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REVIEW

Gasification of refuse-derived fuel from municipal solid waste for energy production: a review

Yan Yang[1,2] · Rock Keey Liew[2,3,4] · Arularasu Muthaliar Tamothran[5] · Shin Ying Foong[2] · Peter Nai Yuh Yek[2,6] · Poh Wai Chia[3] · Thuan Van Tran[7,8] · Wanxi Peng[1,2] · Su Shiung Lam[2,1]

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Abstract

Dwindling fossil fuels and improper waste management are major challenges in the context of increasing population and industrialization, calling for new waste-to-energy sources. For instance, refuse-derived fuels can be produced from transformation of municipal solid waste, which is forecasted to reach 2.6 billion metric tonnes in 2030. Gasification is a thermal-induced chemical reaction that produces gaseous fuel such as hydrogen and syngas. Here, we review refuse-derived fuel gasification with focus on practices in various countries, recent progress in gasification, gasification modelling and economic analysis. We found that some countries that replace coal by refuse-derived fuel reduce CO_2 emission by 40%, and decrease the amount municipal solid waste being sent to landfill by more than 50%. The production cost of energy via refuse-derived fuel gasification is estimated at 0.05 USD/kWh. Co-gasification by using two feedstocks appears more beneficial over conventional gasification in terms of minimum tar formation and improved process efficiency.

Keywords Refuse-derived fuel · Waste-to-energy · Gasification · Co-gasification · Hydrogen · Municipal solid waste · Fossil fuel · Economic analysis · Resources recovery · Syngas

Introduction

Continuous supply of energy and proper waste disposal has always been the global challenges that require continual research and development. Proper waste disposal and the security of public wellbeing should be strengthened and combined when supporting circular economic values (Pio et al. 2020). However, the global energy supply primarily focuses on dwindling fossil fuel resulting in its over-exploitation and utilization, leading to detrimental effect to the environment for instance, production of greenhouse gases in the form of CO_2 and N_2O. In fact, according to

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✉ Rock Keey Liew
lrklrk1991@gmail.com

✉ Wanxi Peng
pengwanxi@163.com

✉ Su Shiung Lam
lam@umt.edu.my

[1] Henan Province Engineering Research Center for Biomass Value-Added Products, School of Forestry, Henan Agricultural University, Zhengzhou 450002, China

[2] Higher Institution Centre of Excellence (HICoE), Institute of Tropical Aquaculture and Fisheries (AKUATROP), Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia

[3] Eco-Innovation Research Interest Group, Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia

[4] NV WESTERN PLT, No. 208B, Second Floor, Jalan Macalister, 10400 Georgetown, Pulau Pinang, Malaysia

[5] Faculty of Science and Marine Environment, Universiti Malaysia Terengganu, 21030 Kuala Nerus, Terengganu, Malaysia

[6] School of Engineering and Technology, University College of Technology Sarawak, Lot 88, Persiaran Brooke, 96000 Sibu, Sarawak, Malaysia

[7] NTT Hi-Tech Institute, Nguyen Tat Thanh University, 300A Nguyen Tat Thanh, District 4, Ho Chi Minh City 755414, Vietnam

[8] Center of Excellence for Green Energy and Environmental Nanomaterials (CE@GrEEN), Nguyen Tat Thanh University, 300A Nguyen Tat Thanh, District 4, Ho Chi Minh City 755414, Vietnam

the Environmental Protection Agency of United State, the emission of CO_2 and N_2O that resulted from the combustion of fossil fuel had achieved approximately 4300 million metric tonnes and 57 million metric tonnes in 2018, respectively. Moreover, increased human reproduction frequency, upgraded living quality, and extensive industrialization have indisputably increased the generated waste volume and demand of energy.

