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Biodegradable and non-biodegradable fraction of municipal solid waste for multifaceted applications through a closed loop integrated refinery platform: Paving a path towards circular economy

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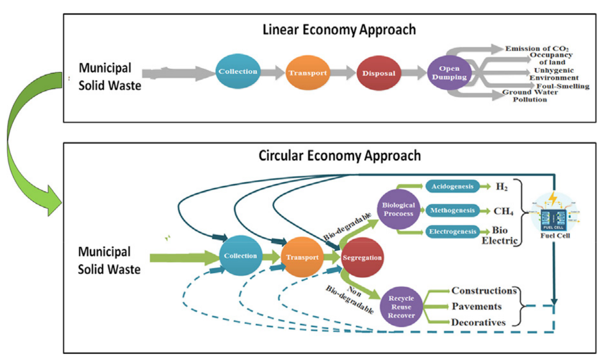
HIGHLIGHTS

- Conversion of municipal solid waste fractions for multifaceted applications
- Integrated closed loop refinery approach paves a path towards circular economy.
- The circular economy minimizes the environmental impact and maximizing the resource recovery from solid waste.
- Application of energy from waste as biofuel in internal combustion engines
- The circular economy's policies stimulates the economy of the country.

GRAPHICAL ABSTRACT



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ABSTRACT

An increase in population, rapid urbanization and industrialization has accelerated the rate of municipal solid waste generation. The current disposal of solid waste is a burgeoning issue and it's in immediate need to shift the existing disposal processes to a sustainable manner. Circular economy (CE) is a conceptual model which is been used for better use of resources and minimization of waste in a closed loop approach which could be appropriate for waste management. In this context, the present review illustrates the effective use of biodegradable and

Abbreviations: AMQP, Advanced Message Queuing Protocol; ARM, Advanced Risc Machines; BMEP, Brake Mean Effective Pressure; BMT, Billion Metric Tonne; BP, Brake Power; BSFC, Brake Specific Fuel Consumption; BT, Brake Torque; BTE, Brake Thermal Efficiency; BW, Bamboo Waste; CE, Circular Economy; CEPL, Circular Economy Promotion Law; CNG, Compressed Natural Gas; COAP, Constrained Application Protocol; CR, Compression Ratio; DDS, Data Distribution Services; DNS, Domain Name System; DSS, Decision Support System; EGT, Exhaust Gas Temperature; EMA, Environmental Management Act; EPC, Electronic Product Code; EXI, Efficient XML interchange; GDP, Gross Domestic Product; GPRS, General Packet Radio Services; GPS, Global Positioning System; GSM, Global System for Mobile communication; HM, Human – Machine; HH, Human – Human; HRR, Heat Release Rate; HSWA, Hazardous & Solid Waste Amendment; IBSG, Internet Business Solution Group; IoT, Internet of Things; ISWMS, Integrated Solid Waste Management System; ITS, Intelligent Transportation System; KG, Kitchen Garbage; LCA, Life Cycle Analysis; LoRA, Long Range; LPG, Liquefied Petroleum Gas; MFC, Microbial Fuel Cell; MON, Motor Octane Number; MQTT, Message Queue Telemetry Transport; MSW, Municipal Solid Waste; NOx, Nitrogen Oxides; OWL, Web Ontology language; PET, Polyethylene Terephthalate; P_{max}, Maximum Pressure; RCRA, Resource Conversion and Recovery Act; RDF, Resource Description Framework; RFID, Radio Frequency Identification Device; RON, Research Octane Number; RVS, Refractory Volatile Solids; SaaS, Software as a Service; SOA, Service Oriented Architecture; SQL, Structured Query Language; SWM, Solid Waste Materials; UMTS, Universal Mobile Telecommunications System; WCDMA, Wideband Code Division Multiple Access; WSA, Waste Substrate Act; WTE, Waste to Energy; XML, Extensible Markup Language; XMPP, Extensible Messaging Presence Protocol.

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non-biodegradable fraction of solid waste in a closed loop integrated refinery platforms for the recovery of bioenergy resources and for the production of value added products. The biodegradable fraction of solid waste could be treated by advanced biological processes with the simultaneous production of bioenergy such as biohydrogen, biomethane, bioelectricity, etc., and other value added products like butanol, ethanol, methanol etc. The scheme illustrates the closed loop approach, the bioenergy generated from the biodegradable fraction of solid waste could be used for the operation of internal combustion engines and the energy could be further used for processing the waste. The non-biodegradable fraction of solid waste could be used for construction and pavement processes. Overall the study emphasizes the paradigm shift of solid waste management concepts from linear economy to a circular economy following the "Zero Waste" concept. The study also explains the circular economy policies practiced for solid waste management that stimulates the economy of the country and identify the pathways to maximize the local resources. In addition the review addresses the advanced information and communication technologies to unfold the issues and challenges faced in the solid waste management. The smart governance of managing waste using the "Internet of Things" (IoT) is one of the great precursors of technological development that could lead innovations in waste management.

1. Introduction

The persistent increase of global population, rapid industrialization and continuous improvement of worldwide welfare has ensued drastic increase of daily consumption of resources and products which results tremendous amount of waste generation. Global population has quadrupled to over 7.7 billion with a 20 - fold growth of Gross Domestic Product (GDP) over the last century and predicted to reach 9.6 billion by 2050 (Biswabandhu and Debabrata, 2019). The consumption patterns of the resources changed radically towards a high demand. For the period of 1900 to 2005, the growth factor for construction industry was 34 and for ores and industrial minerals, the growth factor was 27 (UNEP, 2011). Rapid industrialization and urbanization is creating pressure on the urban bodies to deal with the waste generated. Solid waste is an unavoidable outcome from most of the industrial processes since it encompasses a wide range of materials and hence, it becomes a formidable challenge to manage it in a sustainable manner (Lagerkvist and Dahlén, 2012). In the case of municipal solid waste (MSW) also the generation of waste is huge in quantity which increases the pollution level in the environment and affects the public health (Ferronato et al., 2019). Global MSW generation is estimated as 2.01 billion metric tonnes (BMT) at present and this accounts nearly 5% of global emissions which contribute to about 1.6 BMT of carbon dioxide equivalent. If the same condition prevails, it is predicted to increase 70% waste generation by 2050 and this accounts to increase of 62% global emissions (World Bank Report, 2018). Several million tons of inert wastes such as street sweeping, construction and demolition wastes are the largest waste stream in quantitative terms, which are dumped in landfills. Construction waste as debris is becoming one of the major contributors of negative impact to the environment. Research has been exploring the use of recycling materials such as stone waste (SW), fly ash (FA), palm oil fuel ash (POFA), rubber waste (RW), wood powder (WP), plastic waste (PW), rice husk (RH) and municipal solid waste ash (MSWA) for partial replacement in concrete (Rahal, 2007; Huda and Alam, 2014; Onuaguluchi, 2015; Boyaiah and Rao, 2017; Lu et al., 2019). Recycling of non-biodegradable wastes and it's use in the construction field with different applications not only reduces the landfilling problems but also aid in saving energy and reducing global climate change. Annual solid waste generation in various regions in the world has been shown in Fig. 1.

Generally solid wastes are classified into eight categories based on their origin or sources such as (i) municipal solid wastes (ii) industrial solid wastes (iii) mining solid wastes (iv) fertilizers (v) biocides and pesticides (vi) solid excretory products from human and livestock (vii) e-waste or electronic wastes and (viii) biomedical or hospital wastes. Municipal solid wastes are mainly from domestic commercial, educational and constructional activities, which includes the wastes generated from households, office buildings, marketplaces, shops, cafeterias or restaurants, educational institutions, industrial sites, water and wastewater/sewage facilities, construction and demolition sites, agricultural land and farming activities. Mining solid wastes include dust, slag, toxic chemicals, wastage from ores, etc. which causes vegetation depletion in the circumstances. Fertilizers and pesticides make the land infertile and the soil as solid waste. Poor sanitation resulted in the accumulation of solid wastes from excretory products of humans and livestock. Electronic wastes or e-wastes are the latest, and increased in the last two decades named e-garbage. Biomedical wastes are the most hazardous wastes, which include disinfectants, pathogens and other harmful pharmaceutical and personal care products (Sonali et al., 2018). However, these wastes, which are generally considered to have pollution can also be transformed into resource potential and recover value added prodcuts by effective processing. For instance, at the end of life of a mobile phone, if disposed untreated, it may contaminate the environment. However, while recycling one ton of mobile phones, an average 0.347 kg of gold can be extracted, which is 80% of the material value (Dumlao-Tan and Halog, 2017). Fortunately, most of the solid waste fractions can be converted into resources rather than polluting elements, which could result reduction in resource consumption and also protect the environment (Lagerkvist and Dahlén, 2019).

2. Motivation and objective of the present study

Solid waste disposal is an alarming global issue and the material footprint is increased drastically within a span of 10 years, which spontaneously resulted to augment the volume and complexity of the waste.

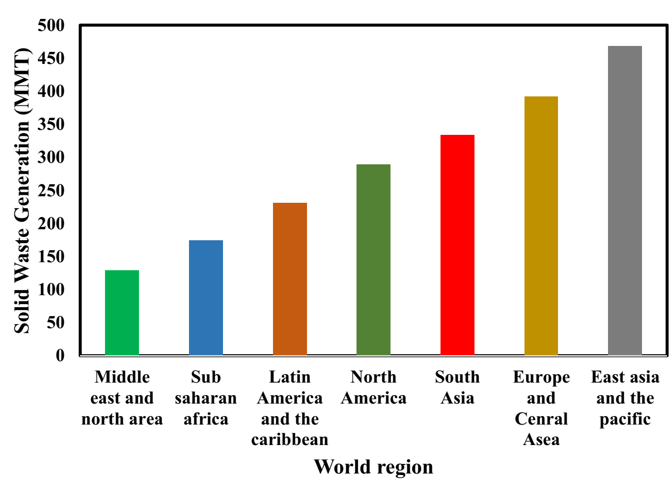

Fig. 1. Annual regional waste generation in million metric tonnes (MMT). Source: World Bank Report (2018).

Many major cities have witnessed waste in the form of heaps of municipal solid waste and the omnipresent stench of rotting garbage, which is posing a serious risk to ecosystems and human health. Hence, it is in dire need to address this issues, which require integrated assessments and holistic approaches. It is also important to build up cities towards sustainable development by transiting the concept of linear economy to circular economy through a closed loop approach which targets to minimize the use of natural resources, energy and waste generation. The circular economy has been studied and explored in terms of economic model as a tool for sustainable development for the long-term economic growth. In literatures, few articles have been initiated to discuss the concept of solid waste management towards a circular economy (Matsakas et al., 2017; Bagheri et al., 2020). Currently, separation of solid waste at sources receives more attention. Separation helps in 3Rs (i.e.) Recover, Recycle and Reject in the waste management systems. Yet, it is important to explore this concept towards zero solid waste management focusing not only on disposal but also on addressing energy production and product development by using both biodegradable and non-biodegradable fractions. As government policies are important to implement these strategies, understanding of circular economy policies practiced in different countries will help to provide a holistic approach to this concept. Moreover, the Internet of Things (IoT) is one of the important areas rapidly gaining a novel paradigm in the modern wireless telecommunications in the areas of Smart Economy, Smart Mobility, Smart Environment, Smart People, Smart Living and Smart Governance. However, the exploration of Smart Environment specific to smart solid waste management is in the nascent stage, hence, it is also one of the potential areas to be reviewed. Production of bioenergy through biological processes has been investigated and a few studies have been carried out in the stages of pilot scale. However, the application to fuel engines is yet to be consolidated.

Keeping the above mentioned gaps, the present study addresses solid waste management in the concepts of circular economy and explains the paradigm shifts of solid waste management from a linear economy model to a circular economy model. Within this context, this review discusses the biological processes used for the treatment of solid waste for the production of bioenergy and its applications in fuel cells. The study also proposes an integrated model in a closed loop approach by using the bioenergy derived from the biological processes for collection, segregation, transportation, etc. In addition, the detailed application of the non-biodegradable fraction of materials through the concept of reuse, recycle and recovery for pavement, construction and automotive applications are discussed. Further, this study also provides the circular economy policies framed for solid waste management and it also discuss the smart handling of SWM using IoT. Overall, the present study explains the zero solid waste pathways from the collection point to treatment followed by application processes, as structured in Fig. 2.

Fig. 2. Structural arrangement of the article.

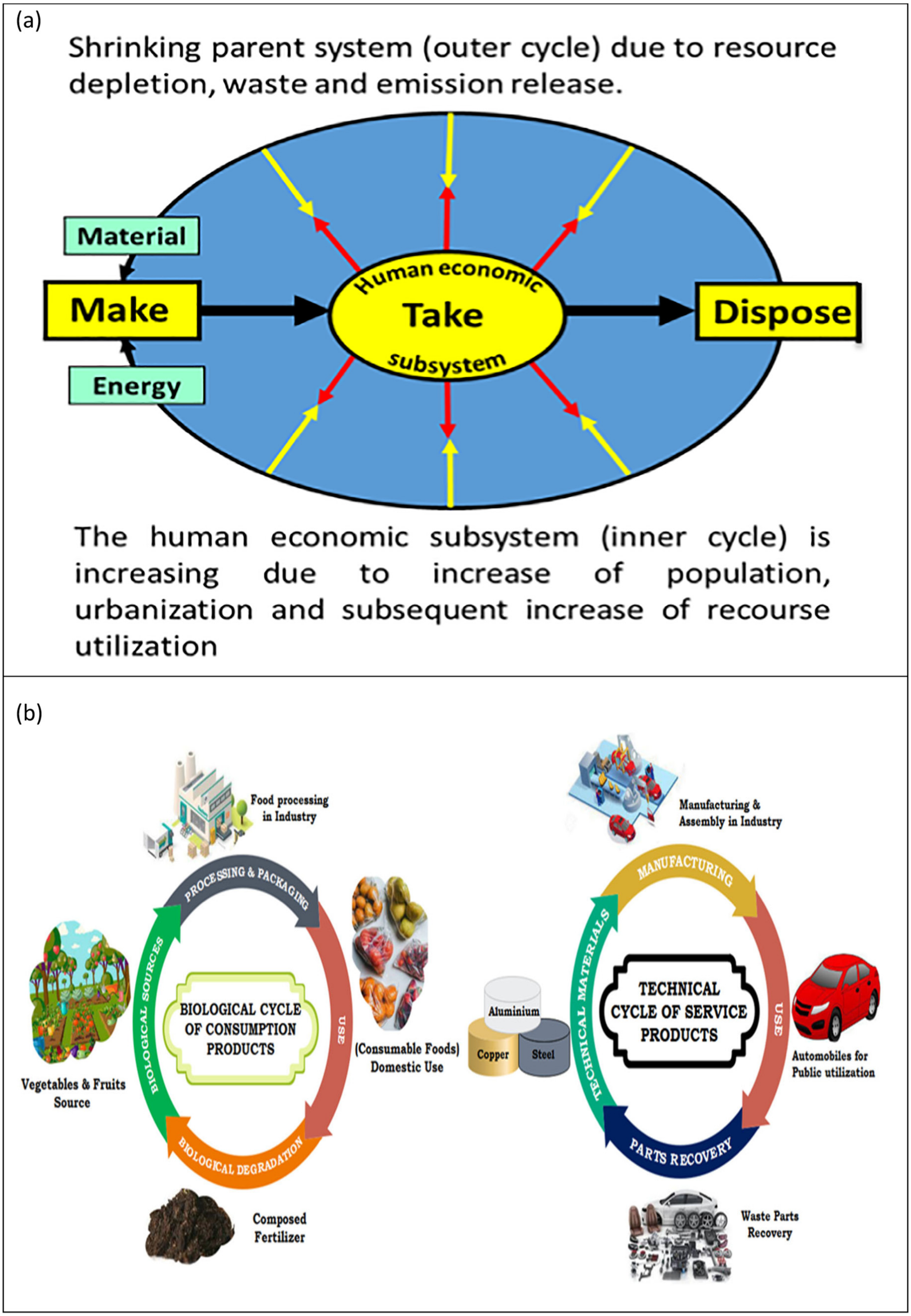

Fig. 3. (a) Linear economy for material and energy flow leads on conflicts between parent system and human economic subsystem. (b) Circular pattern of biodegradable and non-biodegradable natural resources.

3. Solid waste disposal-linear economy model

In the developed and developing countries, the rapid growth of population and urbanization increase the solid waste disposal rate, exponentially (Hoornweg and Bhada-Tata, 2012). Improper management of solid waste not only creates environmental problems but also induces available resources depletion (Cobo et al., 2018). Continuous depletion of the natural resources can't be sustained in the conventional solid waste management model which concentrates mostly on open dumping disposal or inappropriate sanitary landfills (Ferronato et al., 2019). Moreover, the linear (one way) model for material and energy flow makes the global ecosystem shrinking in size and volume (Korhonen et al., 2018). These two contrasting scenarios lead to the head-on collision, which makes the linear system unsustainable with respect to economic, ecological, and social aspects (Fig. 3a). In linear economy the parent ecosystem get shrinks due to the resource depletion, increase in waste generation and release of emissions. In contrary, the human economic subsystem is increasing due to increase in population, urbanization and subsequent increase of resource utilizations. Hence, the balance is lost between the ecosystem and human system in the linear economy model. The detailed stage by stage process of solid waste disposal through the Linear Economy model is discussed in this section.

