioxin are formed as a result of the inert atmosphere used during pyrolysis. The solid products attained after MSW pyrolysis (the biochar) can be utilized in combined heat and power (CHP) plants, because of high calorific value as well as low proportion of the ash. It can also be used for water treatment and as soil amendment agent because of their porous structures. Additionally, liquid and gaseous products can be subsequently transformed into chemicals and fuels (Kamali et al., 2020; Song et al., 2018). Numerous reports on the pyrolysis of wastes are available such as pyrolysis of plastic waste to obtain liquid fuels (Budsaereechai et al., 2019; Ding et al.,

2019; Yayun Zhang et al., 2019), co-pyrolysis of waste mixtures to obtain liquid and solid products (char) (Alvarez et al., 2019; Bernardo et al., 2012; Dai et al., 2017; Jia et al., 2018), pyrolysis of food waste (Chen et al., 2016; Elkhailifa et al., 2019; Giwa et al., 2018; Grycová et al., 2016; Liu et al., 2014), and syngas production (Hu et al., 2017; Zhang et al., 2015).

Fig.4. Approaches used for the conversion of waste-to-energy.

2.1.2. Gasification

It is the partial oxidation of carbonaceous solid waste at high temperatures into H_2 , CH_4 , CO , CO_2 , H_2O , some other hydrocarbons of lower molecular weights using the catalyst (Watson et al., 2018). These products are accompanied by several pollutants such as tiny biochar particles, ash and tars (Belgiorno et al., 2003). The syngas is obtained thereafter, which is high on calorific value and can be utilized in different process equipment (Arena,

2012). Besides, gasification is a quite compliant method to use several sorts of materials and the method conditions can be varied for the selective isolation of gaseous products (Watson et al., 2018). Gasification is categorized as direct and indirect. In case of direct gasification, an oxidizing agent is employed for the partial oxidation of waste material and the energy to maintain high temperature as supplied by the oxidation reaction. On the other hand, indirect gasification involves no oxidizing agent, but instead an external energy source is used. For an efficacious gasification to proceed, a homogeneous carbon-based feedstock is essential. Many materials are not suitable for gasification and may require pre-treatment. Waste materials like plastic waste, paper mills waste, forestry and agricultural discard are appropriate materials (Belgiorno et al., 2003). Substrates having a higher quantity of nitrogen and sulphur cause the release of NO_x/SO_x and catalyst poisoning. Sulphur is released as H_2S , whereas nitrogen in the course of gasification is mostly in the form of organic complexes, which then reacts with hydrogen to form NH_3 and even HCN gases. Sewage sludge and animal waste products consist of significant proportions of sulfur, thereby catalyst poisoning as well as gas treating systems are vital to be deliberated. Substrates with greater amounts of carbon as well as oxygen (agricultural discard and MSW) release higher quantities of CO_2 and CO . At temperatures below 600°C , CH_4 can be produced and its content decreases when the temperature rises because of methane reforming and decomposition reactions (Watson et al., 2018). Various reports on the gasification process are present such as gasification of MSW (Belgiorno et al., 2003; Lin et al., 2020; Wei et al., 2017), food waste (Nanda et al., 2016), sewage sludge (Gai et al., 2016), plastic waste (Burra and Gupta, 2018), agricultural waste (Li et al., 2017), etc.

2.1.3. Incineration

The combustion of organic substances in waste materials can be done at high temperatures between 750 and 1000 °C. The incineration technique for waste management is useful for generating heat, electricity and steam from MSW at a reasonable price. Nearly, 70% of the total waste mass and 90% of the total waste volume can be mitigated on the basis of composition as well as the degree of recovery of some materials. Nonetheless, incineration causes the emission of detrimental air contaminants such as SO_x, CO_x, NO_x and polyaromatic hydrocarbons (Tozlu et al., 2016). Dong et al. suggested that incineration of MSW is much better compared to all the other techniques because of its efficient flue gas cleaning system (Dong et al., 2018). In food waste, ammonia acts as a reducing agent to restrain the release of NO_x at high-temperature area of the primary and secondary incineration (Chung et al., 2016). Several reports on incineration of solid waste are available in the published literature (Abuşoğlu et al., 2017; Gu et al., 2019; Somorin et al., 2017; Zhu et al., 2019).

Table 1. Transformation of various wastes to useful products by the thermal route.

Wastes	Technique	Catalyst	Temperature	Product obtained	Reference
Plastic	Microwave-assisted pyrolysis	NiO	Pyrolysis (500 °C), Catalysis (450 °C)	oil	(Ding et al., 2019)
Pinewood sawdust and rubber from truck tires	Co-pyrolysis	N/A	500 °C	oil	(Alvarez et al., 2019)
Pinewood sawdust	Pyrolysis	Fe/biochar	Pyrolysis (800 °C), catalysis (800 °C)	syngas	(Hu et al., 2017)
MSW	Steam/O ₂ gasification	N/A	1000 °C	H ₂ -rich syngas	(Lin et al., 2020)
Orange peel	Supercritical water gasification	K ₂ CO ₃	600°C	H ₂ -rich syngas	(Nanda et al., 2016)
Coconut shell	Supercritical	K ₂ CO ₃	600°C	H ₂ -rich	(Nanda

	water gasification			syngas	et al., 2016)
Sewage sludge	Steam gasification	Alkali- catalysts	700 -1000°C	H ₂ -rich syngas	(Gai et al., 2016)
Sewage sludge	Incineration	N/A	830 - 900°C	Electricity	(Abuşoğlu et al., 2017)