Municipal solid waste, also generally termed trash or garbage, represents a non-hazardous unwanted item that is constantly supplied by human. Since the past few decades until present, the disposal of municipal solid waste has always been a demanding challenge due to ever-expanding human population. In addition, due to the outbreak of the novel coronavirus disease 2019 followed by the emergency lockdown and stay at home policy enforced in most of the countries, the unprecedented increase in municipal solid waste generated such as increasing use of plastic packaging with approximately more than 6000 tonnes per day in the Southeast Asian countries (Haque et al. 2020) could be even more challenging especially to those countries with unsatisfactory municipal solid waste management (Sarkodie and Owusu 2020). It was forecasted that the production of municipal solid waste will achieve 1.42 kg/capita/day by the year 2025 (Hoornweg and Bhada-Tata 2012) and will likely hit 2.6 billion metric tonnes in 2030 (Statista 2020). Figure 1 illustrates the volume of municipal solid waste generated across the globe (Statista 2018). Improper open dumping of municipal solid waste is still being carried out despite its widely reported adverse and long-lasting effects to the human health and environment such as air and water pollution (Cremiato et al. 2018; Fan et al. 2018; Malav et al. 2020). Therefore, there is an urgent need to research on more environmentally friendly and practical technology to divert municipal solid waste from open dumping.

Municipal solid waste can be segregated into combustible substance, non-combustible substance, and material with high moisture according to Caputo and Pelagagge (2002). The combustible substance which is also known as refuse-derived fuel composes mainly of carbon-based derivatives such as organics, plastic, paper, wood, and textile. The plastic and paper consist of 50–80% are the major fractions composed in refuse-derived fuel, while the remaining fractions are contributed by organics, wood, and textile (Casado et al. 2016; Fyffe et al. 2016). Figure 2 illustrates the compositions of municipal solid waste. Hence, the refuse-derived fuel fraction in municipal solid waste can be potentially used as another source of energy since it contains around 18 MJ/kg of calorific value which is comparable with soon-to be-depleted fossil fuel in less than 50 years from now (Porshnov et al. 2018; Shahbaz et al. 2016). Utilization of refuse-derived fuel as one of the energy sources is also well-aligned with the 7th sustainable development goal: affordable and clean energy (Dada and Mbohwa 2018). Figure 3 outlines the conversion process of municipal solid waste into refuse-derived fuel.