Collection of solid waste designated as the collection from the point of generation or production to the point of treatment or disposal are performed in several ways (i) house to house collection, (ii) providing community bins in the specific fixed locality and thereby, people will dump the waste therein, collected by the municipality for further disposal or treatment, (iii) outside pickups facilitates the residents to leave their used garbage outside their homes and will be picked up by the municipality, (iv) self-delivered wastes directly dispensed to the dumpsite by the user or generator or outsourcing by the municipality, (v) contracted services either by hiring the business firms who dealt with licensed private operators and the charges will be collected from the customers (Hoornweg and Bhada-Tata, 2012). The collected wastes are transported from the place of generation to the point of disposal, usually done with trucks, tankers and trains. The main factors to be considered during the transportations are (i) volume of the waste (ii) distance to be travelled and (iii) nature of the waste (i.e.) heavily polluted large volume hazardous waste causes more deterioration of environmental or human health in case of any accidents. Numerous methods are available for the disposal of solid wastes, including open burning, incineration, dumping into the sea, sanitary landfills, composting, ploughing in the fields, grinding and discharge into the sea, hog feeding, salvaging and fermentation cum biological digestion, etc. (Magutu and Onsongo, 2011). Traditionally, a solid waste disposal management system is approached by the concept of linear economy model, which follows the step-by-step plan of "take-make-dispose". There is an immediate need to shift towards circular economy.

4. Solid waste disposal-circular economy model

The circular economy plays an important role in providing a conceptual pathway to minimize the environmental impact and maximizing the resource (energy & material) recovery from solid waste. Contrary to conventional '*take, make, dispose*' model of the linear economy, the circular economy emphasizes on restoration and regeneration through '*continuous, positive development cycle that aims to keep products, components, and materials at their highest utility and value at all times*' (Ellen, 2017). Studies in the European nation showed that the implementation of the circular economy may reduce the greenhouse gas emission by 70% as well as increase the workforce opportunity by 4% (Stahel, 2016). The CE concept aims to extend the useful life of materials and promotes recycling to maximize material service per resource input while lowering the environmental impacts and resource use. The CE concept is closely related to the 3R Principles: Reduce, Reuse, and Recycle (Ghisellini et al., 2016; Lieder and Rashid, 2016) and legislation on the CE has been effective in China as of 2008 (National People's Congress, 2008).

The concept of CE is taken from nature mimicking the sustainability concept of recycling the nutrients through cyclic uptake, digest and release. The materials in CE can be defined either as biological materials or technical materials. Biological materials are used to make the so-called consumption products, which get consumed during use, such as food, soap or shampoo or wear off during use, such as clothes or shoes. These are designed to be safe for human health and the environment and as such, they can safely return to the natural biological cycle. Technical materials are used to make service products, such as computer, telephone, washing machine, car etc. As they are non-renewable and often hazardous to human health and the environment, these are kept within the industrial technical cycle, where they will be used to make new products (Fig. 3b). The process of circular economy is applied for both the biological and technical materials along with cascading opportunities.

As per the solid waste management hierarchy illustrated in Fig. 4 with the preferred order for managing waste to minimize the environmental impacts, the most important steps are to reduce, reuse, recycle and compost. The next step is to recover, which refers to the recovery of energy and additional metals from residential garbage. Disposing waste into landfill is the least desirable option. Similarly, the present concept of CE prioritizes product reuse, remanufacturing and refurbishment, which demand less energy and material hence, more economical compared with the conventional down cycling practices. Accordingly, conversion to energy is the second last option than the disposal. In this way, the product value chain and life cycle retain the highest possible value and quality as long as possible and are also energy efficient (Korhonen et al., 2018).

Most of the recent studies on CE focus on (a) specific countries, regions and their existing MSW practice and applicability for CE, (b) specific fraction of MSW and their resource values, for recycling, Waste to Energy (WtE), (c) integration of other fields like Life Cycle Analysis (LCA), environmental degradation, economy, etc. with CE (Matsakas et al., 2017; Bagheri et al., 2020). Ferronato et al. (2019) reviewed the CE prospects for big cities in developing countries and showed that there is a need to include the informal sector in MSW practices. Introduction of pretreatment, particularly, for the biodegradable fraction before open dumping or landfilling. In another study, Malinauskaite et al. (2017) evaluated the existing MSW management practices in selected EU countries and their preparedness in implementing CE . They identified the requirement of change in perception of considering 'waste' as 'nuisance' rather than 'resources' and hence the CE milestone is far from being reached. Van Fan et al. (2019) revealed the importance of cross disciplines on sustainable CE (Van Fan et al., 2019). These may consist of a smart energy concept, monitoring and protect the possibilities of any possible environmental degradation during waste valorization, collection of data through IoT, etc. Cobo et al. (2018) identified the shortcomings in applying the methodological approach to Circular Integrated Solid Waste Management System (CISWMS) and suggested that they can be resolved by expanding the boundaries of linear Integrated Solid Waste Management System (ISWMS). They also pointed out that for CISWMS, the environmental and economic benefits are hence to be visible in the field level and yet further study is required. Summary of some of the recent research works and their inferences on the circular economy aspects are mentioned in Table 1.

5. Treatment of biodegradable fraction of solid waste through biological processes

The biodegradable fraction of SW consists of organic substrates of volatile solids (VS) and ash. In the bioconversion processes, the potential will be observed in biodegradable volatile solids (BVS) fraction largely because of the presence of refractory volatile solids (RVS).

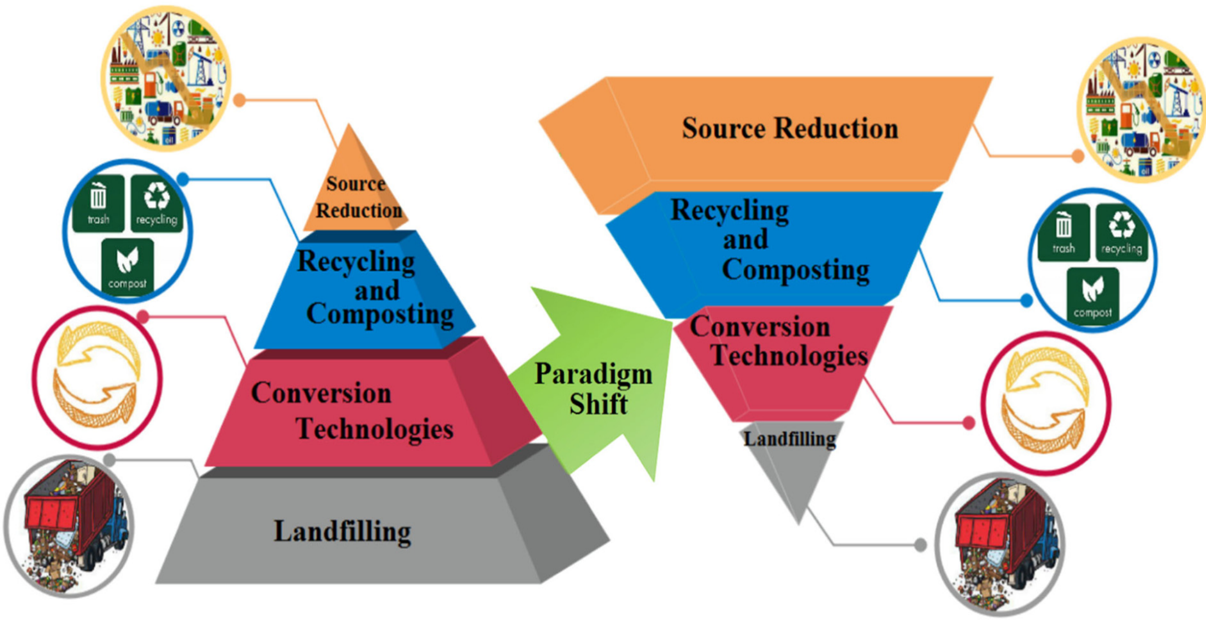

Fig. 4. Representation of paradigm shift in hierarchy of solid waste management strategies.

Generally, the organic fraction of solid waste is nearly 50–60% and has a higher moisture content and is considered to be an effective feedstock for the biological processes (Kayhanian, 1995).

In the 1990s, commercial and pilot scale degradation of organic wastes was performed using anaerobic digestion (AD). In anaerobic digestion, solid waste materials are reduced before disposal into the environment. Several anaerobic microorganisms decompose complex organic matters into simpler forms and generate methane and CO_2. This conversion of SW to safer and simpler forms is performed by different groups of fermentative, acetogenic, syntrophic and methanogenic bacteria. A wide range of waste materials from municipal, agricultural, industrial and plant wastes are digested using AD (Castellano-Hinojosa et al., 2018) (Fig. 5). These microbes are involved in a series of metabolic reactions such as hydrolysis, acidogenesis, acetogenesis, methanogenesis, and bio-electrogenesis. Among these processes, acidogenesis, methanogenesis and bioelectrogenesis are the most important strategies in the degradation of SW fraction through biological processes.

5.1. Acidogenesis

Acidogenesis is the degradation of simple monomers into volatile fatty acids (VFA) such as acetic acid, propionic acid and butyric acid using biological sources. These volatile fatty acids are degraded into acetic acid, CO_2 and H_2. A large group of anaerobic bacteria such as *Clostridium* sp., *Caldicellulosiruptor* sp., *Enterobacter* sp., *Thermotoga* sp., and *Thermoanaerobacterium* sp., convert organic matters under pH ranging between 5 and 6 (Nandi and Sengupta, 1998). Acidogenesis of the solid waste substrate has several constraints such as substrate biodegradability, the inefficiency of microbes to degrade SW and physicochemical parameters (Han and Shin, 2002; Venkata Mohan et al., 2008). Acidogenesis is also known as the acidification process, which diversely affects the large group of bacteria under a strict anaerobic environment. Oxygen utilizing bacteria are very important to remove the available oxygen in the system. Acidogenic bacteria help in metabolizing the organic material to very low pH values (Dahiya et al., 2018; Kondusamy and Kalamdhad, 2014; Sarkar et al., 2017). The mechanism involved in the conversion of the simpler monomer is mentioned in Eqs. (1)–(4).

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 2CO_2 \quad (1)$$

$$C_6H_{12}O_6 + 2H_2 \rightarrow 2CH_3CH_2COOH + 2H_2O \quad (2)$$

$$C_6H_{12}O_6 \rightarrow CH_3CH_2COOH + 2CO_2 + 2H_2 \quad (3)$$

$$C_6H_{12}O_6 \rightarrow 3CH_3COOH \quad (4)$$

Several studies have reported the degradation of solid wastes using variety of fermentation and digestion techniques. Acidogenic fermentation of food wastes as substrates under continuous flow reactor produced 71.2% of degradation using rumen microorganisms and 59.8% of mesophilic acidogenic bacteria (Han and Shin, 2002). Using a rotational drum fermentation system, fresh soybean meals or *Okara* as substrates decreased 9.6–19.4% volatile solids and 10.8–149 g/L volatile solids as acetic acid using mesophilic bacteria at the pH of 4.4 (Jiang et al., 2005). Acidogenesis of solid kitchen wastes at pH 7 solubilized 86% of total organic carbon and 82% of COD and a maximum of 36 g/L of volatile fatty acids were achieved (Zhang et al., 2005). The addition of porphyritic andesite helped in reducing the diameter of 33.05 μm/d and volatile solid degradation rate of 3.53 g/L/d at a hydraulic retention time (HRT) of 4–16 days (Li et al., 2009). An acidogenic reactor employed with a serial methanogenic processes improved the organic loading rate from 2.6 g VS/L/d to 3.0 g VS/L/d (Zuo et al., 2015). Yin et al. (2016), reported that glucose, peptone and glycerol were used as substrates to produce a maximum VFA concentration of 38.2, 32.2 and 31.1 g COD/L respectively and the mixture of three substrates produced 38.5 gCOD/L. Acidogenesis of food wastes in a leach bed reactor at pH 4–7 enhanced 72% degradation and 50.5% recirculation. Overall VFA yield was 330 g COD/kg total volatile solids (TVS) added and 58% of COD (Hussain et al., 2017). Luo and Wong (2019), reported the increase in 50% of leachate recirculation and an increase in the digestion rate of food waste. The overall report suggested that the alteration of physical factors, type of solid waste substrate and type of inoculum would influence the acidogenesis rate of SW degradation.

Improvement of AD systems through anaerobic co-digestion could be one of the circular economy strategies for the treatment of organic waste (Wainaina et al., 2020). The potential of AD depends upon the ability to stabilize organic wastes and to recover bioenergy. Factors such as utilization of mesophilic to thermophilic microorganisms for the digestion of rapidly converted activated sludge to high rated activated sludges and neutralize the waste (Gebreeyessus and Jenicek, 2016). Integrating different technologies with waste reduction for

Table 1
Various research works carried on circular economy.

Investigations	Inference	References
Heat values and emission potential of solid wastes	Highest energy content was derived from plastic waste and highest emission was produced during thermal energy recovery of sewage sludge.	Bagheri et al., 2020
Concepts and practices of circular economy in solid waste management	CE helps in reducing generation of waste, recycling, cost efficiency.	Dumlao-Tan and Halog, 2017
Flow analysis and life cycle assessment of WEEE (Waste Electrical and Electronic Equipment) valorization in Belgium	32% of WEEE materials were being recycled to high end applications and rest 68% in either low end applications or landfill/incineration.	De Meester et al., 2019
Analysis of advantages and opportunities for waste valorization via circular economy	The CE model has potential to be a theoretical framework for big cities/towns of developing countries. However, financial sustainability, stakeholder inclusion and regulation development are required.	Ferronato et al., 2019
Recirculation routes of bio-based plastics in the European Union	Optimal alternative end of use/end of life routes are defined for the organic products, so that that they are converted to valuable resources for the circular economy. Expected impacts include reduction of public health problems, conservation of natural resources, reduction of GHG emissions.	Briassoulis et al., 2019
Discussion of the cross-disciplinary approaches devoted to clean technologies, process modelling, monitoring and management framework	Integration of smart concept in energy, water and waste management could significantly improve environmental performance through the smart sensor and real-time monitoring. However, there is still a research gap on the offset/saving versus the footprint of the IT sector	Van Fan et al., 2019
Developing an integrated design of waste management systems to support circular economy by P-graph (a bipartite graphical optimization tool)	The identification of near-optimal solutions by P-graph is useful in dealing with the trade-offs between conflicting objectives. Developed framework by P-graph turned out to be an effective tool for solid waste systems planning.	Van Fan et al., 2019
To gain insight into the strengths and shortcomings of the methodologies currently being applied, and to identify their applicability to a sustainable CIWMS targeting resource recovery.	CIWMS shortcomings can be improved by expansion of the boundaries of traditional linear IWMS, so that it includes upstream subsystems that will be able to link the conversion of raw materials into MSW with the waste treatment sub-systems.	Cobo et al., 2018
Reviewing the history of the CE & critical examination of how it is applied currently.	Research on CE concept shows that this initiative requires integrated bottom-up and top-down approaches for its implementation and evaluation. Without some evaluation framework or bottom-up support from the industry or the social community, CE initiatives cannot sustain.	Winans et al., 2017
Detailed study about waste generation and treatment on basis of designing and policy instruments for CE.	Database showed that, both high income and low income countries need to increase their recycling and reduce land filling to achieve circular economy.	Tisserant et al., 2017
Study of classification framework to categorize indicators according to reasoning on CE strategies and their measurement scope	Study suggests a set of indicators to be used to assess CE instead of a single indicator.	Moraga et al., 2019
Review of MSW and waste to energy systems in context of CE in Europe	Biggest proportion of waste (above the EU average) was generated in Italy (486 kg/per capita), Greece, and the UK (each 485 kg/per capita). CE can help in overcoming this problem.	Malinauskaite et al., 2017
Critical analysis of CE in context with WCED sustainable development.	CE needs to attract business community as well as policy-making community to maintain sustainability of work.	Korhonen et al., 2018
Analysis of the informal recycling industry, waste generation and its composition in Dhaka, Bangladesh	Source segregation needs to consider all other interconnected aspects of the waste management system that influence and determine sustainability and can lead to improvement.	Matter et al., 2013
Evaluation of the impact of MSWM system in Nagpur city, India.	Results indicated that the combination of recycling, composting and land filling of the residues is the most suitable. Sensitivity analysis also revealed that environmental impacts have an inverse relation with recycling rate.	Khandelwal et al., 2019

product recovery will make the whole factor economically and environmentally favorable and overcome the persistent limitation of the acidogenic process (Venkata Mohan et al., 2019). The residual acid-rich organic fractions originated from the acidogenesis phase will be made economically stable by the integration of a two stage energy generating process. The integration of nutrient (N, P, K) recovery technology during acidogenesis can obtain a clean stream of nutrients (Zhang and Angelidaki, 2015). The integration of strategies will also reduce the waste load with the advantage of value added to the existing process in the form of product recovery, making the whole process economically and environmentally viable.

5.2. Methanogenesis

Methanogenesis is a complex reaction leading to the redox biochemical conversion of SW under an anaerobic environment. The symbiosis of anaerobic bacteria helps in the conversion of multi-molecular organic substances into simple and chemically stable compounds such as NH_4 and CO_2 (Naik et al., 2010). Methanogenesis involves liquefaction, hydrolysis, and gasification and further accompanied by the humification of organic substrates (Lyberatos and Skiadas, 1999). Methanogenic bacteria dwell under absolute anaerobic conditions such as marshlands, rice fields, swamps, sandy lagoons having large dumping of wastewater, sewage sludge, landfill and stomach ruminants (Zeikus, 1977). Methanogens are involved in the conversion of organic matter into methane (Yang et al., 2004). They are involved in the degradation of waste, sedimentation of primary and secondary sludge generated from anaerobic waste treatment plants and wastes produced from pharmaceutical industries (Yang et al., 2004).