N/A: Not available

2.2. Biochemical route

Biochemical method for the conversion of waste-to-energy is quite a convenient approach to obtain bioenergy in the form of biogas, bioethanol and bio-hydrogen. Suitable feedstock for these processes is broadly waste from kitchen, household, agriculture, industries, vegetable markets, etc. Pretreatment of biomass before its conversion to bioenergy is an essential step for improving the yields. Biomass is an organic substrate that can store sunlight as the energy through photosynthesis (Kamani et al., 2019). The pretreatment methods have been discussed prior to the comprehensive analysis of biogas, bioethanol and bio-hydrogen production.

2.2.1. Pre-treatment of biomass

The pretreatment of lignocellulosic biomass is vital for overcoming its recalcitrance towards hydrolysis. Lignocellulose is a poly-carbohydrate complex consisting of lignin, cellulose, and hemi-cellulose. Pre-treatment breaks the lignocellulosic matrix, reduces the crystallinity of cellulose, and enhances the fraction of the amorphous cellulose (Kamani et al., 2019). Various pre-treatment methods have been reported in the literature (Oladi and Aita, 2017; Prasad et al., 2020; Shah et al., 2019; Sharma et al., 2019). The type of waste

material or feedstock is the basis for selecting the suitable pre-treatment approach because of different physical and chemical features (Achinas and Euverink, 2016).

(a) Physical methods

Size-reduction, pyrolysis, pulsed-electric field, microwave irradiation and non-thermal irradiation are among the main physical methods for pre-treatment of biomass. Size of the biomass can be reduced through processes such as ball milling or grinding, which enhances the surface area and decreases the size. The breaking down of lignocellulosic biomass into smaller particles may affect the crystallinity of cellulose. However, this technique is costly, arduous, time-consuming and energy-exhaustive (Veluchamy et al., 2019). Mechanical extrusion is another technique, which includes shearing and mixing of the biomass at high temperatures leading to physical and chemical distortion of the biomass. Pyrolysis includes heating the biomass at high temperatures of 500-800 °C in an almost anaerobic condition, which renders the decomposition of cellulose (Wang et al., 2016). Pulsed-electric field is another method, which exposes the biomass to a high voltage condition (~ 5.0 - 20.0 kV/cm) for very small intervals (10^{-9} - 10^{-3} seconds) leading to breaking of the cellulose into sugars. Microwave irradiation causes internal heating of the feedstock by attacking polar bonds via vibration. This makes lignocellulosic substrate splintered and viable for enzymatic attack (Bichot et al., 2020).

(b) Physicochemical methods

This category includes steam explosion, ammonia treatment and wet oxidation methods. In steam explosion, hydrothermal and sudden pressure change are employed together, which bursts the fiber walls. This treatment is influenced by the temperature,

size, residence time and moisture (Lizasoain et al., 2017; Padilla-Rascón et al., 2020). Pretreatment processes using liquid ammonia have also been explored immensely (Bals et al., 2011; Oladi and Aita, 2017; Uppugundla et al., 2014; Wang et al., 2019). Ammonia fibre explosion (AFEX) is employed at ambient conditions and it is influenced by the instantaneous high pressure exploding the structure. This method is suitable for the feedstock comprising of fibres such as sugarcane bagasse. Ammonia recycle percolation (ARP) is employed at high temperature and recoverable ammonia flows through the reactor. ARP removes lignin with no traces of sodium and sulphur (Kim et al., 2006). Wet oxidation is another technique that treats biomass in air/oxygen with water or hydrogen peroxide at high temperatures (Ref). The hemicellulose is broken down into monomers, lignin is removed and cellulose crystallinity is reduced. However, this process is unachievable at large industrial scales because of the involvement of capital costs (Banerjee et al., 2009).

(c) Chemical methods

These methods employ acid or base for the disruption of hemicellulose and lignin. Dilute acids such as sulphuric acid, nitric acid, oxalic acid, peracetic acid and maleic acid; mild alkali like NaOH, KOH, $\text{Ca}(\text{OH})_2$ and NH_4OH have been widely used in this context (Gu et al., 2015; Kumar et al., 2019; Sharma et al., 2013; Yang et al., 2012). Acid treatment breaks glycosidic linkage of the polysaccharide. Base degrades the side chains of esters and glycosides subsequently causing modification of the lignin structure. It also solubilizes hemicellulose and reduces the crystallinity of cellulose. This method is feasible at the industrial scale since chemicals can be stored for long periods in addition to being

comparatively economical. However, the need for substantial washing to remove acid or salt contents before proceeding further is quite a tedious step (Aditiya et al., 2016; Rastogi and Shrivastava, 2017).