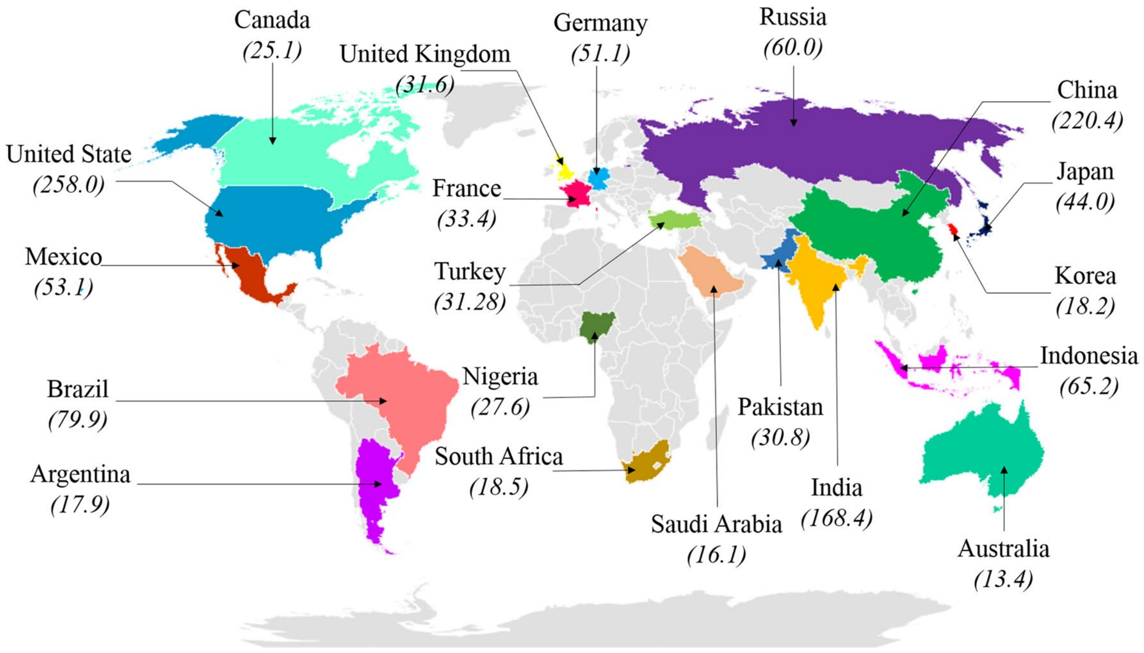


Fig. 1 Volume of municipal solid waste generated in million metric tonnes across the globe (Statista 2018). The USA represents the largest producer of the municipal solid waste across the globe, recording value at 258 million metric tons. Australia produces the lowest amount of municipal solid waste at 13.4 million metric tons, while Indonesia ranked as the top producer in the Southeast Asia