During methanogenesis, methyl-coenzyme M reductases are the key enzymes catalyzing the transformation of CH_4 and anaerobic oxidation of CH_4 using methyl thioether methyl-coenzyme M (CH_3-S-CH_2CH_2-SO_3 or Me-S-CoM) and thiol coenzyme B (CoB-SH) as a substrate for generating CH_4, which corresponds to heterodisulfide (CoB-S-S-CoM) (Friedrich, 2005). The mechanism of methanogenesis is given in Eqs. (5)–(7).

$$CH_3CH_2OH \rightarrow CH_4 + 2CO_2 \tag{5}$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \tag{6}$$

$$2CH_3CH_2OH + CO_2 \rightarrow CH_4 + 2CH_3COOH \tag{7}$$

The major classification of methanogens is based on the utilization of H_2, CO_2, and acetic acid to form CH_4. Methanogens consuming H_2 are known as hydrogenotrophic and methanogens consuming acetic acids are referred as acetoclastic methanogens (Merlino et al., 2013). Methanogens, especially sulfate-reducing bacteria are responsible for

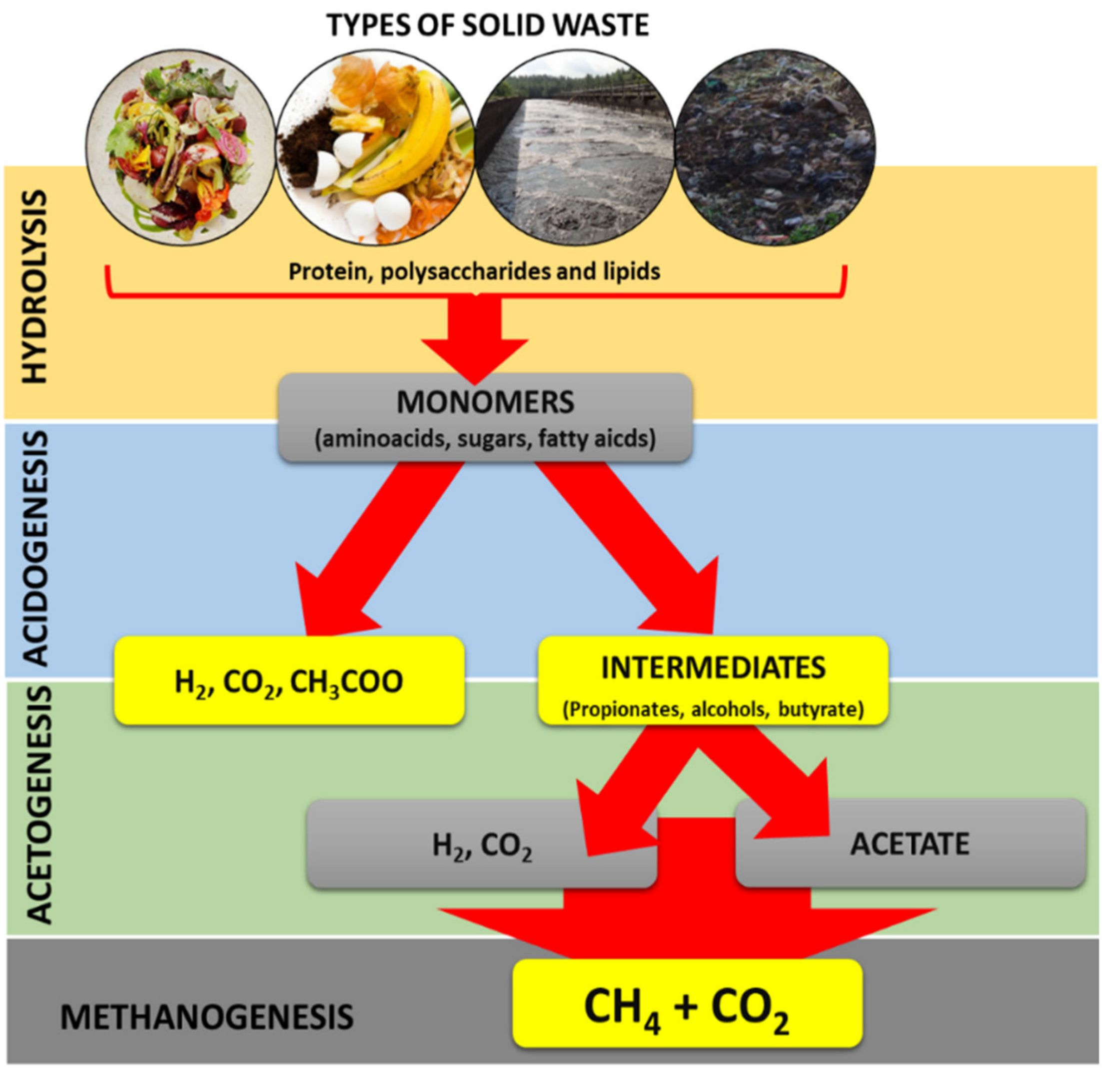

Fig. 5. General scheme on the digestion of biodegradable fraction of solid waste through biological processes.

H_2 removal under an anaerobic environment. The major dominating methanogenic bacteria are acetoclastic *Methanoculleus* sp., such as *Methanobacterium*, *Methanothermobacter*, *Methanobrevibacter* and *Methanosphaera* (Hans and Kumar, 2019; Roy and Das, 2016). The hydrolysis of triglycerides present in the lipids of food waste leads to the production of fatty acids. The accumulation of VFA causes pH to drop and inhibits the growth of methanogens causing an imbalance in the bacterial community (Griffin et al., 1998).

Several reports have suggested the digestion of solid wastes using methanogenesis to produce biogas. Anaerobic sewage sludge combined with cattle manure was loaded in a digester and treated for 20 days with thermophilic bacteria leading to the production of 1.52 m^3/m^3/day of biogas, 59% of methane, 54.5% of volatile solids and 58% of cellulose removal (Griffin et al., 1998). Molecular analysis of microbial diversity present in the closed municipal solid waste landfills has been performed to have Archaea as the major group. Quantitative oligonucleotide hybridization revealed that only 2% of methanogens were present and from the overall population, *Methanomicrobiales* and *Methanosarcinales* were the major methanogens (Huang et al., 2003). Yang et al. (2012) reported that AgNPs would influence the group of methanogenic bacteria present in the anaerobic digestion of municipal solid wastes. During the methanogenic activity, moisture content plays a major role. A study has suggested that the specific methanogenic activity of the mesophilic digest collected from the municipal solid waste digestor was increased by altering or increasing the moisture content, thus, proving the linear link between the methanogenic activity and the moisture content (Le Hyaric et al., 2012). Under dry AD, the population of methanogenic bacteria in the seed sludge had a significant reduction from 18 to 4 in genus diversity causing a major shift from the hydrogenotrophic to the acetoclastic group (Cho et al., 2013). Incorporation of carbon cloth in a reactor with leachate increased the performance and improved the biomethanogenic digestion of the incinerated leachate (Lei et al., 2016). Mixing of food waste especially, vegetable waste in a two-stage digestor regulated pH, restricted the production of propionate and lactate and enhanced methanogenesis by improving the production rate of acetate (Chakraborty and Venkata Mohan, 2018). Therefore, it is understood that methanogenesis is regulated by several factors and helps in the efficient conversion of solid wastes to biogas or methane.

The circular economy strategy can be improved by designing circular resource flows between the industries at the regional and global levels (Loiseau et al., 2016). This strategy combines waste hierarchy and bioeconomy (Deselnicu, et al., 2018). The development or improvement of the economy can only be done by the conversion of biomass or substrates obtained from renewable resources such as agriculture, forest and organic wastes generated from the domestic and municipal wastes (Commission, 2012). Synergism of varied waste treatment technologies can improve the circular economy. During methanogenesis, valorization of the effluent releases the fertilizer slowly and up to 95.4% of nutrients are recovered. This also provides an advantage over the slow loss of phosphorus and nitrogen from the soil. Potential valorization of sludge or solid fractions produced during the thermochemical step can possibly improve the economy (Werle and Sobek, 2019; Hidalgo et al., 2019). Thus, the transition of various products from wastes can help in developing new business, new models for market and conduct of the consumers.

5.3. Bioelectrogenesis

Bioelectrogenesis is the process of generating electricity from living organisms such as bacteria, crustaceans, fish (electric eel, stingray, electric catfish, etc.). The transmembrane ion channel and transporter protein activated electrochemical reaction in a biological cell such as sodium-potassium pump generates electrical impulse under a maintained voltage imbalance between the intracellular and extracellular spaces. During this reaction, the Na-K pump releases 3 Na+ ions and takes in 2 ions of K towards intracellular space of the biological cell leading to the generation of the electrical gradient by uneven separation of the charges and consume ATP in the form of metabolic energy (Baptista, 2015; Schoffeniels and Margineanu, 1990; Velvizhi and Venkata Mohan, 2014).

Microbial fuel cell (MFC) is one of the most promising bioelectrochemical device used for generating electricity using a wide range of solid waste. The utilization of substrates like food waste, sludge waste, wastewater by microorganisms generates bioelectricity. It is the need of the hour to overcome the demand for renewable energy (El-Chakhtoura et al., 2014; Moqsud et al., 2013). MFCs have been used to treat several solid toxicants especially, phenols, chromium and pentachlorophenol (Huang et al., 2013; Li et al., 2008; Liu et al., 2008; Velvizhi and Venkata Mohan, 2015). The MFC consists of an anode and a cathode rod separated electrochemically using a compartment or partition. The separation is done using a layer of soil or sediment in single chamber MFC. The conversion of substrate to sugar under anaerobic conditions occurs in the anode compartment to produce CO_2, protons and electron. The mechanism of electricity generation is mentioned (Eqs. (8), (9)) (Moqsud et al., 2013; Rabaey and Rozendal, 2010).

$$C_{12}H_{22}O_{11} + 13H_2O \rightarrow 12CO_2 + 48H^+ + 48e^- \tag{8}$$

After supplying oxygen, the reaction is changed as mentioned in Eq. (9),

$$6O_2 + 24H^+ + 24e^- \rightarrow 12H_2O \tag{9}$$

Reports are available on the conversion of solid waste for the generation of bioelectricity. This study evaluated bioelectricity generation by using kitchen garbage (KG) and bamboo waste (BW) as a solid waste management option by the microbial fuel cell (MFC) method. Overall, 620 mV of electricity was generated with 0–5 days using kitchen waste while 540 mV of voltage was generated in bamboo waste (Moqsud et al., 2014). Logroño et al. (2015) produced bioelectricity from the digestion of vegetable and fruit wastes in a single chamber MFC. The organic waste was biotransformed to generate bioelectricity in 60 days. The maximum output voltage of 330 mV was generated with a combination of 75:25 ratio of fruits and vegetables (Logroño et al., 2015). Kondaveeti et al. (2019) generated electricity using raw algae biomass and raw algae with acetate in a single chamber air cathode MFC. A combination of raw algae with acetate generated 410 mW/m^2 and raw algae alone generated about 230 mW/m^2. Studies also reported that MFC would be an effective bioelectrochemical treatment system for the treatment of complex wastes (Venkata Mohan et al., 2014).

The economic efficiency during electrogenesis can be improved by intervening in the technological aspects and the optimization of the process. The drawbacks of MFCs, microbial electrolysis cells, and microbial electro synthesis can be improved by garnering biocathodes for balancing the drawbacks of electrogenesis. Bioelectrogenesis can be enhanced by integrating secondary processes viz. microbial electrolysis, MFCs and dark fermentation process (Kondaveeti et al., 2019). This will provide economic benefits and improve energy generation. The integration of MFCs with photosynthetic MFC will enhance several biological processes such as photosynthesis and the generation of byproducts (Xiao et al., 2012). The inclusion of chemolithoautotrophic bacteria in the system can be used in the catalysis of energy by the assimilation of CO_2 (Logan and Rabaey, 2012). The utilization of photocathodes from biological sources will help in the production of oxygen to develop a strong electronegative environment for an increased proton transfer in the environment (Cao et al., 2009). Further improving the configuration of MFCs can help in increasing the electrochemical energy generated from the biological sources. These strategies will ensure bioelectroeconomy and environmental sustainability.

6. Disposal of non-biodegradable solid waste

A non-biodegradable material is a substance that cannot be fragmented down by microorganisms or natural organisms and is a major source of pollution. Non-biodegradable wastes neither get decomposed nor dissolved by natural agents. Various researches on recycled materials from non-biodegradable solid wastes and their applications are mentioned in Table 2. These wastes continue to remain on earth for centuries without any degradation. Thus, the threat, which is caused by these wastes, is far more critical than the biodegradable waste. Moreover, these wastes cannot be decomposed and often get accumulated to make the biological cycles slow and toxic. There are two types of non-biodegradable wastes , which can be recycled known as “Recyclable waste” and which, can't be recycled known as "Non-recyclable waste". There is an urgent need to increase the amount of waste that can be recycled and reused especially, in the construction industry. This will not only generate a potential business opportunity but also employment generation and environmental sustainability (Fig. 6).

6.1. Reusing

Reuse is an unused or a waste product without many transformations and also without altering its shape and is originality. Reuse means that a lesser amount of solid waste is produced. These waste products, which are discarded, can be used by those who require it. Various types of solid wastes that can be reused in construction activities are plastic, timber, glass, concrete and ferrous as well as non-ferrous metals. Reuse of plastic can help in plastic - soil paver blocks for non-load bearing structures and the timber products help in providing a framework and be reused several times. Glass helps in the production of construction activities such as tiles, bricks and paver blocks and can be reused. Concrete from construction and demolished sites can be reused as temporary work. Ferrous and non-ferrous metals are used for the formwork of metals and can be used several times (Huda and Alam, 2014).

6.2. Recycling

Recycling of waste implies the waste material is again processed so that it can be used to make new products. This reprocessing also has an impact on the environment and people's health but usually, these impacts are lower than those, which are caused by making new products from raw or new materials. Thus, recycling can also be defined as considering the materials as valuable resources and not as wastes (Özalp et al., 2016). This problem is solved by using these wastes in construction as it is very cheap compared to a new product (de Oliveira Andrade et al., 2018). Various products that can be recycled and also can be used for construction purposes are listed below.

Table 2
Recycled materials from non-biodegradable solid wastes and its applications.

Materials recycled	Used as	Evaluated parameters	Remarks/conclusion	References
Construction and demolition waste	Concrete	Mechanical properties and carbonation behavior	Recycled aggregate (RA) has similar compressive strength compared to natural aggregate but higher bond strength and higher flexural strength as 50% of recycle aggregate. Carbonation depth higher of RA over natural aggregate by 13%	de Oliveira Andrade et al., 2018
Construction and demolition waste	Ready mixed concrete, paving stones and kerbs	Strength and durability characteristics	Compressive strength of the paving stones and kerbs concrete mixtures with 15% replacement of C& D waste similar to natural aggregates. Water absorption value in recycled products was less over natural aggregate.	Özalp et al., 2016
Construction and demolition waste	High strength/high performance concrete	Strength and durability characteristics	Replacing 50% natural aggregate by of C& D waste shows improved strength and durability characteristics in presence of mineral admixture and by adjusting the w/c ratio.	Ajdukiewicz and Kliszczewicz, 2002
Crumb rubber	Highway and asphalt pavement	Thermal stability	The addition of crumb rubber in asphalt mixes improves thermal stability based on different temperature results	Chen et al., 2019
Crumb rubber	Floors, driveways and walkways	Micro structural composition, mechanical properties	Replacement of sand with crumb rubber in concrete shows most voids filled in concrete mix. Compressive strength of crumb rubber used concrete similar to the control concrete.	Adeboje et al., 2020
Fine crumb rubber (CRP)	Road pavement and construction activities	Mechanical properties, rutting performance and fatigue life	Addition of 20% CRP as filler, it increases the stiffness modulus while higher the CRP percent rises to 40% and 60% respectively the stiffness modulus decreases.	Tahami et al., 2019
Crumb rubber	Concrete in industrial environments	Thermal stability and durability properties	Addition of crumb rubber as additive in 110 kg/m^{3}of concrete has high resistance to temperature and chloride-ion penetration.	Zhu et al., 2018
Crumb rubber	Cement concrete	Fresh, strength and durability properties	When 50% of sand is replaced with crumb rubber, it produced the best performance in fresh, strength and durability performance for concrete pavement.	Kardos and Durham, 2015
Crushed glass	Cement concrete	Workability, strength and air content	By replacing aggregate with glass powder in 20% replacement by mass gave increased value of compressive strength and negligible air content.	Afshinnia and Rangaraju, 2016
Finely ground glass (FGG)	Cement concrete	Pozzolanic activity, strength and durability properties	Usage of FGG in the range of 10–20% increases the rate of pozzolanic reactions and alkali silica reactions leading to formation of more C-S-H gel resulting in high strength up to 49% and loss of weight was reduced up to a maximum of 61% with the resistance against leaching increasing to 150%	Dyer and Dhir, 2001
Waste glass powder	Reinforcement cement concrete	Strength and durability properties	Usage of glass powder with a geopolymer as a precursor, with 20–30% replacement of cement reduces the chloride ion penetration by 40–90% and increasing the 28 day compressive strength by 40%.	Alomayri, 2017
Waste glass	Cement concrete	Workability, compressive strength, durability characteristics	With 20% replacement of fine aggregate the 28 day compressive strength was increased up to 25% and the weight getting reduced by 5% with addition of 40% of glass.	Olumoyewa and Obanishola, 2018
Plastics	Self-compacting mortars	Physical, mechanical and ultrasonic pulse velocity testing	Considering density of materials, the mortars with 50% of plastic waste offer better results than other with percentage of the waste possessing mechanical strength suitable for lightweight materials. Cement mortar containing 20–50% plastic waste replacement gave comparable results with conventional materials.	Safi et al., 2013
Plastics	Concrete used in footpaths	Strength properties	The compressive and splitting tensile strength values were reduced although coarse aggregate substitute are feasible up to minimal 20% by volume for recycled plastic waste	da Silva et al., 2014
Plastics	Recycled plastic granules	Strength, stiffness and resilient module	Polyethylene plastic waste containing up to 5% content are suitable for road construction material, along with different proportions of demolition wastes.	Arulrajah et al., 2017
Plastics	Bitumen mixes	Binding property and Marshall stability value	Plastic based bitumen mix provided better resulting in terms of stability and binding performance. Using this mix resulted in roads acting well due to improved Marshall stability value and used as raw material for construction of flexible pavement.	Vasudevan et al., 2012
PET bottles	Sustainable paving material in modified asphalt	Feasibility, storage stability, rheological and chemical properties	Using the derivative additives of waste PET and scrap tire rubber in asphalt helps recycle waste plastic and rubber, moreover it also increases the engineering characteristics of asphalt pavement.	Leng et al., 2018
PET bottles	Geotechnical application	Los Angeles abrasion, modified Proctor compaction, and California bearing ratio (CBR)	Crushed PET bottle mixes performed better than natural soil which blends easily with base material as well as the CBR value and axial stress improved with addition of 5% blends.	Perera et al., 2019
Aluminium containing salt slags	Cement mortar	Mechanical properties, compression and flexure	Test results showed decreasing compressive and flexural strength irrespective of curing periods. No significant decrease at 10% replacement.	Pereira et al., 2000
Aluminium dross	Concrete	Mechanical and chemical properties, corrosion resistivity, setting times	Test results showed improvement in properties up to a particular limit (15%) and enhanced corrosion resistivity and accelerated setting time.	Ozerkan et al., 2014
Aluminium dross	Bricks	Physico-mechanical properties	Studies conducted on volume shrinkage, bulk density, crushing strengths and permeability showed that aluminium dross powder can be used to make acid refractory bricks.	Adeosun et al., 2014