(d) Biological methods

This method employs microorganisms for disintegrating the lignocellulosic materials. Different fungi, bacterial strains have been investigated for the disintegration of lignin and hemicelluloses (Alexandropoulou et al., 2017; Shah et al., 2019; Ushani et al., 2017; Xie et al., 2017). These methods are not energy-exhaustive and operate under mild conditions without requiring any external chemicals. No toxic chemicals are released in the environment when this approach is used. The side products obtained after the biological pretreatment may not impede the subsequent hydrolysis. Although, slow hydrolysis rate of the biological method is its shortcoming, which renders it incapable to be employed at large industrial scale (Sindhu et al., 2016).

2.2.2. Anaerobic digestion for biogas production

Solid waste management via biochemical route is quite an appealing alternative. In anaerobic digestion, organic matter is decomposed in the absence of oxygen to produce biogas which mostly comprises of methane, carbon dioxide and nitrogen. Food waste particularly consists of a significant percentage of organic matter, which makes anaerobic digestion viable. Roughly 0.1 m³ of CH₄ gas is produced per kg of the food waste. The removal of food waste from the landfills can reduce the leak of leachate into the groundwater saving thereby the price of leachate management and decreasing the harmful impact on the environment (Eriksson et al., 2015). It was reported that 2.04 kW h of

electricity could be generated using 1 m³ of biogas obtained via anaerobic digestion (35% efficacy), which is equivalent to 21 MJ of energy (Murphy et al., 2004). Biogas is employed for heating, cooking, electricity, steam generation and as vehicle fuels. The feedstock for aerobic digestion comprises of MSW, agricultural discard, fruit and vegetable waste (Ullah Khan et al., 2017). According to Molino et al., this process usually occurs in three steps (Molino et al., 2013). In the first step, organic substrate is broken down by bacteria and transformed into simpler units like amino acids, monosaccharides and fatty acids. The second step encompasses acidogenesis, which is the translation of broken material to organic acids (volatile fatty acids) and other simple products like H₂ and CO₂. The third and final step is where methanogens transform organic acids to CH₄ gas as shown in Fig. 5.

Sufficient knowledge and comprehension of microbes are essential for inoculation of the specific microorganism to obtain superior results (Ghosh et al., 2020). The digestants procured as by-products are rich in nutrients and can be employed as fertilizers. Parameters such as pH, temperature, reactor-type, type of co-substrates, and microbes, etc., influence the productivity of anaerobic digestion and their optimization is thereby imperative. The chief modes of process are batch, continuous one-stage and two-stage processes with various methanogens. Furthermore, co-digestion of waste permits complete capture of CH₄ to eventually utilize it constructively. This also helps to balance the C/N ratio for optimal methane and biogas yield. During this process, chemical oxygen demand is transported into energy-rich CH₄. Nitrogen is transformed into ammonium in the aqueous phase, which could be eliminated by nitrification/denitrification processes or deammonification (Nghiem et al., 2017). But if free NH₃ (as a result of degradation of protein components rich in N₂) is present in high concentration, then it can be toxic to the

activity of methanogenic microbes. The co-digestion of food waste with other wastes, which has lower lipid concentration of N_2 and lipid content is suitable to avoid this problem. Also, the concomitant release of gases like NO_x , SO_x , and H_2S during anaerobic digestion pollutes the environment. It was suggested that high salt content in food waste could impede the anaerobic digestion because of the presence of several cations like sodium, potassium, calcium and magnesium (Pham et al., 2015).

Various reports on anaerobic digestion are summarized in Table 2. (Suksong et al., 2020) studied biogas production using and empty fruit bunches via coupled liquid and solid-state anaerobic digestion processes. Palm oil mill effluent acted as a feedstock for liquid anaerobic digester yielding 329.5 mL CH_4 /g of volatile solids. The concoction of discharge from liquid anaerobic digester and empty fruit bunches was utilized as a solid-state anaerobic digester giving a maximum yield of 134.9 mL CH_4 /g of volatile solids attained at optimal conditions. (Ghosh et al., 2020) investigated the biogas production by co-digesting organic part of MSW with sewage sludge at various ratios. The MSW consisted of 65% of organic waste, ~25 % of paper waste, plastic, metal, textile and 10% inert materials. The total yield obtained was 586.2 mL biogas/g of volatile solid (VS) with a maximum CH_4 concentration of 69.5% at an optimal ratio of 40:60 (w/w). The mono-digested sample of organic fraction of MSW manifested the biogas as well as CH_4 yield of 220.5 mL/gVS and 24.03 mL/gVS, respectively. The co-digestion exhibited a remarkable increase of 2.66-times in biogas production and 15-times in CH_4 yield, respectively compared to mono-digested MSW.

Shahbaz et al., (2019) utilized MSW and FW for biogas production by co-digestion. The co-digestion at mesophilic conditions helps to maintain optimal C/N ratio. About 827 mL biogas /g VS and 474.44 mL CH₄/g VS at C/N ratio of 20. Panigrahi et al., (2020) examined anaerobic digestion of food waste and yard waste at varying food/microorganism ratios. The yard waste was given thermal pretreatment by the microwave to get rid of recalcitrance. The maximum CH₄ yield procured was 431 mL/g VS_{added} at a food/microorganism ratio of 1.5. Liu et al., (2020) investigated biogas and methane production by sewage sludge, raw, thermally pretreated and pretreated alkaline-thermal. The anaerobic digestion was carried out in continuous stirred tank reactors. The effect of hydraulic retention time (HRT) was investigated. At HRT of 25 days, the alkaline-thermally pre-treated sludge produced the highest CH₄ and biogas yields of 234.9 ± 13.0 mL/g and 321.9 ± 10.3 mL/g of volatile solids. The CH₄ production enhanced when HRT decreased from 25 to 15 days.