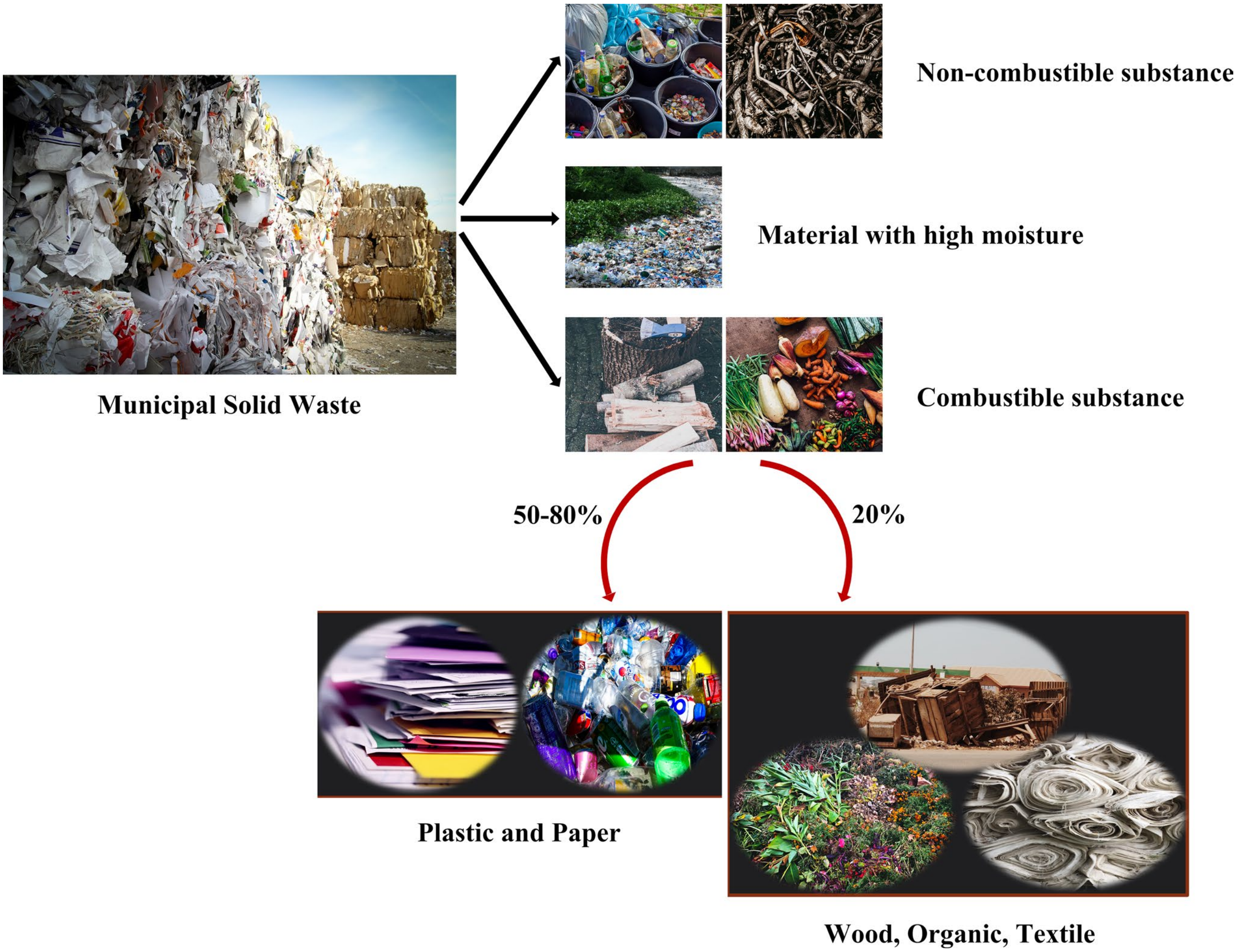
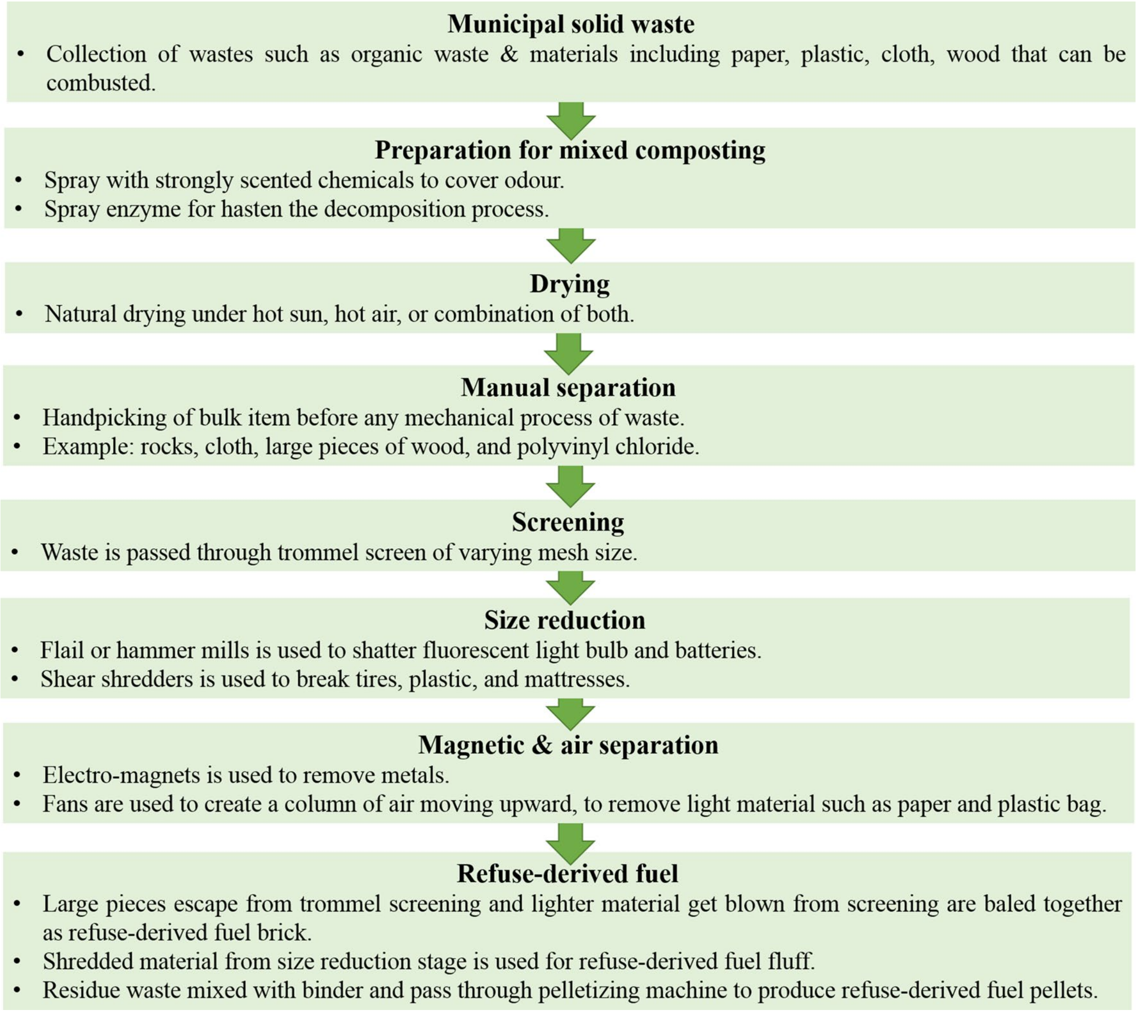