6.2.1. Construction and demolition (C&D) waste

The materials comprise of waste that is generated during the construction and demolition of buildings, roads, and bridges, is Construction and Demolition (C&D) waste. The C&D waste generated in India is nearly 530 million tonnes, annually. Nevertheless, potential material savings from C&D waste recycling are hard to enumerate in the Indian context. C&D waste constitutes 36% of silt, sand and gravel, 31% of bricks and masonry, 23% of concrete, metals 5% and others 5%. C&D waste

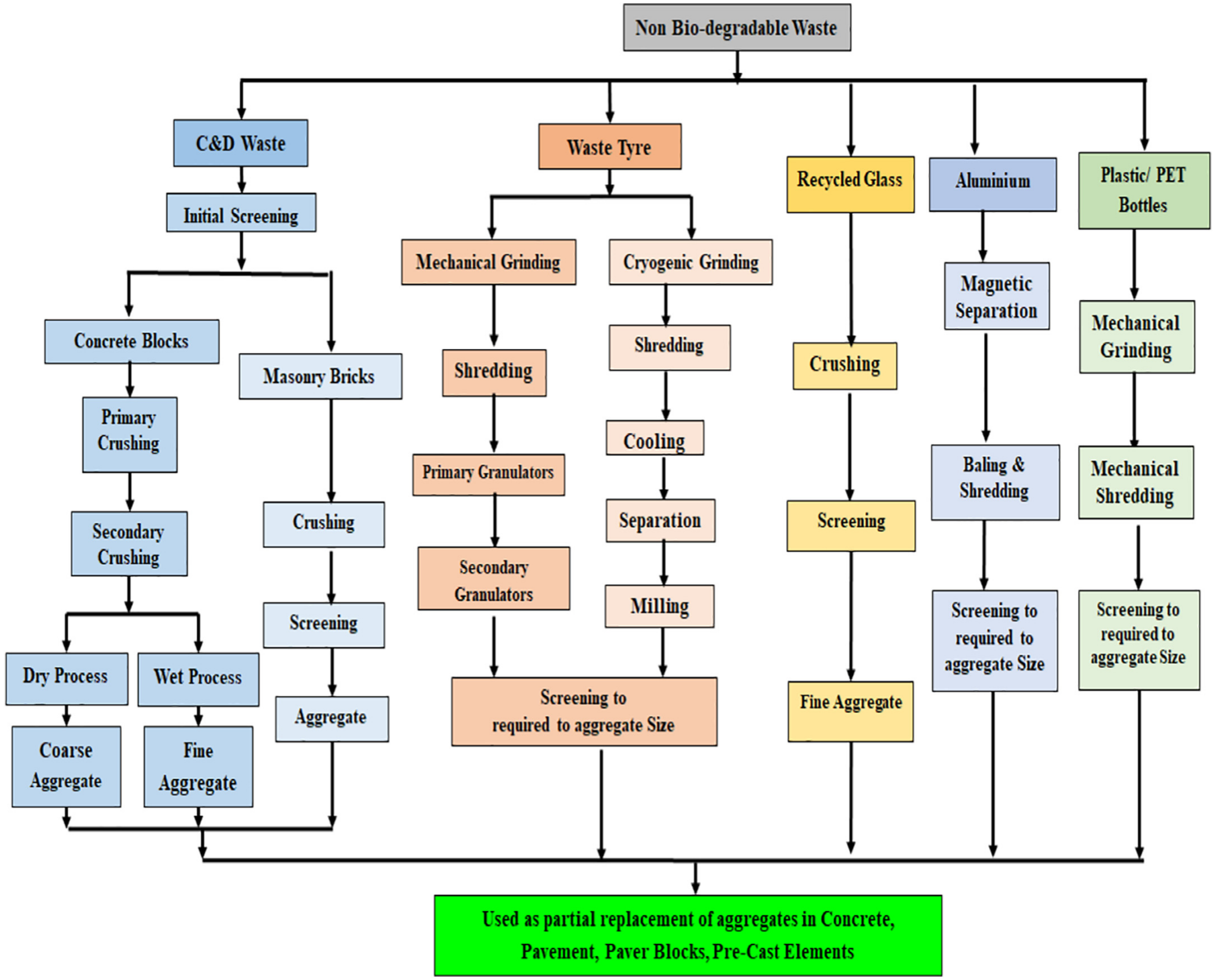

Fig. 6. Schematic flow diagram for processing of non-biodegradable solid waste.

recycling starts with the segregation of unwanted materials such as plastic, wood, metal fragments, etc. (which constitutes 10% of the total waste). A major portion of the waste that is generated is masonry and concrete, which can be used as recycled aggregate in concrete. When RCA is added to the concrete mix, it makes the concrete lighter and improves the strength and durability properties, marginally, up to 30% than the natural aggregate concrete mix (Huda and Alam, 2014; Rahal, 2007).

6.2.2. Crumb rubber from waste tyire

The inclusion of waste materials such as recycled tires into the concrete mix, can achieve a direct reduction in the cost and impart a quantifiable impact on the environmental lifecycle on comparing with the conventional concrete. The economic benefits of recycled aggregates (recycled waste tire), when added to concrete, are not achieved through direct cost. It is achieved as a result of the lesser distance between the source and placement and as it can be available to the nearby construction industry with ease. The concrete mix can be achieved by mixing the base mix with rubber powder or crumb rubber made out of composite materials that improve the strength and durability properties (Zhu et al., 2018; Tahami et al., 2019). Rubber is a superelastic material; thereby, helps in improving the internal structure of concrete without altering the chemical properties and also induces physical action in concrete (Kardos and Durham, 2015). When compared to concrete, the elastic modulus of rubber can be considered almost negligible. Due to this, the addition of rubber particles is considered as elastic pores, thereby, preventing the formation of microcracks and improving the ductility of concrete. It may also help in improving the frost resistance of concrete and its resistance to chloride-ion migration (Onuaguluchi, 2015).

6.2.3. Waste glass

One of the major environmental problems in today's world is waste glass disposal. This is due to an increase in demand for natural resources, for spaces to be used as landfills and as a greater emphasis on reducing the carbon footprint emitted from the construction industry. In earlier days, the use of glass beads was limited in making of jars and bowls. However, as technology advanced, the applications of glass included windows, lighting, fiber optic cables, etc. This was possible due to an increase in the discovery of different types of glass having properties varying from one another. Appropriate reduction in the size of the particle is the way through which, waste glass can be used as a partial replacement of aggregates. Waste glass particles are chemically inert and possess high intrinsic strength. When the waste glass is used as a very fine aggregate, it increases the compressive strength of concrete and decreases water absorption. This occurs due to the pozzolanic reaction of very fine glass particles (Topcu and Canbaz, 2004; Turgut, 2008). Recycled glass, when used as aggregates, helps in improving the fresh properties such as slump value of the concrete due to the smooth surface and the relatively low water absorption of the glass aggregates, which leads to the de-bonding between the cement gel and the glass surface (Afshinnia and Rangaraju, 2016). A considerable increase in the strength of concrete is observed in replacing 30% of aggregates with recycled glass (Lu et al., 2019).

6.2.4. Aluminium waste

The most common solid waste generated in the country is the aluminium waste. The major problems to the future generation arrive due to the increase in the number of by-products for utilization in various municipal and industrial processes. One such waste product is aluminium dross (Al-dross) consisting of various crystalline forms of Al_2O_3 along with the minor amounts of free Al-metal, Al-nitride (AlN), Al-carbide (Al_4C_3), Al-sulfide (Al_2S_3) and $MgAl_2O_4$-spinel. According to previous literature (Reddy and Neeraja, 2018), about 4 million tons of aluminium waste is generated annually in India, 95% which is expected to landfill. On replacement of 20% of the aggregates with dross particles, an increase in strength is observed but only when the size of the particles is limited to 10 μm. Also, it was noticed that the introduction of coarse and even dross particles showed a significant increase in wear resistance of concrete and can be used in pavement construction (Kevorkijan, 1999).

6.2.5. Plastic/PET bottle waste

The municipal and commercial industries generate huge amounts of plastic wastes, annually in all developed and developing nations. The growing rate of plastic generation has prompted to look for ways to resolve the industry's waste disposal. Projects typically utilizing substantial amounts of plastic and other related wastes as a substitute for construction materials will turn away substantial amounts of these waste materials. The waste plastic, which is generated by industrial and domestic sectors can be treated as a basis of raw material for flexible pavement construction. The importance of recycling these, both ecologically and economically, corresponds to the fact of it being non-biodegradable as well as the pollution caused on account of dumped in the landfills (Saikia and De Brito, 2012). The exchange of conventional construction materials with the recycled materials will provide a sustainable resolution, which diminishes landfilling concerns. Polyethylene terephthalate (PET) is broadly utilized in the production of drinking bottles, food packaging, etc. The unsuitable disposal of the huge extent of PET waste might cause severe environment treated difficulties.

7. Application of energy from waste as biofuel in internal combustion engines

Biodegradable fraction of solid waste synthesizes various forms of biofuels such as as liquid biofuels and gaseous biofuels by anaerobic digestion process. Hydrogen, Compressed Natural Gas (CNG), biogas and syngas are the gaseous biofuels. Ethanol, methanol, butanol, and biodiesel are liquid biofuels. Both forms of biofuels ideally and blended with fossil fuels are utilized as an alternative source of fuel for internal combustion engine applications. Fig. 7a provide the significant physical properties of various alternative fuels (Montoya et al., 2018). Further, to propagate the capability of alternative fuel utilization in IC engines, the combustion nature of gaseous and liquid biofuels and their respective performance and emission characteristics are discussed.

7.1. Gaseous fuels in IC engines

Among the various alternative energy sources, gaseous biofuels offer a promising breakthrough for sustainable development in the fuel and transportation sector equivalent to liquid biofuels. The performance, combustion and emissions effects of various gaseous fuel powered compression ignition and spark ignition engines are presented in Table 3.

7.1.1. Hydrogen

Dark fermentative H_2 production from food waste produces higher H_2 production. The produced hydrogen could be used as gaseous fuel, which can be used both in CI and SI engines under different operating modes. Typically, the compression processes in CI engine self-ignite fuel-air mixture, the higher self-ignition temperature of hydrogen hinders the usage of hydrogen as a monofuel. Hence, the carbon-free hydrogen fuel is utilized along with the diesel fuel in the CI engine. During the combustion process, the rapid combustion nature of hydrogen increases the peak pressure, respective to an increase in the hydrogen flow rate. Also, the presence of hydrogen exhibits the explosive and premixed type of combustion rather than a typical diffusive mode of combustion in diesel fuel. This leads to an increase in the higher heat release rate for a hydrogen-powered engine. Moreover, the better mixing nature with air and in addition to its faster burning characteristics, increases the brake thermal efficiency (BTE) and a decrease in specific fuel consumption is exhibited due to higher energy content and better combustion characteristics (Saravanan and Nagarajan, 2009; Masood et al., 2007). However, the use of hydrogen and diesel fuel mixture eliminates other combustion problems like backfiring, per-ignition (Masood et al., 2007; Saravanan and Nagarajan, 2008). Even in emission aspects, the hydrogen blended with diesel has lower emissions of CO and CO_2 due to the non-carbon nature of the fuel. The HC emission also decreases, while the increasing hydrogen content increases the combustion temperature, which promotes a complete combustion of the supplied fuels and also, hydrogen is a carbon free fuel. The very lean mixture of hydrogen under part-load condition reduces the NO_x emission and on full load condition, due to its high heat release rate, increases in-cylinder temperature results in an exponential increase of NO_x emission (Karagöz et al., 2015; Sandalcı and Karagöz, 2014). Since hydrogen is a carbon-free fuel, the smoke emission decreases greatly.

In the SI engine, the presence of a spark plug creates feasibility to use hydrogen as a mono-fuel. The performance characteristic is a concern, the brake power of hydrogen is higher than that of gasoline because of low specific energy content by volume under slow speed operation. The drawback of low brake power can be solved by super charging (Kahraman et al., 2007). However, the fast burning characteristics of hydrogen cause a notable improvement in power output and brake thermal efficiency under highspeed operation. Also, the wider flammability nature of hydrogen has a higher in-cylinder pressure comparable to that of gasoline (Ceviz et al., 2012; Yu et al., 2019). In emission aspects, the complete elimination of CO and HC emissions are due to no trace carbon atom in hydrogen fuel. The high in-cylinder temperature and higher flame speed result in a dramatic increase in NO_x emission (Yu et al., 2019; Karagöz et al., 2019).

7.1.2. Compressed natural gas (CNG)

Waste-to-energy (WTE) pathways for production of compressed natural gas (CNG) using food waste via anaerobic digestion is one of the challenging and sustainable aspects. The produced natural gas can be applied to the in-use vehicles without any significant modifications. Like hydrogen, due to its higher autoignition temperature, it requires additional supplementary fuel to start the combustion. The combustion characteristics of CNG (methane) in the CI engine exhibit higher heat release compared to diesel due to wider flammability (Karagöz et al., 2016a, 2016b). The brake thermal efficiency of CNG is lower than that of diesel fuel due to the slower burning rate, and more heat loss during combustion. Even, CNG has a lower volumetric efficiency which increases the consumption of fuel (Zhou et al., 2014; Mahla and Dhir, 2019). Moreover, at the end of the combustion process, the flame quenching obstructs the ignition of the unburnt fuel resulting in a higher HC emission relative to gasoline. Also, the presence of lower oxygen content in the rich fuel zone creates higher CO emission. The

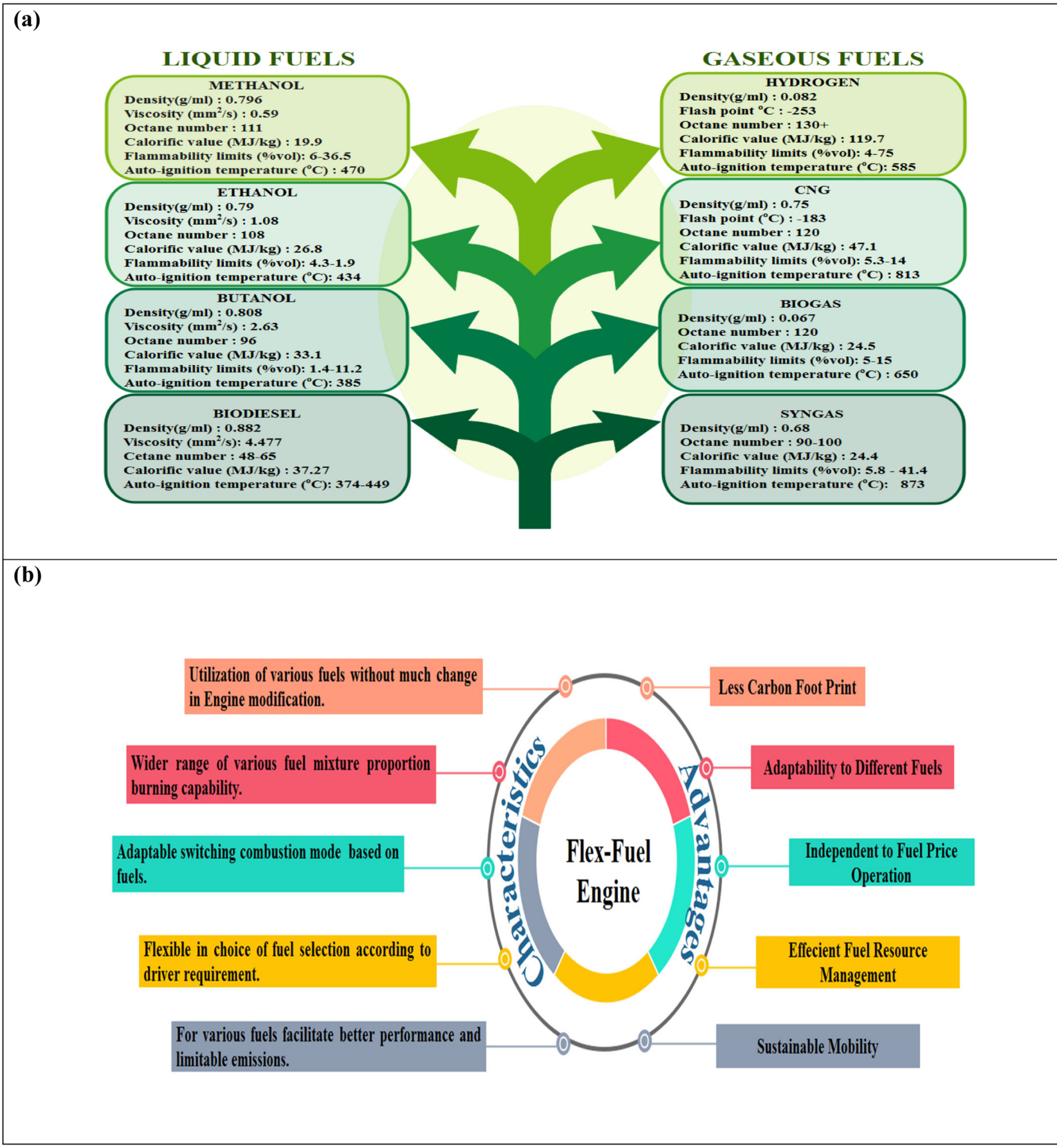

Fig. 7. (a) Various physical properties of gaseous and liquid biofuels for IC engine applications. (b) Advantages and characteristics features of flex-fuel engine.

presence of a dominant higher combustion temperature of CNG causes a dramatic increase in NOx emission. Nonetheless, the soot formation decreases due to the extension in ignition delay and also, CNG does not contain soot forming substances like aromatics, sulphur (Zhou et al., 2014; Karagöz et al., 2016a, 2016b).