Table 2. Biogas production by various substrates via anaerobic digestion.

Feedstock	Digester	Methane yield (mL/g VS)	Biogas yield (mL/g VS)	Reference
Palm oil mill effluent	Liquid anaerobic digester	329.5	N/A	(Suksong et al., 2020)
Mixture of effluent from liquid anaerobic digester + empty fruit bunches	Solid-state anaerobic digester	60.9	N/A	(Suksong et al., 2020)
Co-digestion of OFMSW and sewage sludge	Batch anaerobic digester	377	586.2	(Ghosh et al., 2020)
Mono-digestion of OFMSW	Batch anaerobic digester	24.03	220.5	(Ghosh et al., 2020)
Co-digestion of MSW and FW	Batch anaerobic digester	474.4	827	(Shahbaz et al., 2019)
Co-digestion of food	Solid-state	431	N/A	(Panigrahi

waste and yard waste	anaerobic digester			et al., 2020)
Raw sewage sludge	CSTR	98.9 ± 7.1	147.9 ± 6.1	(Liu et al., 2020)
Thermally pretreated sludge	CSTR	192.6 ± 13.7	275.8 ± 12.3	(Liu et al., 2020)
Alkaline-thermally pretreated sludge	CSTR	234.9 ± 13.0	321.9 ± 10.3	(Liu et al., 2020)

CSTR: Continuous stirred tank reactors; VS: volatile solids; N/A: Not available

Fig. 5. Various steps involved in anaerobic digestion.

2.2.3. Bioethanol production

The waste/biomass can be converted into ethanol via biochemical pathways. The growing cognizance about bioenergy has led the governments towards stern policy-making and adaptation of these technologies. European Union has set the target to substitute 10% of road transport fuel with biofuel by 2020, while USA has intended to substitute 20% of transport fuel with biofuel by about 2022 (Saladini et al., 2016). Indonesia has set the target of substituting 15% gasoline by ethanol, while twelve bioethanol plants are already being installed in Thailand, which is projected to produce about 2.6 million liters of ethanol per day (Zhou and Thomson, 2009). In the biochemical route of converting waste to bioethanol, appropriate biomass for bioethanol is the matter that contains sugar molecules,

edible biomass such as sugarcane, vegetable oil, corn, lignocellulosic biomass comprising of MSW, agricultural discard, rice straw, switchgrass, and forestry waste, as well as algal biomass. Appropriate pretreatment of the feedstock is necessary to be carried out first. Subsequently, enzymatic hydrolysis of the sugars and then fermentation into ethanol can be achieved. In the final stage, distillation of the fermented broth procures fuel-grade bioethanol (Gavahian et al., 2019), and the steps involved in bioethanol production are displayed in Fig. 6.

Saccharification is the primary step where enzymatic hydrolysis of the feedstock occurs providing the fermentable sugar solution. The glycosidic linkages get broken during hydrolysis to release sugars such as glucose, arabinose, mannose, galactose, and xylose as well as the metabolic activity of the fermentation agent such as yeast or bacteria. *Saccharomyces cerevisiae* (yeast) and *Zymomonasmobilis* (bacteria) consume hexose-sugars. Fermentation of pentose sugar has been reported to be performed by using the microorganisms such as *Candida shehatae*, *Pichia stipitis*, and *Pachysolen tannophilus* (Kamani et al., 2019). Third and the final step is the distillation or dehydration of fermented broth to recover ethanol. The traditional distillation has a drawback of giving ethanol with a poor energy efficacy due to the formation of azeotrope with water. This step is highly energy-intensive and the cost of bioethanol production is chiefly affected by this step. In this sense, alternative techniques for distillation on the basis of equipment configuration and physicochemical properties of the mixture of ethanol and water have been sought by the researchers (Gavahian et al., 2019). Many methods were investigated to combat this challenge including heat-integrated distillation (Grisales Díaz and Olivar Tost, 2016), feed-splitting distillation (Tavan and Shahhosseini, 2016), ohmic-assisted

distillation (Gavahian et al., 2016) and membrane-based vapor stripping (A. Khalid et al., 2019).

In order to improve the efficacy of bioethanol production by lignocellulosic biomass, integration of saccharification and fermentation has been suggested (Jang et al., 2012; Kamei et al., 2012; Luiza Astolfi et al., 2020). In simultaneous saccharification and fermentation (SSF), a single reactor is employed for saccharification of biomass and instantaneous fermentation of sugar. The merit of this method is that there is no amassing of inhibitory sugars as they instantly get transformed into ethanol. The other benefits of SSF are the need to low cost equipment, easy operability and less susceptibility to contamination. But, the drawbacks of this technique are optimization of the process parameters. Further, simultaneous saccharification and co-fermentation (SSCF) is another method which is a concoction of microbial incorporation of sugars released previously during the pre-treatment step and hydrolytic processes of lignocellulosic feedstock. SSCF helps to reduce the inhibition of saccharification caused by glucose and xylose and increase bioethanol. Less operation time, cost-effectiveness, minimal contamination-risk, etc., are some of the benefits of SSCF (L. Liu et al., 2019).