Fig. 2 Composition of municipal solid waste. The municipal solid waste consists of combustible substance, non-combustible substance, and material with high moisture. The combustible substance comprises up to 80% of plastic and paper, while the remaining 20% represents wood, organic, and textile waste. Due to the high organic contents of these combustible substance, it could be a promising feedstock as refuse-derived fuel for further processing into gaseous fuel

Waste-to-energy represents a viable solution that gains significant interest and attraction in the world due to its ability to provide simultaneous waste disposal and environmental protection (Ramos et al. 2018). Waste-to-energy can be realized via gasification, pyrolysis, and combustion (Gunarathne et al. 2019; Nanda and Berruti 2020a). Commercial plants of pyrolysis and combustion for waste-to-energy are available at industrial scale (Foong et al. 2020c; Pio et al. 2020), while gasification plant is comparatively limited. Despite that these technologies are commercially available, the research work on optimization and exploration of its further potential is still undergoing vigorously (Ge et al. 2020, 2021; Gutiérrez et al. 2020; Hameed et al. 2021; Liew et al. 2018b; Ma et al. 2019; Pedrazzi et al. 2019). Among these, gasification is getting increasing attention due to its capability in producing higher yield of cleaner gaseous fuel such as hydrogen and syngas than combustion and pyrolysis (Jiang et al. 2019).

In light of the above-mentioned studies, this review highlights the recent progress in gasification of refuse-derived fuel for energy production and its existing research gaps to be filled in by future research. This review covers the existing efforts of refuse-derived fuel production in several countries, recent progress of refuse-derived fuel gasification for energy production, modelling of gasification, economic assessment along with future challenge and prospects of this technology.



Municipal solid waste
- Collection of wastes such as organic waste & materials including paper, plastic, cloth, wood that can be combusted.

Preparation for mixed composting
- Spray with strongly scented chemicals to cover odour.
- Spray enzyme for hasten the decomposition process.

Drying
- Natural drying under hot sun, hot air, or combination of both.

Manual separation
- Handpicking of bulk item before any mechanical process of waste.
- Example: rocks, cloth, large pieces of wood, and polyvinyl chloride.

Screening
- Waste is passed through trommel screen of varying mesh size.

Size reduction
- Flail or hammer mills is used to shatter fluorescent light bulb and batteries.
- Shear shredders is used to break tires, plastic, and mattresses.

Magnetic & air separation
- Electro-magnets is used to remove metals.
- Fans are used to create a column of air moving upward, to remove light material such as paper and plastic bag.

Refuse-derived fuel
- Large pieces escape from trommel screening and lighter material get blown from screening are baled together as refuse-derived fuel brick.
- Shredded material from size reduction stage is used for refuse-derived fuel fluff.
- Residue waste mixed with binder and pass through pelletizing machine to produce refuse-derived fuel pellets.