Likewise, for an application of CNG in the SI engine, the lower energy density of CNG reduces the torque and it can be improved by the installation of turbocharger and supercharger (Açıkgöz et al., 2015). The high diffusive nature of CNG creates a better mixing capability resulting in rapid and stable combustion, thus, provides a thermal higher efficiency than that of gasoline. The low energy density of fuel and low volumetric efficiency in the combustion chamber reduce the BSFC to achieve an equivalent power obtained from the gasoline. However, the exhaust gas temperature of CNG is lower than the gasoline because of higher research octane number (RON) and motor octane number (MON) rating (Lather and Das, 2019). Regarding emissions, the higher combustion temperature in the cylinder enhances the combustion of the fuel completely, resulting in a decrease of HC emission. The higher in-

Table 3
Applications of various gaseous fuels in internal combustion engines.

Engine specifications	Test conditions	Fuel used	Reference fuel/parameter	Combustion	Performance	Emission	References
Kirloskar, AV1 make, 1-cylinder, 4S/vertical, water cooled CI engine, CR-16.5, power-3.7 kW, speed-1500 rpm	Variable load (port injection)	(10 to 35.85) % of hydrogen + (90 to 64.15) % of diesel	Diesel	Cylinder pressure ↑, HRR ↑, EGT ↑	BSFC ↓, BTE ↑	HC ↔, NOx ↓, CO ↓, smoke ↓	Saravanan and Nagarajan, 2009
	Variable load (manifold injection)	(9.44 to 36.67) % of hydrogen + (90.56 to 63.33) % of diesel	Diesel	Cylinder pressure ↓, HRR ↑, EGT ↑	BSFC ↓, BTE ↑	HC ↑, NOx ↓, CO ↓, smoke ↓	
Kirloskar AV-1 RP-3.7 kW, diesel engine, speed-1500 rpm, CR-16.5	Variable load, variable compression ratio	10 to 100% of hydrogen + diesel	With CR (16.35 to 24.5)	Cylinder pressure ↑, HRR ↑	BTE ↑	HC ↓, NOx ↑, CO ↓, PM ↓	Masood et al., 2007
Kirloskar, AV1, 1-cylinder, 4-stroke, water cooled, direct injection CI engine, CR-16.5, power-3.7 kW, speed-1500 rpm	Variable load	10 to 100% of hydrogen	Diesel	Cylinder pressure ↑, HRR ↑	BSFC ↓, BTE ↑	HC ↓, NOx ↓, CO ↓, PM ↓	Saravanan and Nagarajan, 2008
Fiat licensed Tofas 124, 4-cylinder, 4-stroke SI engine, power-60HP, speed-5600 rpm.	Variable speed	Hydrogen	Gasoline	EGT ↓	(BMEP, BP) ↓ up to 3100 rpm, (BMEP, BP) ↑ above 3100 rpm, BTE ↑	HC ↓, NOx ↓, CO ↓, CO_2 ↓	Kahraman et al., 2007
Ford MVH-418, 4-cylinder, water cooled SI engine, CR-10, power - 93 kW, speed - 6250 rpm	Various air fuel ratio	(0, 2.14, 5.28, 7.74) % of hydrogen by volume + gasoline	Gasoline	Cylinder pressure ↑, cylinder temperature ↑	BSFC ↓, BTE ↑	HC ↓, NOx ↑, CO ↓	Ceviz et al., 2012
4-Cylinders, naturally aspirated; SI engine	Various air fuel ratio	Homogeneous hydrogen + gasoline, stratified hydrogen + gasoline	Gasoline	P_{max} ↑	BTE ↑	HC ↓, NOx ↑, CO ↓	Yu et al., 2019
Honda single cylinder, air cooled, SI engine, CR-8.5, power-8 kW, speed-3600 rpm	Variable speed	Hydrogen	Gasoline	Cylinder pressure ↑, HRR ↑	BT ↓, BP ↓, BMEP ↓, BSFC ↓, BTE ↑	HC ↓, NOx ↑, CO ↓	Karagöz et al., 2019
Ferryman, 4-stroke CFR engine, single cylinder, water cooled, power-7.5 kW, speed-2000 rpm	Variable load	Hydrogen + diesel	Diesel	Cylinder pressure ↑, HRR ↑	BSFC ↑, BTE ↓	HC ↑, NOx ↓, NOx ↑ (100% load), CO ↓, CO_2 ↓, smoke ↓	Karagöz et al., 2015
Single cylinder diesel engine, CR-17.5, speed-1000 to 4000 rpm	Variable air fuel ratio	(5, 10, 20, 30, 40, 50%) hydrogen + diesel	Diesel	–	BP ↑, BMEP ↑, BTE ↑	CO ↓	Ghazal, 2013
Ferryman 4-stroke CFR engine, single cylinder, water cooled CI engine, power 7.5 kW, speed-2000 rpm, CR-19	Variable energy fraction	Hydrogen	Diesel	Cylinder pressure ↑, HRR ↑	ISFC ↑, ITE ↓	HC ↑, NOx ↑, CO ↓, CO_2 ↓, smoke ↓	Sandalcı and Karagöz, 2014
Erin-motor engine, single cylinder, water cooled CI engine, CR-14.7, power - 40 kW, speed-2700 rpm	Variable energy fraction	15, 40, 75% (hydrogen + methane)	Diesel	Cylinder pressure ↑, HRR ↑	BSFC ↑, BTE ↓	HC ↑, NOx ↓ (15, 40%), NOx ↑ (75%), CO ↑, smoke ↓	Karagöz et al., 2016a, 2016b
Lombardini/LGW523MPI, 2-cylinder, SI engine CR-10.7, power-21 kW	Variable speed	10 + 90%, 20 + 80%, 30 + 70% of (H_2 + CH_4)	CH_4	–	BT ↓, BP ↓ (10%), BP ↑ (20, 30%), BSFC ↑, BTE ↓	HC ↓, NOx ↓, CO ↑, CO_2 ↓	Açıkgöz et al., 2015
ISUZU 4HF1, CR:19, 4-cylinder, power-88 kW, speed-3200 rpm	Variable BMEP	100% methane, H30 + M70, H50 + M50, H70 + M30, 100%H_2	Diesel (baseline)	(Cylinder pressure ↓, HRR ↓) at 10% load, (cylinder pressure ↑, HRR ↑) at 90% load	BSFC ↑, BTE ↓	HC ↑, HC ↓ (for H_2), NO_2 ↑, CO ↑, CO ↓ (for H_2), PM ↓	Zhou et al., 2014
Honda L15A, 4-stroke, 4 cylinder, SI engine	Variable speed, variable throttle	CNG (20% & 80%) throttle	Gasoline	IMEP ↓	BSFC ↑, BP ↓, BTE ↓	HC ↑, CO ↓ at (80%), CO ↑ at (25%)	Putrasari et al., 2015
Honda L13A4 i-DSI, CR-10.8, power-63 kW, speed-5700 rpm	Variable speed	25% and 75% throttle opening of CNG	Gasoline	EGT ↑	BT ↓, BP ↓, BSFC ↓, volumetric efficiency ↓	HC ↓, NOx ↑, CO ↓, CO_2 ↓	Yontar and Doğu, 2018
Single cylinder, 4-stroke, spray guided direct injection SI engine	Various mass fraction	25%, 50%, 75% and 100% methane	Gasoline	Cylinder pressure ↓, HRR ↓	BTE ↓	NOx ↓	Pan et al., 2018
1.1-L, multipoint fuel injection (MPI) engine, 4-cylinder, CR-9.1	Variable speed	CNG	Gasoline	EGT ↓	BT ↓, BP ↓, BSFC ↓, BTE ↑, volumetric efficiency ↓	HC ↓, NOx ↓, CO ↓, CO_2 ↓	Lather and Das, 2019
Single cylinder, 4-stroke, air cooled direct injection diesel engine	Variable load	CNG + diesel, CNG + B20	Diesel	Cylinder pressure ↓, HRR ↑	BSFC ↑, BTE ↓	HC ↑, NOx ↓, CO ↑, smoke ↓	Mahla and Dhir, 2019
Erin-motor engine, natural aspiration, single cylinder, water cooled CI engine, CR-14.7	Various energy fractions of natural gas	15%, 40%, and 75% energy fraction of natural gas	Diesel	Cylinder pressure ↑, HRR ↑ (at 15%), HRR ↓ (at 40% & 75%), EGT ↑	BSFC ↑, BTE ↓	HC ↑, NOx ↑, CO ↑ (15%, 40%), CO ↓ (75%), smoke ↓	Karagöz et al., 2016a
Beijing Hyundai Motors, 4-cylinder, SI engine, RP-82.32 kW, RS-6000 rpm	Various excess air ratio	2.5% syngas	Gasoline	P_{max} ↑	ITE ↑	HC ↓ up to λ-1.2, HC ↑ above λ-1.2, NOx ↑, CO ↑	Dai et al., 2012

Table 3 (*continued*)

Engine specifications	Test conditions	Fuel used	Reference fuel/parameter	Combustion	Performance	Emission	References
4-Cylinder 1Z type, 4-stroke, CR: 19.5, turbocharged, DI, diesel engine, power-66 kW, speed-4000 rpm	Variable IMEP (with & without EGR)	Biogas (methane + CO_2)	Diesel	–	BSFC ↑, BTE ↓	HC ↑, NOx ↓, CO ↑, CO_2 ↑	Makareviciene et al., 2013
4 - cylinder, 4-stroke, CR: 18.25, WC, turbocharged, CI, power-48 kW	Variable load	Biogas (M60 + C40)	Diesel	Cylinder pressure ↑, HRR ↓	–	HC ↑, NOx ↑, smoke ↓	Yilmaz and Gumus, 2017
Honda 1-cylinder, 4-stroke, SI engine, CR-8.5, power-6.3 kW, speed-3600 rpm	Various speed	Biogas	Gasoline	–	BSFC ↑	HC ↑, NOx ↓, CO ↑	Karagöz, 2019
6-Cylinder natural gas SI engine, power-117.6 kW, speed-2300 rpm	Variable H_2 concentration	Biogas with H_2	CNG	–	BTE ↓	HC ↓, NOx ↑	Park et al., 2011
1-Cylinder, AC, 4-stroke, SI engine, CR-14	Variable load	Syngas (H_2/CO)	CNG	Cylinder pressure ↑, HRR ↑	BSFC ↑, BTE ↓	HC ↓, NOx ↓ (at low load), NOx ↑ (at	Hagos et al., 2014

(continued on next page)

cylinder temperature increases the NO_x formation and also promotes the oxidation of CO resulting in a higher CO_2 emission (Yontar and Doğu, 2018).

7.1.3. Biogas and syngas

Gasification of municipal solid waste (MSW) is an efficient pathways to utilize the gas as a fuel which could be combusted in a conventional burner or in a gas engine to utilize the heat or produce electricity. Biogas generated using solid waste through the biological processes are CH_4 (55–60%), CO_2 (30–35%), N_2 (4–5%) and a trace amount of H_2S. during start-up operation and 715 kWh of electricity could be produced by the maximum conversion of organic waste to COD (Zulkifli et al., 2019; Couto et al., 2013). Studies have reported that the heating value of the syngas can vary between 3 MJ/m^3 and 15 MJ/m^3 (Couto et al., 2013). The syngas composition of MSW involves H_2 (8–23% mol) CO (22–24% mol) CH_4 (0–3% mol) CO_2 (6–15% mol) and HHV (3–7) MJ/m^3 (Niu et al., 2013). The use of raw gas in engine operation exhibits a lower brake power and torque than gasoline because of its lower heating value and slower flame velocity though the lower heating value property requires a higher burning capacity to obtain an equivalent power to gasoline. The in-cylinder pressure and temperature are lower because of slower flame propagation and that has resulted in the flame speed of biogas. Even, the heat release rate of biogas was lower than that of diesel due to slower flame propagation nature (Yilmaz and Gumus, 2017). The use of biogas facilitates a reduction in NO_x emission because the carbon dioxide content present in the biogas reduces the combustion temperature by reducing the heating value. Typically, the levels of CO and CO_2 emission are primarily influenced by the concentration of CO_2 present in the biogas. Similarly, HC emission purely relies on the proportion of methane level in the fuel; presence of higher level of methane reduces combustion temperature through incomplete combustion, which leads to the occurrence of HC (Makareviciene et al., 2013; Karagöz, 2019). The antiknocking ability of biogas can be estimated by Methane Number (MN), which seems to be higher for biogas among all the other fuels. Therefore, the life of the biogas fuelled engine would be longer without any operating issues. However, the concentrations of inert gas and hydrogen sulfide are needed to be regularly monitored for long term applications of biogas in the SI engine.

The use of syngas in the engine obtained lower level brake thermal efficiency due to lower heating value property compared to gasoline. Moreover, the gaseous nature of the fuel and lack of evaporative cooling reduces volumetric efficiency. The higher compression ratio is very much essential to improve thermal efficiency. In syngas, the presence of H_2 content reduces autoignition temperature along with a decrease in laminar flame velocity. Therefore, the combustion duration and ignition delay period are getting shortened (Dai et al., 2012). In emission aspects, the formation of HC emission is greatly reduced due to the absence of hydrocarbon content in it. On contrary, the low carbon content and wider flame propagation lead to shorter flame quenching distance by the H_2 gas content in syngas, which has resulted in lower CO emissions. Also, the low self-ignition temperature property and fast flame propagation features of syngas reduce cylinder pressure and cylinder temperature, which cause a reduction in NO_x emission (Park et al., 2011; Hagos, et al., 2012).

7.2. Liquid fuels in IC engines

Liquid biofuels are being increasingly used as an alternative fuel to conventional petroleum-based gasoline and diesel derivatives. Generally, liquid fuels will be the perfect replacement for the existing fossil fuels due to more safety and convenience to handle when compared to the gaseous fuels. In this section, the properties of liquid fuels, applications in the IC engine and their combustion output characteristics of performance and emissions are discussed. The performance, combustion and emissions effects of various liquid fuels on both Compression ignition (CI) and spark ignition (SI) engines are presented in Table 4.

7.2.1. Methanol

The waste-to-methanol (WtM) process and related economics are assessed to evidence that WtM is a valuable solution from economic, strategic and environmental perspectives. The methanol fuel application in CI engine, performance characteristic of BSFC will be higher because of the low latent heat of vaporization of fossil fuels blended with methanol (Sayin, 2010). In methanol added diesel fuel blend, laminar flame speed is increased, which leads to a high combustion temperature and reduces combustion duration. An improvised combustion process also restricts the CO formation, especially, at increased engine speed. Even, the higher cylinder temperature enhances the binding of nitrogen and oxygen, which leads to higher NO_x formation. The presence of oxygen content in the fuel promotes fuel rich zone formation, which will reduce the smoke opacity of methanol (Sayin et al., 2009).

In methanol powered SI engines, the low calorific value of methanol increases BSF compared to gasoline as in CI engine. An increase of methanol content in the gasoline blend exhibits higher BTE and lower BSFC. This is due to the higher flame speed of methanol when compared to gasoline, which causes complete combustion of fuel and reduces heat loss from the cylinder surface. Similarly, the volumetric efficiency of methanol increases because of the higher latent heat of vaporization, which is higher than that of gasoline and tends to absorb more heat from the cylinder and increases the density of fuel charge (Celik et al., 2011; Liu et al., 2007). In-cylinder pressure of ethanol increases due to the oxygenated properties of methanol promoting better combustion compared to gasoline fuel (Tian et al., 2020; Agarwal et al., 2014). In emission characteristics, the HC emission is higher because of the higher latent heat of vaporization, which decreases the in-cylinder temperature. Due to this, higher latent heat of vaporization misfire and incomplete combustion also occurs particularly at lower speeds. However, the CO emission is lower for the methanol blend because of its oxygen content, which helps for complete combustion. Due to the higher LHV of methanol and lower combustible mixture temperature in the engine cylinder, the NO_x formation decreases when compared to gasoline (Celik et al., 2011; Tian et al., 2020).