Table 3 reports on the production of bioethanol by various substrates. Gumienna et al., (2014) produced bioethanol by utilizing sugar beet pulp, concentrated raw and thick sugar beet juice. Sterilization pretreatment of the feedstock was also done. Fermentation by *Saccharomyces cerevisiae* was carried out for 72 h at 30 °C for the stationary batch culture process. Sugar beet pulp, concentrated raw beet juice, and thick sugar beet juice offered 87.7%, 94.2% and 92.6% ethanol, respectively. (Narra et al., 2015) utilized the lignocellulosic biomass for ethanol production pretreated by acid treatment, as well as by

simultaneous saccharification and fermentation via the yeast strain *Kluyveromyces* sp. under sterile conditions. The highest yield of ethanol obtained from rice straw, wheat straw and sugarcane bagasse were 23.23, 18.29 and 17.91 g/L, respectively, under the optimum conditions achieved (60 h; 10% solid loading; enzyme loading~9 FPU/ g substrate). Neves et al., (2016) utilized native and ethanol-extracted sugarcane bagasse as a raw material for producing ethanol by fermentation via *Saccharomyces cerevisiae*. Steam explosion pre-treatment was carried out under auto-hydrolysis and dilute acid hydrolysis (H_3PO_4 + H_2SO_4) conditions and the former was found to be the best method. Separate hydrolysis and fermentation processes yielded ethanol (25 g/L) in greater amounts compared to SSF (18 g/L) and pre-hydrolysis followed by SSF (pSSF) (16 g/L). Nonetheless, pSSF procured superlative total ethanol productivity of 0.58 g/ L/ h. Sivarathnakumar et al., (2019) employed pre-treated woody stem *Prosopis juliflora* for producing ethanol. Here, *Kluyveromyces marxianus* was employed for separating the hydrolysis and fermentation steps. The maximum yield of bioethanol of 21.45 g/L was obtained at 41 °C and pH of 4.9 at the substrate and inoculum concentrations of 5% (w/v) and 3% (v/v), respectively. Naresh Kumar et al., (2020) utilized deoiled algal biomass residue (dominated by *Chlorella* sp. and *Scenedesmus* sp.) for producing bioethanol, where the feedstock was pretreated by several routes. Physicochemical pretreatment included acid treatment with subsequent autoclave treatment. Enzymatic pre-treatment encompassed loading by the commercial-grade α -amylase and cellulase. Hybrid pre-treatment involved the addition of 20% of deoiled algal biomass to water and autoclaving in acid conditions. Fermentation of hybrid pre-treated feedstock by *Saccharomyces cerevisiae* resulted in a maximum bioethanol yield of 0.145 ± 0.008 g/g substrate at pH 5.5.

Alfonsín et al., (2019) produced bioethanol from an industrial algae waste *Eucheuma Denticulatum Spinosum*. The feedstock was firstly pre-treated and subsequently hydrolyzed in acidic conditions. Optimal H₂SO₄ concentration and acid/dried algae ratio were discovered to be 9% wt and 7, respectively. The fermentation by *Saccharomyces cerevisiae* gave a maximum bioethanol yield of 11.6 g/g of algae. In another study Jugwanth et al., (2020), sugarcane bagasse was utilized for bioethanol production using *Saccharomyces cerevisiae*, wherein the steam-assisted sequential salt-alkali pretreatment was done. The response surface methodology (RSM) was employed in the mentioned study for the optimization of various factors such as temperature, enzyme loading and yeast titre. Around 4.88 g/L of bioethanol was procured at the optimum conditions (yeast titre of 1 time, enzyme loading of 100 U/g and 39 °C temperature).

Table 3 Bioethanol production by various substrates.

Substrate	Pretreatment	Fermentation strain	Overall ethanol yield	Reference
Sugar beet pulp	Sterilization	<i>Saccharomyces cerevisiae</i>	87.7%	(Gumienna et al., 2014)
Concentrated raw beet juice	Sterilization	<i>Saccharomyces cerevisiae</i>	94.2%	(Gumienna et al., 2014)
Thick sugar beet juice	Sterilization	<i>Saccharomyces cerevisiae</i>	92.6%	(Gumienna et al., 2014)
Rice straw	Acid treatment	<i>Kluyveromyces</i> sp.	23.23 g/L	(Narra et al., 2015)
Wheat straw	Acid treatment	<i>Kluyveromyces</i> sp.	18.29 g/L	(Narra et al., 2015)
Sugarcane bagasse	Acid treatment	<i>Kluyveromyces</i> sp.	17.91 g/L	(Narra et al., 2015)
Sugarcane bagasse	Steam explosion	<i>Saccharomyces cerevisiae</i>	25 g/L	(Neves et al., 2016)
Woody stem <i>Prosopis juliflor</i>	Auto hydrolysis +	<i>Kluyveromyces marxianus</i>	21.45 g/L	(Sivarathnakumar et al., 2019)

<i>a</i>	acid treatment + ultrasonication			
Deoiled algal biomass	Autoclaving in acid conditions	<i>Saccharomyces cerevisiae</i>	0.145 ± 0.008 g/g	(Naresh Kumar et al., 2020)
Industrial algae waste	N/A	<i>Saccharomyces cerevisiae</i>	11.6 g/galga e	(Alfonsín et al., 2019)
Sugarcane bagasse	Steam-assisted sequential salt-alkali pretreatment	<i>Saccharomyces cerevisiae</i>	4.88 g/L	(Jugwanth et al., 2020)

Fig.6. Steps involved in bioethanol production from the waste materials.