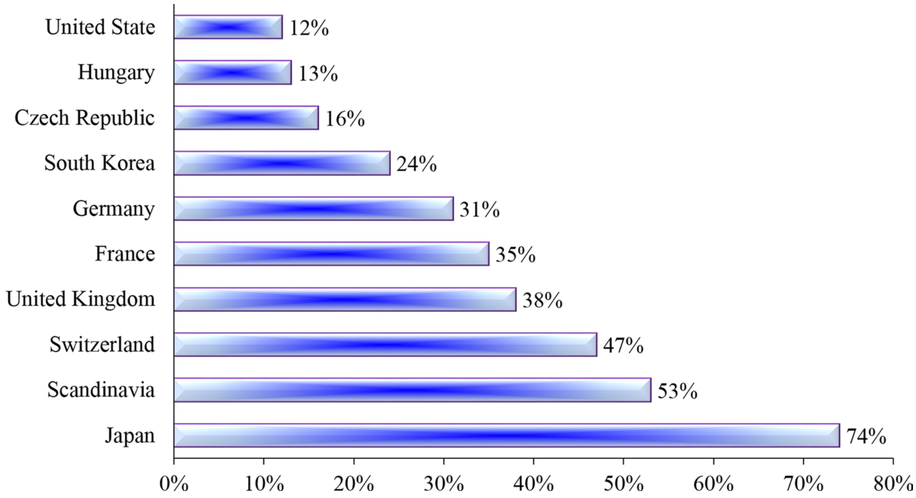
Fig. 3 Conversion procedure of municipal solid waste into refuse-derived fuel starting from collection of waste followed by pre-treatment of the mixed composting with spraying of chemicals and enzymes. Next, the mixed composting is dried under hot sun. The bulk item is separated manually followed by screening of mixture according to desire mesh size. After the mixture was separated, it will then undergo further size reduction mechanically followed by magnetic and air separation to remove metals and light materials. Finally, refuse-derived fuel is produced in the form of brick, fluff, and pellets

Refuse-derived fuel production in several countries

The development of renewable energy has been a continuous effort in the USA since the enforcement of American Clean Energy and Security Act of 2009. More than ten waste-to-energy facilities were built for the processing of municipal solid waste to obtain refuse-derived fuel as boiler fuel. In fact, these facilities pursue fairly comprehensive processing of municipal solid waste and obtain fuel of better quality compared with direct energy extraction from municipal solid waste in other waste-to-energy facilities. Figure 4 illustrates the amount of energy recovered from municipal solid waste in different countries. In addition to achieving their ambitious target to fulfil one-tenth of the electricity demand via renewable energy (Adaramola et al. 2017), the municipal solid waste that is commonly predestined for pilling up at the landfill sites would be diverted as feedstock for refuse-derived fuel production. As a result, the demand for refuse-derived fuel is estimated to significantly increase to, for instance, approximately 115 million tonnes if it is intended to substitute 5% of the coal usage for electricity generation (Gershma 2010).

Refuse-derived fuel has been progressively recognized as an alternative renewable energy in the UK. In fact, production of refuse-derived fuel in the waste-to- energy facilities has contributed up to 50% reduction of municipal solid waste being sent to the landfill in the past decade (Brew 2018). In general, most of the refuse-derived fuel producers focus on “one-time pass” processing technologies to

Fig. 4 The amount of energy recovered from municipal solid waste via waste-to-energy plants in the selected country. Japan, Scandinavia, and Switzerland recovered most energy from municipal solid waste due to the little open space for landfill. This could also indicate that Japan, Scandinavia, and Switzerland have more advanced and effective waste-to-energy plants for energy recovery from municipal solid waste



produce refuse-derived fuel that can be used directly as fuel without further treatment to minimize the start-up capital, processing cost, and maintenance frequency. The refuse-derived fuel obtained is commonly used as coal substitute in cement industry to reduce 40% emission of CO_2 (Rodrigues and Joekes 2011). Nevertheless, vigorous efforts have been invested on researching innovative technologies and improving the existing technologies to realize better fuel quality and larger profit margin. In short, production of refuse-derived fuel is expected to impart with revolutionized role in the renewable energy sector of the UK.

Other than developed countries, the interest on recovery of refuse-derived fuel from municipal solid waste has also been extended to a few developing countries such as Indonesia, India, and Thailand. Indonesia is identified as one of the countries in the world with the highest growth of population, estimated to hit 270 million people that would produce 150,000 ton/day of municipal solid waste by 2025 (Kubota and Ishigaki 2018). Efforts have been undertaken by their government on the management of municipal solid waste by putting high hope in the conversion of this waste into refuse-derived fuel as a replacement for coal. This includes publishing guidelines to highlight the proposed facility design for the processing of refuse-derived fuel with optimum quality, the regulation of feed-in-tariffs for refuse-derived fuel processing facility, and more stringent municipal solid waste management law. Similar efforts were also performed by the government in India and Thailand where waste management and energy-related policies have been enforced to promote the transformation of municipal solid waste into refuse-derived fuel as coal substitute (Pandey et al. 2019; Srisaeng et al. 2017).