7.2.2. Ethanol

Biodegradable fraction of municipal solid waste subjected to several pretreatment and saccharification processes simulates effective production of ethanol (Althuri and Venkata Mohan, 2019). In ethanol, the properties like viscosity, vaporization temperature, flammability, flash point are very much close to that of fossil fuels. Hence, for internal combustion engine applications, it can be a better substitute for fossil fuels (Sayin, 2010). The lower heating value of ethanol relative to diesel increases the BSFC and decreases the thermal efficiency during low load conditions. Nevertheless, under high load conditions, the BSFC decreases and improvement in combustion efficiency is spotted (Huang et al., 2009). In emission aspects, at full load conditions, an occurrence of complete combustion reduces the CO emission of ethanol. Even during high speed operation of the engine, the higher cylinder temperature enhances the chemical reaction that takes place between fuel and oxygen. Therefore, the presence of a complete combustion environment decreases the HC emission. At low speed running conditions, NO_x emissions of ethanol and its blends are low and at the high load conditions, NO_x emissions are higher and unstable sometimes (Barabas et al., 2010; Rakopoulos et al., 2008).

Similarly, in SI engines, adding ethanol to gasoline reduces engine torque and loss of fuel economy. This is due to the fact that the heating value of ethanol is lower when compared to that of gasoline (Tian et al., 2020). The BSFC of ethanol blend increases due to the lower LHV. However, at higher flame speed, it tends to complete combustion of fuel and reduces the heat losses from the cylinder surfaces, thus, the brake thermal efficiency tends to increase. By adding ethanol to gasoline, it tends to decrease the combustion duration as ethanol has a tendency of faster velocity in its laminar flame (Tian et al., 2020; Hasan et al., 2018). The HC and CO emissions decrease because the oxygen content in ethanol fuel blends improves the quality of combustion (Mourad and Mahmoud, 2019). Since ethanol has a low adiabatic temperature, higher heat of vaporization when compared to gasoline, the maximum temperature inside cylinder tends to decrease. Hence, the NO_x emission in the engine fuelled with ethanol decreases (Balki and Sayin, 2014).

7.2.3. Butanol

The starchy and lignocellulosic materials present in the MSW subjected to enzymatic hydrolysis has the high potential for the production of butanol. The combustion characteristics of fuel in engines depend on their physicochemical properties. The high latent heat of vaporization of butanol decreases the in-cylinder combustion temperature of CI engine and also extends the ignition delay period resulting in a higher heat release rate. The lower values of viscosity, density and boiling point of butanol promote the fine spray atomization leading to better evaporation processes by which a higher premixed combustion regime exists. Therefore, higher peak values are observed in in-cylinder pressure and also in heat release rate (Li et al., 2019). From a performance point of view, the lower calorific value of butanol offers higher brake thermal efficiency compared to diesel and also increases brake specific fuel consumption as exhibited to achieve equivalent torque of diesel (Rakopoulos et al., 2010; Li et al., 2019). In case of emissions, the exhaust temperature is lowered due to the higher heat of evaporation of butanol resulting in a decrease of NO_x emission. The CO emission of butanol also decreases when the ratio of butanol content in the diesel blend increases. Similarly, HC emission from the engine exhaust decreases when a higher proportion of butanol is present in the butanol-diesel blend (Yusri et al., 2019).

In the SI engine, the brake thermal efficiency of butanol increases with an addition of butanol to the gasoline blend. This is caused by low viscosity, high fuel lubricity and high amount of oxygen properties of butanol. However, the addition of butanol to gasoline, has to be in particular level of proportion because brake torque, brake specific fuel consumption are getting negatively influenced after a particular limit (Mourad and Mahmoud, 2019). The lower latent heat of vaporization of butanol lowers the heat release rate and reduces the in-cylinder combustion temperature. The occurrence of lower exhaust gas temperature in butanol blended gasoline fuel increases the HC emission by inhibiting the oxidation of HC. Further, the addition of butanol to gasoline reduces NOx emission because of the faster laminar flame speed and less combustion duration. The butanol fuelled engine experiences lower CO emissions. This is due to the enhanced supply of oxygen content by adding butanol to the gasoline whereas, CO_2 emission is higher (Tian et al., 2020).

7.2.4. Biodiesel

The lipids present in the Organic fraction of MSW will be extracted for the production of biodiesel. Food waste has a great potential for lipid production with a ratio of 2:1 (solvent:food waste) the extracted lipid have efficient potential for biodiesel production (Barika and Paul, 2017). The food waste consists of saturated and unsaturated fatty acids and subsequently biodiesel quality depends on the amount of unsaturated fatty acids fraction. In general higher amount of saturated fraction, has lower quality and can cause knocking or plug flow problems in engines. In the performance characteristics, torque value decreases due to the lower calorific value of biodiesel compared to that of diesel fuel in the CI engine. Also, the poor combustion process because of the higher viscous property and lower heating value of the biodiesel, have decreased BTE (Buyukkaya, 2010). The BSFC of pure biodiesel is higher than that of diesel fuel due to the nature of lower energy content that requires more fuel for the demanded torque (Chauhan et al., 2012). During the combustion of biodiesel, the in-cylinder pressure, peak cylinder temperature and the total energy released decrease when compared with diesel due to the lower calorific value of biodiesel (An et al., 2012). Nevertheless, when there is an increase in the injection pressure, it increases the fine spray cone angle and also its penetration, resulting in an increase of heat release rate. As there is an increase in the injection pressure, there will be a slight increase in the ignition delay period of the biodiesel blends. Even, as the proportion of biodiesel quantities is higher in blends, the period of ignition delay is prolonged (Gharehghani et al., 2017). The combustion attribute of prolonged ignition delay period in biodiesel exhibits a higher range of exhaust gas temperatures. Also, the higher viscosity nature of biodiesel fuel leads to the existence of unburnt fuels in the phase of premixed combustion and continues to burn in the later phases of combustion, hence, increases the exhaust gas temperatures (Sayin et al., 2012). Higher NO_x is observed generally for biodiesel fuelled engines. In general, NO_x emission will be higher due to the combustion temperature being higher, availability of oxygen content, and longer duration of combustion inside the engine cylinder and so on. As the biodiesel fuel is oxygenated and holds a shorter delay of ignition due to its cetane number, it is expected that neat biodiesel fuels will result in the improved rate of combustion and hence, higher formation of NO_x (Ibrahim, 2016). The moderate level of CO emissions is observed because of more oxygen atoms in the biodiesel, which rapidly reduces the flame temperature (An et al., 2012; Muralidharan and Vasudevan, 2011). In some cases, the same oxygenated property of biodiesel becomes advantageous because it leads to complete combustion and results in higher CO_2 emissions. This also can be attributed to the combined effect of higher cetane number and the oxygen content of the biodiesel (Gnanasekaran et al., 2016). The HC emission decreases with increasing the blending percentage of

Table 4
Applications of various liquid fuels in internal combustion engines.

Engine specifications	Test conditions	Fuel used	Reference fuel/parameter	Combustion	Performance	Emission	References
Single-cylinder, 4-stroke, air cooled, low power gasoline engine (DATSU LT 200), CR-8.5	Variable compression ratio	Ethanol	Gasoline	Cylinder pressure ↑, HRR ↓, HRR at CR-9.5 (irregular)	BMEP ↑, BTE ↓	HC ↓, NOx ↓, CO ↓, CO↑ (for CR-8), CO_2 ↓, CO_2 ↑ (for CR-9.5)	Balki and Sayin, 2014
		Methanol	Gasoline	Cylinder pressure ↑, HRR ↓, HRR at CR-9.5 (irregular)	BMEP ↑, BTE ↓	HC ↓, NOx ↓, CO ↓, CO_2 ↓ (for CR-8 & 9), CO_2 ↑ (for CR-8.5 & 9.5)	
Super Star 7710, single cylinder, 4-stroke, CI engine, CR-17, power-7.4 kW, speed-1900 rpm	Variable speed	Ethanol (E5, E10)	Diesel	–	BSFC ↑, BTE ↓	HC ↓, NOx ↑ CO ↓, smoke ↓	Sayin, 2010
		Methanol (M5, M10)	Diesel	–	BSFC ↑, BTE ↓	CO ↓, smoke opacity ↓	
Lombardini LM 250, single cylinder, 4-stroke, CR-6 to10, speed–3600 rpm, air & water cooled	Variable speed	Methanol with CR-6,8,10	Gasoline	Cylinder pressure ↑ (CR-8,10), cylinder pressure ↓ (CR-6)	BT ↑ (CR-8,10), BT ↓ (CR-6), BP ↑ (CR-8,10), BP ↓ (CR-6), BSFC ↑, BTE ↑	HC ↑, NOx ↓, CO ↓, CO_2 ↓	Celik et al., 2011
Four cylinder, direct injection SI engine, CR-9.6, power-128 kW	Variable speed	Ethanol (E10, E20), methanol (M10, M20), butanol (Bu10, Bu20)	Gasoline	P_{max} ↑, HRR ↑, EGT ↓	BT ↑, BSFC ↑, BTE ↑	HC ↑, NOx ↓, CO ↓, CO_2 ↓	Tian et al., 2020
	Variable throttle position	Ethanol (E10, E20), methanol (M10, M20), butanol (Bu10, Bu20)	Gasoline	P_{max} ↑, HRR ↑, HRR ↔ (Bu10, Bu20), EGT ↓	BT ↑, BT ↔ (Bu10, Bu20), BSFC ↑, BTE ↑	HC ↑, NOx ↓, CO ↓, CO ↔ (E10, M10, Bu10, Bu20), CO_2 ↓	
Zen 2001/Maruti Suzuki, 4-cylinder, 4-stroke, water cooled SI engine, power-40PS, speed-3500 rpm, CR-8.8	Variable speed with load	Methanol (M10, M20)	Gasoline	Cylinder pressure ↑, HRR ↓, EGT ↓	BSEC ↓, BSFC ↑, BTE ↑	HC ↑, NOx ↓, CO ↓, smoke ↓	Agarwal et al., 2014
Single-cylinder, 4-stroke, water cooled, direct injection CI engine, CR-20, power-8.82 kW, speed-2000 rpm	Variable load, variable speed (1500, 2000 rpm)	Ethanol-diesel (E10, E20, E25, E30)	Diesel	–	BSFC ↑, BTE ↓, (at low load), BSFC ↓, BTE ↑ (at high load except E10)	HC ↑, NOx ↓ (except E10), CO ↑ (at low load), CO ↓ (at high load), smoke ↓	Huang et al., 2009
4 in line, CR-17, direct injection, speed-1800 rpm, power-46.5 kW, CI engine	Variable load	Ethanol + biodiesel + diesel (D85B10E5, D70B25E5, D80B10E10)	Diesel	–	BSFC ↑, BTE ↓	HC ↓, NOx ↑, CO ↓, CO_2 ↑, smoke ↓	Barabas et al., 2010
Mercedes-Benz, OM 366 LA, 6-cylinder, 4-stroke, water cooled direct injection CI engine, speed–2600 rpm, CR-18, power-177 kW	Variable pressure (3.56, 7.04, 10.52 bar), variable speed (1200, 1500 rpm)	Ethanol + diesel (E5, E10)	Diesel	–	BSFC ↑, BTE ↑	HC ↑, NOx ↓, CO ↓, soot density ↓	Rakopoulos et al., 2008
Air cooled, single – cylinder 4-stroke petrol engine, power-1.2 kW, speed-2500 rpm	Variable compression ratio (4, 5.5, 7, 8.5, 10)	Ethanol + gasoline (E10, E20)	Gasoline	–	BMEP ↑, BSFC ↑, BTE ↑	HC ↓, NOx ↑, CO ↓, (except CR 4, 5.5), CO_2 ↓	Hasan et al., 2018
Hyundai G4eh 4-cylinder, 4-stroke, water cooled, port-fuel injection SI engine, power - 61.78 kW, CR-9.5, speed-5500 rpm	Variable speed	(Ethanol + butanol) + gasoline	Gasoline	Cylinder pressure ↓	BP ↓, BSFC ↑, BTE ↓	HC ↓, NOx ↑, CO ↓, CO_2 ↑	Mourad and Mahmoud, 2019
Four cylinder, turbocharged Isuzu diesel engine, 4-stroke, CR – 17.5, common rail injection	Crank angle	Butanol + diesel (DBu5, DBu10, DBu15)	Diesel	Cylinder pressure ↓, ROHR ↓, ROPR ↓	–	CO ↓, HC ↓, NOx ↓, CO_2 ↓	Yusri et al., 2019
Single cylinder, 4-stroke, air cooled, direct injection TecQuipment TD212 diesel engine, CR-22, power-3.5Kw, speed - 3600 rpm	Variable load	Butanol (Bu10, Bu20, Bu100)	Diesel	Cylinder pressure ↓, HRR ↑	BSFC ↑, TE ↓	NOx ↑	Ibrahim, 2016
		Biodiesel (B50, B100)	Diesel	Cylinder pressure ↓, HRR ↑	BSFC ↑, TE ↓ (except B50 at high load)	NOx ↑	
4-Cylinder, 4-stroke, water cooled, direct injection, CI engine, power-85 kW, speed-3500 rpm	Variable load	(n-Butanol + biodiesel) NB10, NB20, NB30	Diesel	Ignition delay ↑, combustion duration ↓, EGT ↓	–	HC ↑, NOx ↑, CO ↓, soot ↓	Xiao et al., 2019
Ricardo/Cussons 'Hydra', single-cylinder, 4-stroke, water cooled, direct injection CI engine, speed-4500 rpm, CR-19.8	Variable load	Butanol (8%, 16%, 24%)	Diesel	EGT ↓	BSFC ↑, BTE ↑	HC ↑, NOx ↓, CO ↓, soot ↓	Rakopoulos et al., 2010

(continued on next page)

Table 4 (*continued*)

Engine specifications	Test conditions	Fuel used	Reference fuel/parameter	Combustion	Performance	Emission	References
4-Cylinder, 4-stroke, water cooled, direct injection, CR-18.5, power-75 kW, speed-3600 rpm	Variable speed	Biodiesel (B10, B20, B50, B100)	Diesel	Cylinder pressure ↓, HRR ↓ (except B10), EGT ↓	BT ↓, BSFC ↑, BTE ↑ (except B10)	HC ↓, NOx ↓, CO ↑, CO_2 ↓ (except B10)	An et al., 2012
3-Cylinder port fuel injection, Spark ignition engine	Variable speed	Methanol (M10)	Gasoline	–	BP ↓, BT ↓, BTE ↑	HC ↓, NOx ↓, CO ↓	Liu et al., 2007
YC4FA115-40, 4-cylinder, 4-stroke diesel engine, WC, CR-17.5, power-85 kW, speed-3200 rpm	Variable EGR %, crank angle	Butanol (Bu30) (70% of diesel + 30% of butanol)	Diesel	Cylinder pressure ↑, HRR ↑, cylinder temperature ↑	BSFC ↑, BTE ↑	HC ↑, NOx ↑, CO ↓	Li et al., 2019
FARYMANN 18 W, single cylinder, 4-stroke, water cooled diesel engine, CR-18.2, speed-1800 rpm	Variable premixed ratio %	Biodiesel (B20, B40)	Diesel	P_{max} ↑, P_{max} ↓ (at 85%), ignition delay ↓, EGT (B20 ↑) (B40 ↓), combustion duration ↓	IMEP ↓, ITE ↓	HC ↑, CO ↓	Mohebbi et al., 2018
Single-cylinder variable compression ratio (VCR) Ricardo E6 diesel engine	Variable load	Biodiesel	Diesel	Cylinder pressure ↑, HRR ↑	BSFC ↓, BTE ↑	HC↓, NOx ↑, CO↓	Gharehghani et al., 2017
Single cylinder, 4 stroke diesel engine at 1500 rpm, power-3.7 kW, CR-5 to 22 (variable)	Variable compression ratio	Biodiesel	Diesel	EGT ↓	BSFC ↓, BTE ↑	HC ↑, NOx ↑, CO↑	Muralidharan and Vasudevan, 2011
Lombardini 6 LD 400, 1-cylinder, CR-18, 4 stroke diesel engine, speed-1500 rpm, power-7.5 kW	Variable compression ratio & variable Injection pressure	Biodiesel (B100)	Diesel	–	BSFC ↑, BTE ↑	HC ↓, NOx ↑, CO ↓, smoke ↓	Sayin and Gumus, 2011
Kirloskar, single cylinder, 4 stroke, air cooled diesel engine, speed-1500 rpm, CR-17.5, power-7.4 kW	Variable load	Biodiesel	Diesel	Cylinder pressure ↓, HRR ↓	BSFC ↑, BTE ↓	HC ↓, NOx ↑, CO ↓, smoke ↓	Chauhan et al., 2012
Lombardini 6 LD 400, single cylinder, 4 stroke diesel engine, power-8 kW, speed-2000 rpm, CR:18	Variable load	Methanol	Diesel	EGT ↑	BSFC ↑, BTE ↓	HC ↓, NOx ↑, CO ↓, CO_2 ↑, smoke ↓	Sayin et al., 2009
Super Star 7710, single cylinder, 4 stroke diesel engine, power-7.4 kW, speed-1900 rpm, CR:17	Variable speed	Ethanol	Diesel	–	BSFC ↓, BTE ↓	HC ↓, NOx ↑, CO↓	Sayin and Canakci, 2009
MAN, 6-cylinder, 4-stroke, direct injection CI engine, turbocharged, power - 164 kW, speed-2100 rpm, CR:17	Variable speed	Biodiesel	Diesel	Cylinder pressure ↓, HRR ↓	BSFC ↑, BTE ↓	HC ↓, NOx ↑, CO ↓, smoke ↓	Buyukkaya, 2010

↑ - increases, ↓ - decreases, ↔ - equal.

biodiesel due to the high oxygenated nature of biodiesel enhancing complete combustion (Gharehghani et al., 2017; Sayin and Gumus, 2011).