2.2.4. Bio-hydrogen production

Hydrogen is a clean source of energy in the secondary form producing water as the primary product post-combustion. The energy content of hydrogen is quite high ~122 kJ/g and the energy yield in H₂ fuel is 2.75-times greater than hydrocarbon fuels. Hydrogen fuel cell vehicles have thrice the efficacy compared to gasoline engines (Sharma et al., 2020). Hydrogen as a fuel source finds wide applications in electricity generation, transport systems (Wadjeam et al., 2019), hydrogenation of fats and oils (Konkol et al., 2016), desulfurization of gasoline (Abbasov et al., 2017), steel processing (Allen and Nelson,

2019), etc. Nonetheless, hydrogen production is mainly from the fossil fuels. The conventional methods followed for hydrogen production are steam reforming of hydrocarbons (Wu et al., 2015), water electrolysis (Gaoqiang Yang et al., 2019), gasification (Yuksel et al., 2019), non-catalytic partial oxidation (Guiberti et al., 2016), etc. However, the conventional route is costly, energy-intensive, inefficient and non-friendly with the environment (Sharma et al., 2020). Photocatalysis has also been explored extensively for this purpose (Mishra et al., 2019a, 2019b; Rao et al., 2019; C. V. Reddy et al., 2020b; K. R. Reddy et al., 2019; N. L. Reddy et al., 2019; N. R. Reddy et al., 2020). Biological approach for the hydrogen production utilizes agricultural waste, animal manure and industrial wastes (wastewater from dairy, brewery and plastic industry) (Sharma et al., 2020). This approach encompasses mainly that of the fermentation process (dark, photo and combined dark-photo fermentation) (Fig. 7). Prior to the fermentation process, suitable pretreatment is vital for better productivity.

(a) Dark fermentation

It is the acidogenic fermentation of substrates enriched with carbohydrates in dark and anoxygenic conditions for producing hydrogen. Several microorganisms have been investigated for dark fermentation such as *Bacillus coagulans* (Kotay and Das, 2007), *Thermoanaerobacterium spp.* (O-Thong et al., 2008), *Clostridium butyricum* (Mishra et al., 2016), *Clostridium thermolacticum* (Collet et al., 2004), etc. Hydrogen production is dependent on the temperature and pH as well as the type of biocatalyst and feedstock employed. However, in this case, H₂ yield is very low as hydrogen consuming bacteria reduce H₂ to CH₄ and organic acids. Only about 33% of COD (chemical oxygen demand) gets

converted to hydrogen and organic acids obtained as the side-products that get accumulated. Nonetheless, the product yield can be upgraded by suppressing methanogenic activity by limiting H₂-consuming bacteria and growing H₂-producing bacteria (Sharma et al., 2020). Nevertheless, pretreating inoculums by an appropriate technique in order to inhibit H₂-consuming bacteria, such as heat treatment (Turhal et al., 2019), dilute acid treatment, aeration (Guang Yang et al., 2019), ultra-sonication, microwave (Kannaiah Goud and Venkata Mohan, 2012), treatment by sodium 2-bromoethanesulfonic acid (Zhuang et al., 2012) and electroporation (Karim et al., 2019) have been practiced. Dark fermentation depends on pH, temperature, hydraulic retention time (HRT) and inoculum source in addition to substrate type (Santiago et al., 2019).

(b) Photo fermentation

This process includes the fermentation of organic matter in the presence of photosynthetic non-sulfur bacteria to give H₂ and CO₂ under the sunlight without oxygen. The grasped light-energy enables photosynthetic bacteria to complete the conversion of the substrate (Elkahlout et al., 2017). Thus, photofermentation exceeds the yield efficacy when compared to the dark fermentation (1 mol of H₂/mol) as substrate conversion in former is brought to completion. Various microorganisms have been explored for photo fermentation such as *Rhodobacter sphaeroides* (Sargsyan et al., 2016), *Rhodobacter sulfidophilus* (Maeda et al., 2003), *Rhodobacter capsulatus* (Elkahlout et al., 2017), *Rhodospirillum rubrum* (Dadak et al., 2016) and *Rhodopseudomonas palustris* (Hitit et al., 2017). The rate of photo-fermentative hydrogen production is dependent on the substrate, light intensity and strain type. Also, wastewaters from different sources diverge in the

clarity and turbidity, which require diverse light intensities. However, highly turbid media may not allow proper penetration and eventually reducing the efficacy of light conversion (Sharma et al., 2020). Photosynthetic bacteria contains hydrogenase as well as nitrogenase enzymes, while the latter has the chief role in hydrogen production (Argun and Kargi, 2011). The activity of nitrogenase is inhibited in the presence of O_2 or NH_3 or when high N/C ratios are used. Therefore, ammonium-limited and non-oxygenic conditions are essential.