South Africa is heavily dependent on coal usage to satisfy more than 75% energy demand by the nation (Joshua and Bekun 2020). This no doubt puts South Africa into the dilemma of energy security and environmental issues simultaneously. Therefore, to tackle these crises, the government launched carbon tax in 2019 with the aim to reduce the carbon emission resulting from industries, mainly power production plants (Slater 2020), while also slowly diverting the utilization of fossil fuel to renewable energy. In addition, the government offers carbon tax discount to those companies contributing to the growth of renewable energy development and application. This in turn stimulates the progress in production of refuse-derived fuel from municipal solid waste which becomes increasingly attractive within the country (Slater 2020).

Refuse-derived fuel is also getting attention in middle east countries. The exploration of refuse-derived fuel from municipal solid waste as potential renewable energy has been triggered in the Kingdom of Saudi Arabia despite this country represents the second-largest producer of petroleum in the world (Investopedia 2020). The energy demand in Kingdom of Saudi Arabia is increasing and estimated to achieve more than 100 GW by 2032 (Ouda et al. 2017). Therefore, the government is now making efforts to explore the potential of renewable energy with the aim to fulfill 60% of the energy demand prior to reducing the dependence on petroleum (Nizami et al. 2015; Ouda et al. 2016). In the United Arab Emirates, their progress on refuse-derived fuel production is one step ahead compared to Kingdom of Saudi Arabia. The first refuse-derived fuel production plant resulted from the collaboration between the government and a local company was launched on October 2020 to transform up to 80% of the municipal solid waste into refuse-derived fuel. Similar to other countries, the quality of the refuse-derived fuel makes it as a coal substitute for use in cement industry (Clarke 2020).

The application of refuse-derived fuel as a multipronged solution to dwindling fossil fuel energy, sustainable municipal solid waste management, and increased energy demand is gaining attraction throughout the globe. As nations are moving towards addressing climate change issues such as greenhouse gas emissions by signing onto global agreements such as Kyoto Protocol and Paris Agreement. The prospect of municipal solid waste as a potential source of energy will be supported by various countries and application of refuse-derived fuel as feedstock will be an attractive investment.

Recent progress in refuse-derived fuel gasification for energy production

Gasification represents a thermal-induced chemical reaction in which the organic fraction of the material is extensively oxidized at high temperature with more than 1500 °C in the presence of finite oxygen, air, CO_2, or H_2O/steam (Lam et al. 2016). This process generally yields syngas comprises of CO plus H_2 as gaseous fuel associated with minor fractions of CH_4 and CO_2 (Foong et al. 2020a, 2020c). The main reactions occur during gasification are usually exothermic as shown in Table 1. Gasification also shows high flexibility in feedstock variation (Saidi et al. 2020). The common feedstock for gasification includes biomass (Putro et al. 2020; Sittisun et al. 2019), coal (Grabowski et al. 2020), carbonized products (Chen et al. 2019; He et al. 2019), plastics (Nanda and Berruti 2020b), and municipal solid waste (Martínez et al. 2020).

In 1975, the first resource recovery plant was established in Iowa, the USA, that converts municipal solid waste into refuse-derived fuel for energy production in local power plant (Sequeira 2019). The research interest on refuse-derived fuel gasification for energy recovery continually increases since then (Achinas and Kapetanios 2013; Corella et al. 2008; Galvagno et al. 2006; Morris and Waldheim 1998). Dalai et al. (2009) conducted gasification of refuse-derived fuel using steam as a gasifying agent to produce syngas. The selectivity and energy value of the resulted syngas were found to be influenced significantly by the ratio of steam to refuse-derived fuel and temperature. Chiemchaisri et al. (2010) converted refuse-derived fuel mainly into gaseous fuel in a small-scale downdraft gasified with air as gasifying agent. Other than investigations on the influence of process parameters, the production cost of energy via refuse-derived fuel gasification was also estimated to be USD 0.05/kWh.