8. Multifuel powered internal combustion engines

Multifuel engines are very much essential to prolong the period of the world's oil supply with the use of alternative fuels from waste utilities whenever the availability is present. Even, if the source of any alternative fuel for a course of period is temporarily unavailable, the engine can switch to run on gasoline or diesel. The market share of the multifuel powered vehicles keeps on increasing year by year among the customers because it offers the benefit of selecting the desired fuel according to price and performance. However, the development of such multifuel engines has numerous obligations and constraints, which are focused in this section. The multifuel vehicles are classified as Bi-fuel, dual-fuel and flex-fuel engines based on the use and storage of fuel during engine operation.

8.1. Bi-fuel and dual-fuel engines

Bi-fuel engines are capable to run on two different fuels one at a time; whereas dual-fuel engines run on a single fuel as well as both fuels simultaneously in proper mixing ratio. The two separate fuels are stored in two separate tanks and can be automatically or manually switched back and forth during the vehicle operation. The Bi-fuel and dual-fuel engines are acceptable to operate with alternative fuels in the form of both gaseous and liquids. Based on availability, automatically switch between the types of fuel, which has the most fuel-efficient. The alternative fuels like CNG, LPG, biogas, hydrogen, methane, propane, ethanol and methanol are most commonly used along with gasoline or diesel for bi-fuel and dual-fuel operation. In most cases, the gaseous fuel is used as a primary fuel and gasoline or diesel as its secondary fuel in Bi-fuel engines (Sáinz et al., 2012). Though gaseous fuels have a good mixing capability and clean burn characteristics, their low volumetric efficiency results in power loss. Hence, in order to prevent the power loss, the bi-fuel engine has to be equipped with variable turbo-chargers or by elevating the compression ratio through a variable valve timing facility (Tennant et al., 1994). The optimal use of variable valve timing also enables to run in the stoichiometric mixture without backfire through better scavenging of exhaust gases (Verhelst et al., 2010). In dual-fuel engines, to avoid the power shortage during the demand, the proportion of gasoline or diesel fuel is increased relative to the gaseous fuels (Karim, 1980). The requirement of a variable supply of fuels can be managed by an electronically controlled solenoid-actuated valve system assisted by an active realtime controlled ECU. Moreover, the set of optimum ignition timing significantly provides maximum torque and high knock resistance. In bi-fuel engines, the use of a single ignition curve causes a significant power drop or occurrence of knocking when operated with fuels not meant for. Hence, there must be a change in the ignition curves with respect to the fuel operation (i.e. Dual ignition curves to achieve maximum results on both the fuels) (Bosch, 2010; Lawankar and Dhamande, 2012). Typically, the advance spark timing is utilized for the gaseous fuels because of lower burning speed than gasoline and diesel (Ben et al., 1999). Even in dual-fuel engines, an optimum ignition curve is essential to be framed for the various proportions of two fuel mixtures, especially, during acceleration and heavy loads. For stable combustion of any fuel more turbulence is required and based on the property of the fuel, the nature of mixture character varies. Hence, the mixture problem in bi and dual-fuel engines is controlled by an active adjustment of valve movement with dissimilar valve lift in respect to the use of fuel to increase swirl motion in the engine (Ramasamy et al., 2016). The supply mode of fuel is also very important for efficient engine operation, especially, for gaseous fuels, the current induction method of supply via port injection produces lower brake power compared to gasoline or diesel fuel (Kalam and Masjuki, 2011). Hence, the direct injection of high pressure gaseous fuel straight into the cylinder is more suitable for the future fuel delivery system to produce similar or higher power and range to gasoline or diesel fuel (Devarajan et al., 2015). On the whole, several technical problems in bi and dual-fuel engines still need to be investigated for the heterogeneous fuel (i.e. CNG + gasoline) operation compared to the homogeneous (i.e. Methanol + gasoline) fuel. Even though the best compromise between emissions and fuel economy is achieved by an optimal set point, research in an aspect of long term operation has to be carried out for the sustainable operation of various fuel powered engines. The use of alternative fuels creates filter clogging, injector coking, more carbon deposits, lubricant degradability, corrosion, surface degradability and much more compared to conventional fuels over the long period of run.

8.2. Flex-fuel engines

Flex-fuel engines are designed to support in an aspect of utilizing the biofuels as well as conventional fossil fuels for their flexible mode of operation across different fuel sources. The flex-fuel engine advantages and their unique characteristics differ from conventional engines as shown in Fig. 7b. Unlike bi-fuel engines, the different fuels are stored in the single common tank for a flex-fuel engine. The on-board sensor modules dynamically diagnose the characteristics of fuel or blend proportion filled in the tank, and adjust the engine operating parameters based on the torque demand from the engine (Bosch, 2007). Typically, liquid biofuels like ethanol, methanol, butanol blended with gasoline (SI) or diesel (CI) are used in flex-fuel engines. The first successful development of flex-fuel vehicles was in 2003, which had the capacity to operate in gasoline blended with ethanol (E-85) or 100% ethanol (de Melo et al., 2012). On the other hand, because of limited arable land for ethanol production, methanol (from wood and agriculture waste products) or gasoline blended with methanol-based flex-fuel engines are also developed. Many significant amounts of research have been carried out to develop a flex-fuel engine with any proportion of alcohol operation. However, as the engine is a complex system, huge technical difficulties are present to optimize the engine performance and emissions for various fuels and their blends. For alcohol, the operation requires a higher compression ratio (CR) to elevate the knock resistance, whereas, the compression ratio (CR) no longer has to be increased over a limit for gasoline (Vancoillie et al., 2013). Hence, an optimized intermediate compression ratio is essential for the flex-fuel engines to operate on variable fuels i.e. (from 10.8:1 up to 13:1 for ethanol and gasoline flex-fuel engine) (Júnior et al., 2011).

In flex-fuel engines, the use of alcohol or alcohol blended fuels creates trouble during the cold start of the engine and increases HC, CO and aldehyde emissions (Sales and Sodré, 2012). Thus, to encounter cold start issues, a tiny auxiliary gasoline tank is used alone for the cold start operation. In a recent development to avoid the use of auxiliary gasoline, as a replacement strategy facilitates heating coil set up in a fuel tank to warm up the alcohol fuels or simultaneous heating of intake air and fuel through electric resistances. The improved cold start system reduces the HC, CO emissions but no significant changes in NO_x and aldehyde emissions (Sales and Sodré, 2003; Brunocilla and Lepsch, 2006). Since the flex-fuel engines can operate on various concentrations of the fuel blends, an adaptation of the respective stoichiometric air-fuel ratio is important for the emission reduction (Ahn et al., 2009). Such engine control adjustment requires the knowledge to diagnose the type of fuel or blend concentration. It can be established through sensor mounting in a tank or in the fuel line but due to the high additional cost of fuel detection, sensors are not widely used (Oliverio et al., 2009). On the other hand, the oxygen sensor signal can detect the level of oxygen content in the exhaust gas, through which, it is able to estimate the fuel oxygen content to identify its type or blend concentration (Volpato et al., 2005; Seitz et al., 1998). Though the diagnosis of fuel by the exhaust gas oxygen sensor is an acceptable accuracy, during engine start-up, it cannot be used and also, there is a presence of long delay in the feedback loop. Next, the control of spark timing corresponding to the use of fuel is important, a precise adaptive ECU is essential for the active spark timing control to obtain the maximum torque as well as to keep the engine below the knock limit. Overall, to exploit the potential advantages of biofuels in flex-fuel engines, dedicated adaptive engine control systems and low-cost supportive hardware components are yet to be developed for the current emission standards as well as to improve the fuel economy. In addition to the fuels, to generate varies products integrated biorefinery processes is an effective processes.

9. Integrated biorefinery platform for a closed loop approach

Integrated biorefinery is an effective process to recover energy and biomaterials through a sequence of unit operations (Venkata Mohan et al., 2016). The unit operations get connected to each other such that the inlet and outlet of each process gets used with effective cycling of resources through a circular pathway (Venkata Mohan et al., 2016). In general the biorefinery concept was well practiced for biomass volarization to value added products and bioenergy. Now it has been initiated to treat solid waste as biodegradable and non-biodegradable fractions through a sequence of operations such as raw material collection, transportation, distribution, processes, products and applications through an integrated refinery processes (Fig. 8). The fore most step is the collection of segregated solid waste from different sources (Raw material), Transport the waste to the common collection point (Transportation), distribution of segregated waste as biodegradable and non-biodegradable (Distribution), selection of processes such as biological, thermochemical, mechanical/physical, chemical, etc. whichever is feasible (Processes), separate the processed product based on energy and material (Products) and use the energy and material for different applications (Applications). The solid waste which has higher potential could be considered as effective feed stock when it's segregated as biodegradable and non-biodegradable fractions. The separated fraction has the capacity to produce bioenergy, biobased products and value added chemicals when it follows a closed loop integrated biorefinery processes (Soetaert, 2009; Cherubini et al., 2009).

The closed loop emphasis that the bioenergy generated through the bioprocesses could be used in the reverse processes. As discussed in previous sections, the characteristics of solid waste are complex hence it requires different refinery and recycling technologies. The foremost is source segregation which has become an accepted paradigm for effective management of waste. Segregation of solid waste increases the processes efficiency by effective utilization of the waste based on its properties such as wet waste and dry waste. The biodegrades fraction of solid waste can be converted into various bioenergy such as biomethane, biohydrogen, bioelectricity, etc., as mentioned in the above sections and other value added products through biological processes. However, the produced bioenergy could be purified and used for combustion of engines and the energy generated from those processes which has the feasibility to back use for the collection, transportation, to run the biological reactors, etc. hence the loop gets closed

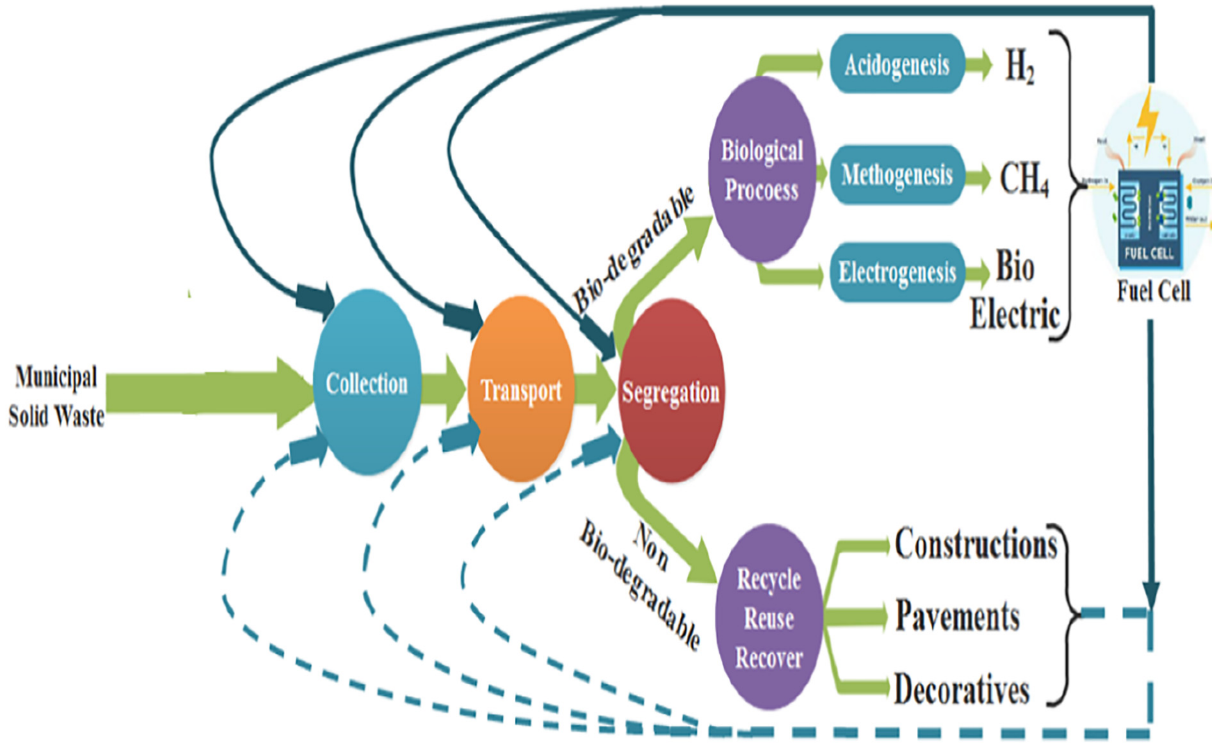

Fig. 8. Integrated refinery platform for closed loop approach for both biodegradable and non-biodegradable.

(Fig. 8). Studies reported that production of H_2 through dark fermentation is estimated to have 340 times lower process costs than that of photosynthetic processes inferring that the fuel and material produced from MSW through the biorefineries has good economic value (Atif et al., 2005). Bioconversion of 1 kg of crude glycerol can produce 48.14 L of H_2 and 307.06 g of 1,3 propanediol whereas the present market value of H_2 for one cubic meter is $7.75–$11.50 and butyric acid is $2 to $50/kg 1,3 propanediol is $288/L (Sarma et al., 2015). Studies could be optimized to enhance the yield from the waste by engineering the biocatalyst used in the biological processes with various techniques and by other operational factors.

The non-biodegradable fraction of solid waste which can be reused without many transformations, recycle it by reprocessing the waste mildly and recovery the waste with effective segregation also has good economic value. The physical, chemical, thermolysis, and mechanical methods are playing a crucial role in the conversion of a non-biodegradable fraction of solid waste for various applications. The inert material could be processed and converted to value added products and the recovered materials could be used for construction, pavement, reused for mechanical parts of machinery and also used for decorative purposes. This could partially close the loop through the integrated refinery processes which is paving the road to the circular economy. In general the single product processes in a biorefinery also produces chemicals and materials however the production in an integrated biorefinery processes targets for zero waste discharge, the waste from one processes will be the feedstock for other processes will be a superior approach for the sustainable valorization of biomass and solid waste. The main concept of this integrated refinery processes is to shift the paradigm from a linear economy to circular for greener footprint. To make the processes effective the policies play a major role.

10. Policies for solid waste management

The current section discusses the general solid waste management policies practiced in many countries followed by circular economy policies initiated in few countries. Waste management law is being followed by different trajectories from the principle based approach with respect to common and civil law. Its legislators were initiated by addressing human health and environmental issues followed by avoiding waste and recovering resources from waste.

10.1. General policies for solid waste management

The waste management transition varies between the countries, in UK the waste management has been traced back to 1388 and introduced act as "Act of Richard II" "removal of refuse on pain of forfeits" but was not active and serious until the 19th Century. The Public Health Act 1848 was implemented to avoid depositing of waste followed by "Control of Pollution Act 1974 (COPA)", "Environmental Protection Act 1990 (EPA)", "The Packaging Waste Regulations - 1997". Other acts like "Landfill (England and Wales) Regulations 2002", "Waste and Emissions Trading Act 2003", "Hazardous Waste Regulations 2005", "Pre-treatment of inert or non-hazardous wastes in 2007". In 2015, legislation law to separate recyclable material (paper, plastic & glass) from other waste to ensure improvement to the quality and quantity of recycling (https://www.gov.uk/topic/environmental-management/waste). In Germany, based on the constitution amended in 1972 "The Waste Disposal Act" was introduced for siting centralized larger facilities for effective disposal of waste. To overcome the waste crisis the "Waste Avoidance and Waste Management Act 1986, – AbfG" was practiced to valorize resource recovery over disposal. "The Closed Substance Cycle Waste Management Act 1994 (KrW-/AbfG)" is the expression of a centralized waste management system. In Netherlands, "Nuisance Act 1875" is the first piece of Dutch legislation dealing with the issues arising from waste management, "Waste Substances Act 1977 (WSA)" deals with surface waters, air, chemical waste and noise, Environmental Management Act 1993 (EMA). The "Packaging and Packaging Waste Regulation 1997" is an expression of the extended producer. United States of America "Solid Waste Disposal Act" was formulated in the year 1965 for improving the method of disposal followed by the "Resource Recovery Act 1970" and "Resource Conservation and Recovery Act of 1976 (RCRA)", "The Hazardous and Solid Waste Amendments of 1984

(HSWA)" Other policies such as the "Medical Waste Tracking Act of 1988", "Ocean Dumping Ban Act of 1988", RCRA clean-up reforms I&II of 1999 and 2001, etc.

Sweden is the global leader in sustainable waste management and the environmental regulation begins in 1960s by passing the "Nature Conservancy Act-1964". Environmental Protection Agency was established in 1967 and the advisory committee was formed followed by Act on "Products Hazardous to Health and the Environment" was passed in 1973. In the 1980s, the act focused on quantity, hazard and environmental impact of waste. In 1992, a bill introducing the concept of "eco cycles" was introduced with the concept of sustainable reuse, recycling or safe disposal of everything taken from nature. Management of "end-of-life" products in an ecologically sustainable society in 1997 is to reduce the landfilling of waste. Sweden views 2030 Agenda and the sustainable development of global goals, as an overarching and forward-looking commitment. It is an agenda linked to fighting poverty and hunger and inequality within and between countries, in order to build peaceful, fair and inclusive societies for a common and long-term sustainable environmental, social and economic development.