(c) Integrated dark and photo-fermentation

Individual fermentation processes (both dark and photo) have a downside that organic acids get accumulated causing poor hydrogen yield, resulting in high costs. Combining dark and photo fermentation in a single or two-stage reactor is beneficial as the effluent of dark fermentation is utilized as the substrate for photo fermentation. In dark fermentation, the highest yield is 4 mol H_2 /mol glucose if only acetic acid is produced as the by-product (Eq. 1). In photo fermentation, acetic acid produces 8 moles of H_2 (Eq. 2). Thus, integrated fermentation whether single-stage or two-stage gives a cumulative theoretical yield of 12 mol H_2 /mol glucose as the by-product formed in dark fermentation is used as the substrate in the integrated process. In a two-stage sequential fermentation, the first step is dark fermentation by anaerobic bacteria generating H_2 and short-chain organic acids such as lactic acid, acetic acid, butyric acid, etc., and the alcohols. In the second stage, photo fermentation by photosynthetic bacteria converts organic acids to H_2 . In the case of single-stage fermentation, co-culture of bacteria is done, which reduces the side products. A single stage process is comparatively simpler and has many benefits over

the two-stage approach. The acidification due to dark fermentation could be adjusted by alkalization during the course of photo-fermentation and thereby, no external pH correction is required. Also, there is no need for an intermediary dilution stage (Hitit et al., 2017; Seifert et al., 2018; Sharma et al., 2020). The available reports on the bio-hydrogen production by dark/photo/integrated fermentation process are summarized in Table 4. The general equation of the dark fermentation and photo fermentation are presented in Eq. 1, and Eq. 2, respectively.

Table 4 Bio-hydrogen production by fermentation.

Substrate	Inoculum source	Fermentation process	Overall H ₂ yield	Reference
Citrus wastewater pretreated by electroporation	Anaerobic sludge	Dark fermentation	2.24 mmol H ₂ /g COD	(Karim et al., 2019)
Cassava starch wastewater and Buffalo dung	None	Dark fermentation	165 ± 25.16mL H ₂ /g COD _{removed}	(Wadjeam et al., 2019)
Sequential dilute acid and enzymatic hydrolysis pretreated oil palm empty fruit bunch	Anaerobic sludge	Dark fermentation	282.17 mL H ₂ /g total sugar	(Gonzales et al., 2019)
Waste from chewing gum production	Mixed bacterial culture and <i>Rhodobacter sphaeroides</i>	Sequential dark and photo fermentation	6.7 L H ₂ /L non-diluted effluent	(Seifert et al., 2018)

	O.U.001			
Rice straw hydrolysate	<i>Bacillus cereus</i> (KR809374) and <i>Rhodobacter sphaeroides</i>	Sequential dark and photo fermentation	1.82 mol H ₂ /mol glucose	(Dinesh et al., 2019)
Rice husk hydrolysate	<i>Bacillus cereus</i> (KR809374) and <i>Rhodobacter sphaeroides</i>	Sequential dark and photo fermentation	1.73 mol H ₂ /mol glucose	(Dinesh et al., 2019)
Paperboard mill wastewater	Anaerobic sludge and Purple non-sulfur bacteria	Sequential dark and photo fermentation	788.6 ± 238.4 mL H ₂ /g COD	(Elsharkawy et al., 2020)
Potato starch, Glucose	<i>Clostridium butyricum</i> and <i>Rhodopseudomonas palustris</i>	Single stage dark and photo fermentation	6.4 ± 1.3 mol H ₂ /mol glucose	(Hitit et al., 2017)
Corn starch	<i>Clostridium acetobutylicum</i> and <i>Rhodobacter sphaeroides</i>	Single stage dark and photo fermentation	2.62 mol H ₂ /mol hexose	(Zagrodnik and Łaniecki, 2017a)
Starch	<i>Clostridium acetobutylicum</i> and <i>Rhodobacter sphaeroides</i>	Single stage dark and photo fermentation	5.11 mol H ₂ /mol hexose	(Zagrodnik and Łaniecki, 2017b)

Fig.7. Hydrogen production by dark/photo fermentation of waste materials.

2.3. Agricultural waste to energy

The contribution of agriculture-sector in the world GDP is ~33% and worldwide employment is 26.81% whereas 38.14% of land is utilized for agriculture purposes (Ref). This implies that agriculture sector has a significant position in the global economy. The agricultural waste includes discard produced in farming fields, animal discard, and effluent from agro-industries (Nazimudheen et al., 2020). The geographical location influences the sort of agricultural by-products. The production of useful products like wheat, rice, sunflower oil, cotton, etc. is the primary objective of most agricultural activities (Yilmaz et al., 2018). The proper disposal of agricultural waste is quite a challenge for the farmers from the perspective of cost. However, improper dumping causes grievous environmental pollution; in fact, imprudent burning of crop residue (especially rice straw) in open field is a critical issue in India. The burning of residues leads to release of air pollutants i.e., particulate matter, greenhouse gases, polyaromatic hydrocarbons, volatile organic compounds, and elemental as well as organic carbon. The emissions because of burning of

crop residue could rise by 45% till 2050 in India. This is a serious hazard for both environment and health for living beings (Bhattacharyya et al., 2020; Ravindra et al., 2019).