India's Environment Protection Act was started in 1986 and various solid waste management rules were framed under it. Hazardous Waste Management and Handling Rules – 1989, Manufacturing, Storage and Transportation of Hazardous Waste Rules - 1989 amended in January 2003, August 2010. Biomedical Waste Management and Handling - 1998, Municipal Solid Waste Management and Handling – 2000 and upgraded in 2016 emphasizing the separation of solid waste Plastic Waste Management and Handling – 2011, E-Waste Management and Handling Rules – 2011. Japan policies on waste management was initiated with "Waste disposal law – 1970", "Resource efficient law - 1991", "Environmental law - 1993", "The law of separate collection and recycling of container and packaging - 1995", "Special household machine cycle law - 1998", "Sound material cycle society law - 2000", "Building construct recycling law - 2000", Small home appliance recycling act – 2013, etc. (Ogunmakinde, 2019). Though there are several solid waste related policies were framed and practiced, as traditional polices however it's a dare need to go towards circular economy since the concept is observed as a new engine of green growth worldwide which suits the current needs (Welfens et al., 2017).

10.2. Circular economy policies for solid waste management

General policies for solid waste management mentioned above are the main sources for developing the circular economy policies. International and National Policies are the effective tools to promulgate circular economy concepts as a new central path to prevail in a sustainable condition. The circular economy's vision helps to stimulate the economy of the country and identify the pathways to maximize the local resources which shift its path from linear to circular (MacArthur, 2013; Suárez-Eiroa et al., 2019). The circular economy (CE) concept is gaining traction as a sustainable strategy for reducing waste and enhancing resource efficiency. This concept has been adopted in some countries such as China, Denmark, Scotland, Sweden, Japan, Netherlands, Germany, England, Austria and Finland etc. (Ogunmakinde, 2019). Few of the country's economic policies are discussed below.

Chinese government instigated the promotion of CE as a solution to the country's many environmental problems with an origin of cleaner production, industrial ecology and ecology modernization thinking (Shi et al., 2010; Guo et al., 2017). The first economy model is "Circular Economy Pro-motion Law (CEPL)" which is in effect from 2009 (Geng et al., 2012). To assess the performance of the CE policies in china several indicators were used, initial the general performance was assessed using indicators such as 3R principles (Geng et al., 2012), macro-level (Region and Country wise) (Jakhar et al., 2019) and Meso-level (industrial parks), (Guo et al., 2017) eco-city (Guo et al., 2017). Environmental protection and resource conservation committee stated that the economy, resources and the environment have changed significantly after the implementation of CEPL for a span of 10 years in China (Zhang, 2015). The performance was evaluated by circular degree evaluation. The four-stage evaluation of natural resource utilization during production, consumption, integrated recycling, waste disposal and pollution emission can be used to identify the integrated circular degree of the economy (Wang et al., 2018). The study inferred that the economic development model amendment could emphasis on policies and government actions rather than legislation for more sustainable practices (Wang, 2013). The policies are required to be reframed by considering the zero-waste economy (Veleva et al., 2017), innovative economy (De Jesus and Mendonça, 2018), energy-efficient and renewable energy-based economy, (Ellen MacArthur Foundation, 2013) low carbon economy, (Ellen MacArthur Foundation, 2015), smart economy spatially effective economy bio-economy (Ladu and Blind, 2017) service/performance economy (Ellen MacArthur Foundation, 2015) collaborative/sharing economy socially oriented economy, etc. The policies framed in the circular economy show environmental win, economical win and social win as explained in Fig. 9.

In Europe, Germany passed the law on the circular economy in the year 1996 as "kreislaufwirtschaft" this law seeks to reduce land for waste disposal and closed loop recycling (Geng, et al., 2013; European Commission, 2010; EUROPEAN UNION (EU), 2015). The law also emphasizes that the products manufactured should be designed to minimize waste and ensure waste recovery and reuse. It is also been planned for zero waste from 2009 resulting in 50% of waste is recycled. Implementing EU guidelines the law was revised in 2012 including improved environment, climate and resource protection (Jenkins, 2002). CE entered with the road-map to a resource efficient Europe and it was announced as Circular Economy Package and upgraded to "Closing the Loop-An Action Plan for the Circular Economy". Later the action plan proposed the amendment to legislation relating specifically to waste and landfills. However, the CE policies were formulated based on the general solid waste policies practiced globally (Eurostat, 2018; Avdiushchenko and Zając, 2019; Jaron and Kossmann, 2018).

Japan's CE concept was initiated way back in 1870 due to its lack of landfill space due to rocky topography, limited domestic metal and mineral resources but the law for effective utilization of recyclables were implemented in 1991 (Ghisellini et al., 2016). Japan believed the circularity get enhanced by the effective collaboration between consumers and manufacturers (Benton and Hazell, 2015). The consumer's role is to include source separation of recyclables, prompt payment of recycling fees and protecting their right as pubic. Manufacturers' roles are the use of more recycled materials, manufacturing production of long-lasting products and design for repair, reuse, and recycling. Japan aimed at zero-emission by using the life cycle assessment system, waste minimization system, resource recycling system, the industry chain of waste recycling and the recycling, transport, and trading system of waste. It was considered in their lifestyle not only as economic behavior but also as social one (Ji et al., 2012). The resource efficient law was one of the CE law implemented in the year 1996 emphasizing on to reduce oil dependence and high energy consumption to adjust energy structure and to improve efficient energy utilization. They followed the top-down approach considering enterprises, industrial parks and society.

India's circular economy aims to unlock climate-resilient growth and the national policy makers to develop an economic model based on recycling, reusing and repairing raw materials and products. Government of India has launched National Biotechnology Development Strategy 2015–2020 to develop a bio-manufacturing hub and significantly invest in creating new biotech products, develop infrastructure for R&D, commercialization and empower India's human resources (https://pib.nic.in/newsite/PrintRelease.aspx?relid=134035; Venkata Mohan et al., 2018). India is planning a sustainable economy by encompassing in the domain of food, energy, resource recovery, diagnostics, health care and environment utilizing renewable resources for the production of biobased products and biofuels (Venkata Mohan et al., 2019; Venkata

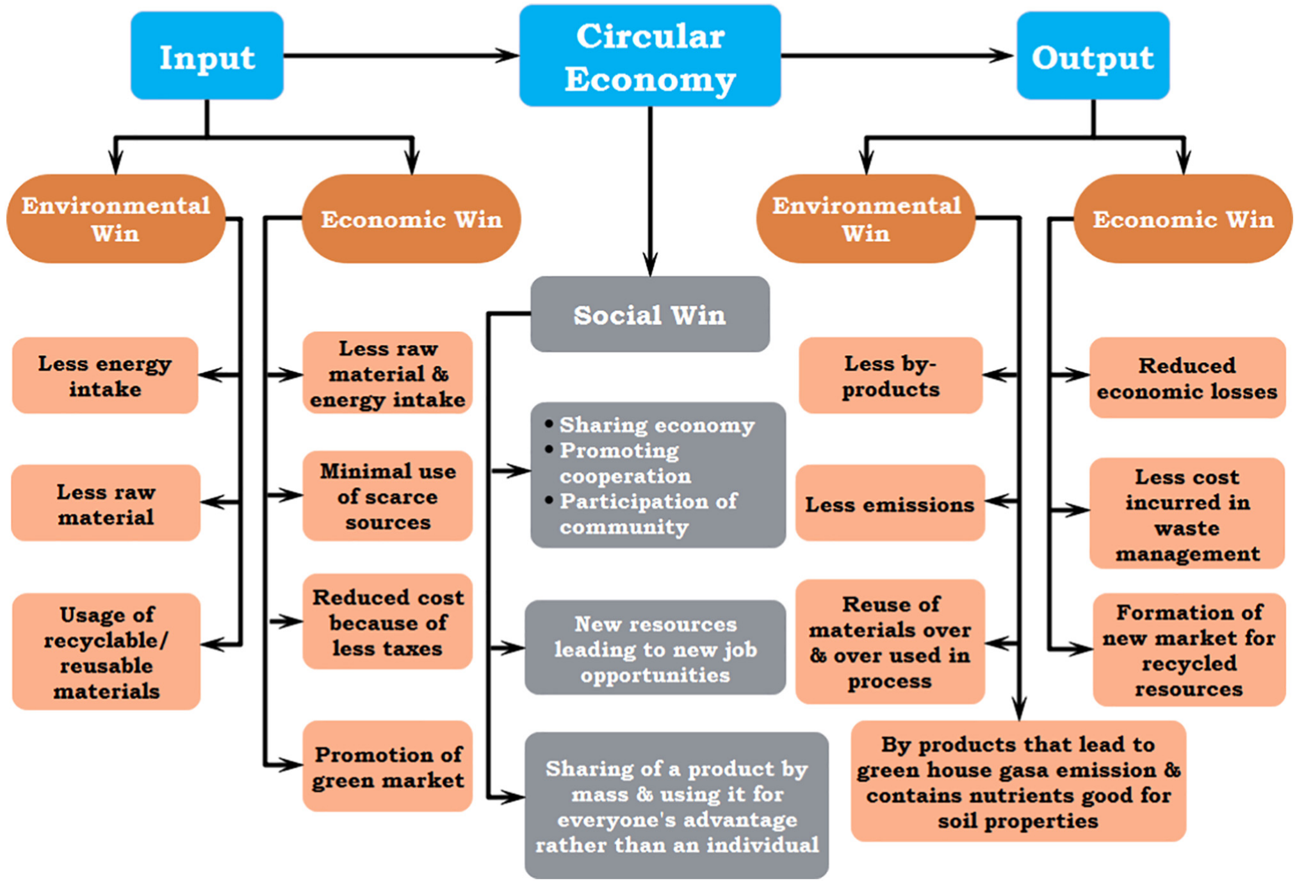

Fig. 9. Environmental, social and economical win of circular economy.

Mohan et al., 2018). The advancement of technologies also plays a crucial role for effecting practicing of solid waste management in the current scenario.

11. IoT-enabled service in waste management

Internet of Thing (IoT) is one of the smart communication technologies that interconnect ordinary physical objects to the internet and provides smart services (Atzori et al., 2010; Hannan et al., 2018; Batalla, 2017; Bueno-Delgado et al., 2019). The concept of IoT envisioned connecting different kinds of sensors and actuators to the internet via heterogeneous access networks enabled by different technologies (Narendra Kumar et al., 2014). The main difference between internet and IoT is internet connects intelligent devices whereas IoT has the additional sensing layer and connects among the non-intelligent or weakly-intelligent devices to interpret the data's effectively and provide smart services especially in the areas of solid waste management (Cerchecci et al., 2018). IoT works under three visions like "things oriented" "Internet-oriented" and "semantic-oriented" (Fig. 10) (Giusto et al., 2010; Atzori et al., 2010; Bandyopadhyay and Sen, 2011; Malina et al., 2016). In smart city infrastructure, solid waste management (SWM) is one of the important domains to be effectively monitored and managed for the above mentioned visions (Agnihotril and AtulSrivastava, 2017). The IoT concept could be used for the process of tracking, collecting, segregating, transporting, storing, treatment and disposal of SWM systems. By using sensors, the data collected from the garbage bins are sent through a gateway using LoRA transceiver module and sent to the cloud over the Internet using the MQTT (Message Queue Telemetry Transport) protocol (Al-Fuqaha et al., 2015). No SQL is a database which will be used to collect and store those data. It is inferred that the use of LoRa enables long distance data transmission along with low power consumption as compared to Wi-Fi, Bluetooth or Zigbee (Fargas and Petersen, 2017). ICT is playing a major role in collection and resource recycling (Anagnostopoulos et al., 2015), it has been established in China that 49 urban mining pilots implementing intelligent collection (Xue et al., 2019). Human-human interaction collection (HH) and Human-Machine (HM) interaction collection are practiced. HH is practiced with several ICT tools by five steps: the generator gets an appointment about collection time and item using smart phone App, the server assigns collection order to the nearby location, the collector collects at the door, collector sends the information to the server and the generator receives the credit. WIFI or GPRS are used for data accomplishment. In HM, the collection is done by the machine. The machine is embedded with ICT devices such as sensors, barcodes, and data communication devices. First, the machine identifies the generator account, who has already registered and then, the generator hands over the recyclable, materials, followed by the machine sending the information to the server and then, the generator will be credited. ICT tools barcode identifier, sensor monitors the recyclable data and GSM/GPRS transmits to the server. The intelligent collection is an organized collection and in normative collection, the system can identify the location and track the logistic routes, data are accurate, traceable and instant, has efficient material and cash flow. The intelligent collection increases the recycling rate to 35% by 2020 (Xue et al., 2019).

Intelligent Transportation Systems (ITS) include IoT components such as RFIDs, sensors, cameras, actuators and surveillance systems for efficient waste collection. Advanced Decision Support System (DSS) incorporates a model for data sharing between truck drivers in real-time in order to perform waste collection and dynamic route optimization using IoT components. The SWW is the real field data hence, it is advisable to design a cloud system for the organization of waste collection processes and applications for waste truck drivers. Software-as-a-

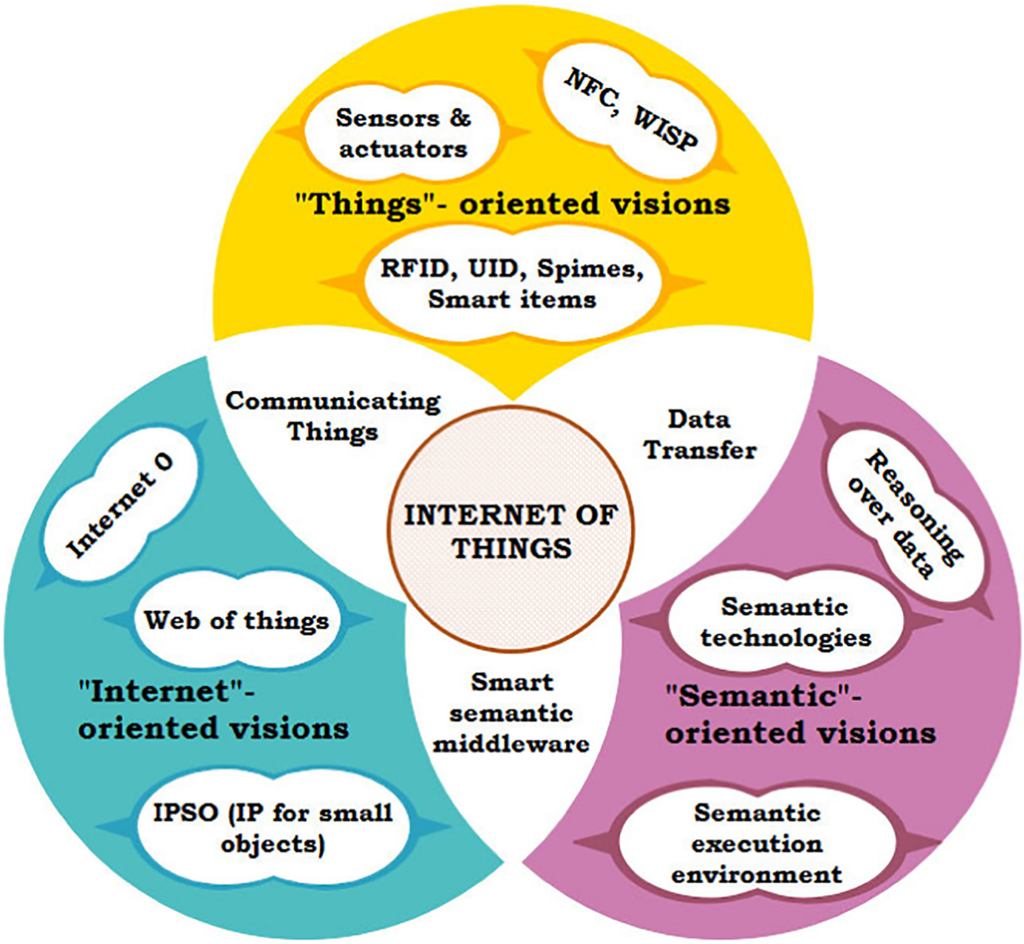

Fig. 10. "Internet of things" paradigm as a result of the convergence of different visions.

service (SaaS) to the commercial waste management company was used. The study inferred that implementing on board surveillance cameras in conjunction with a cloud DSS system and dynamic routing models can give a significant increase in cost-effectiveness (Medvedev et al., 2015; Koshizuka and Sakamura, 2010).

12. Conclusions

The present review explores the potential of biodegradable and non-biodegradable fractions of solid waste through a closed loop integrated refinery processes for the recovery of bioenergy and value added products. The integrated refinery processes targets for zero waste discharge considering the waste from one processes will be the feedstock for other processes is a superior approach for the sustainable valorization of solid waste. The main concept of this integrated refinery processes is to shift the paradigm from a linear economy to circular for greener footprint. It is a need to shift the conventional disposal of solid waste to a closed loop integrated refinery approach which is of sustainable that could promote efficient economy and reduce the environmental impacts. The study infers that treating the biodegradable fraction of waste with simultaneous production of bioenergy and recycling, reusing and recovering the non-biodegradable fraction of waste will pave a path towards circular economy. The study has discussed in detail about the liquid and gaseous biofuels synthesized from the biodegradable fraction of waste and their applications in internal combustion engines as single fuel and multi-fuel engines. The non-biodegradable fraction of solid waste that could be recovered and reused for different applications such as construction, pavement etc., In addition, the study discusses the circular economy's policies which helps to stimulate the economy of the country and identify the pathways to maximize the local resources. The paper also briefly reviews that IoT based technologies are effective tools to tackle the problems faced by the present solid waste management system.

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