The agricultural waste is a significant energy source as it constitutes many energy-rich components. Crop residue (including rice, wheat, corn, etc.) has been comprehensively utilized used for the generation of bioethanol, biogas and bio-hydrogen (Ashoor and Sukumaran, 2020; Corneli et al., 2016; M. J. Khalid et al., 2019; Kotarska et al., 2019; Kumar et al., 2019; Prasad et al., 2020; Shah et al., 2019). The agricultural biomass is first given an appropriate pre-treatment as it is rich in lignin. Ravindra et al., (2019) reported that crop residue could generate 120 TWh of electricity in biomass power plants. Safieddin Ardebili, (2020) observed that, in Iran, 24.3 million tons of crop waste (constituting of wheat, rice, barley, maize, potato, apple, sugar beet, etc.) could yield 6,542 million m³ of biogas besides 2,443 million liters of butanol, and 2,082 million m³ of hydrogen. The over-all potential for power generation in Iran by means of these organic materials in addition to slaughter waste was evaluated to be 62,808×10⁶ kWh/year. Thus, crop residue can be employed to generate bioenergy which concurrently solves the problem of waste management and environmental pollution.

3. Conclusions and future outlook

The escalating waste generation related environmental pollution and upsurge in energy-requirements are the foremost global concerns. The non-renewable traditional fossil fuels are not considered as sustainable sources of energy to fulfill the ongoing energy-demands of the modern society. In addition, burning of any kind of fossil fuels contributes to unrestricted CO₂ emission and eventually climate change. In order to deal with these impediments, the employment of waste materials for producing bioenergy or valuable

products is need of the modern era. This helps in shifting from the linear system, which is based on “make-use-throw” approach to a much more reasonable circular system grounded on the “make-use-recycle-reuse” approach. In any case, the waste-to-energy nexus is founded on the 5R principle i.e., “Reduce, Reuse, Recycle, Recovery and Reclamation”. The waste-to-energy technologies are categorized mainly into thermal and biochemical. The thermal methods of waste-treatment include disintegration of organic materials at high temperatures. The topmost thermal technologies among these are pyrolysis, incineration and gasification. The pyrolysis of waste procures solid char, wax or oil, and combustible gases along with some ash residues. Gasification of waste produces syngas, which has a high calorific value. The incineration of organic matter in waste materials occurs at ~750 up to 1000 °C. The incineration technique is beneficial for generating heat, electricity and steam from MSW at a rational price. Biochemical route includes anaerobic digestion for biogas production, fermentation to obtain bioethanol and dark/photo fermentation to acquire biohydrogen.

The pretreatment of lignocellulosic biomass is essential to combat the recalcitrance towards hydrolysis and eventually obtain excellent output. Chemical, physical, physicochemical and biological methods of pretreatment are most commonly used, and the technique is selected based on the feedstock. Anaerobic digestion includes disintegration of waste without oxygen to produce biogas consisting of methane, carbon dioxide and nitrogen. The main steps in anaerobic digestion include hydrolysis, acidogenesis and methanogenesis. Various parameters such as pH, temperature, reactor-type, type of co-substrates, and microbes, etc., are vital to be optimized for better productivity of anaerobic

digestion. Additionally, co-digestion of different waste materials allows the complete capture of CH₄ and in balancing the C/N ratio.

Biogas has several uses such as heating, cooking, electricity, steam generation and as vehicle fuels. The biodegradable MSW includes agricultural discard, fruit and vegetable waste all of which are most suitable for aerobic digestion. The bioethanol production by biochemical approach occurs via hydrolysis and fermentation of the substrate rich in sugar molecules like lignocellulosic biomass and beet molasses, while algal biomass is appropriate for bioethanol production. After the pretreatment, enzymatic hydrolysis of the substrate is done and subsequent fermentation by *Saccharomyces cerevisiae*, *Zymomonas mobilis*, *Candida shehatae*, *Pichia stipitis*, etc., can be performed. The final step is the distillation of fermented broth to acquire bioethanol, which finds applications in transportation.

Biohydrogen production by dark/ photo/integrated fermentation is another favorable approach. Hydrogen is a clean source of energy, which has a high energy-content (~122 kJ/g) and finds applications in transport, heat and electricity. Dark fermentation is carried out by anaerobic bacteria (*Bacillus coagulans*, *Thermoanaerobacterium spp.*, *Clostridium butyricum*) producing hydrogen and short-chain organic acids. Photo fermentation is carried out by photosynthetic bacteria (*Rhodobacter sphaeroides*, *Rhodobacter capsulatus*, *Rhodospirillum rubrum* and *Rhodopseudomonas palustris*) in the presence of light. The individual processes give poor H₂ yield and coupling dark and photo fermentation in a single co-culture or two-stage sequential system is an excellent way to enhance the efficacy. The cost of pretreatment of biomass, purification of bioenergy,

maintenance of the reactor must be considered. A proper emphasis on making these techniques more economically viable and environment-friendly is essential for reaching the target of sustainable development and a healthy modern society.

Conflict of interest

All the authors declare that there are no conflicts of interest.

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