However, the problematic tar compound that characterized as black–brown viscous liquid generated in the refuse-derived fuel gasification usually creates troubles where the tar could adhere strongly on the surface of the machinery parts that would lead to process malfunctioning (Singh et al. 2014). In addition, other problems such as production of unwanted dark residues and discharge of NO_x, hydrogen sulphide, and SO_x were also observed when gasification was performed on plastic wastes and coal, respectively (Shahbaz et al. 2020). Hence, in the past decade, the research focus has been directed towards the co-gasification of refuse-derived fuel with biomass. The co-gasification process is deemed to be more beneficial over conventional refuse-derived fuel gasification process in terms of minimum tar formation, improved process efficiency, and exploration on the synergistic effects between refuse-derived fuel and biomass with different compositions (Masnadi et al. 2015b).

Cai et al. (2021) performed co-gasification of refuse-derived fuel and straw mixtures adopting a laboratory scale of fixed-bed reactor under the temperature ranging from 600–900 °C. The results were compared with gasification of single feedstock to examine the synergistic effects of the co-gasification process. The author revealed that co-gasification showed improved yield on gaseous products, better efficiency of cold gas, and carbon conversion than normal gasification. Similar findings were also reported by Burra and Gupta (2018) in co-gasification of refuse-derived fuel and wood pellet. Furthermore, the addition of straw mixture could have concealed the melting agglomeration of inorganic content that usually forms sticky ash due to the presence of calcium, aluminosilicate, and carbonates (Cprek

Table 1 Enthalpy change of main reactions occurs during gasification. The positive sign indicates endothermic reaction, while the negative sign indicates exothermic reaction (Ramos et al. 2018; Sansaniwal et al. 2017; Werle 2014)

Reaction name	Chemical equation	Enthalpy change
Boudouard reaction	$C + CO_2 \leftrightarrow 2CO$	ΔH = − 172 kJ/mol
Dry reforming reaction	$CH_4 + CO_2 \leftrightarrow 2CO + 2H_2$	ΔH = + 247 kJ/mol
Methanation	$C + 2H_2 \leftrightarrow CH_4$	ΔH = − 75 kJ/mol
Oxidation of Char	$C + 1/2\ O_2 \leftrightarrow CO$	ΔH = − 111 kJ/mol
	$C + O_2 \leftrightarrow CO_2$	ΔH = − 394 kJ/mol
Oxidation of CO	$CO + 1/2\ O_2 \leftrightarrow CO_2$	ΔH = − 283 kJ/mol
Oxidation of H_2	$H_2 + 1/2\ O_2 \leftrightarrow H_2O$	ΔH = − 242 kJ/mol
Primary water–gas reaction	$C + H_2O \leftrightarrow CO + H_2$	ΔH = − 131 kJ/mol
Secondary water–gas reaction	$C + 2H_2O \leftrightarrow CO_2 + 2H_2$	ΔH = − 90 kJ/mol
Steam reforming reaction	$CH_4 + H_2O \leftrightarrow CO + 3H_2$	ΔH = + 206 kJ/mol
Water–gas shift reaction	$CO_2 + H_2 \leftrightarrow CO + H_2O$	ΔH = − 41 kJ/mol

et al. 2007; Smidt et al. 2010) at the reactor bottom when only refuse-derived fuel is gasified.

Aside from the research at laboratory scale, the co-gasification has also been advanced to pilot scale (Pio et al. 2017, 2020). The co-gasification of refuse-derived fuel and pine biomass was conducted in a 80 kW_{th} bubbling fluidized bed reactor associated with the assessment of several parameters such as lower heating value of producer gas, efficiency of cold gas, and carbon conversion. Again, the synergistic effect shown by the co-gasification of refuse-derived fuel and pine biomass was obvious compared with gasification of only pine biomass. The authors found that the co-gasification had improved the yield of methane and ethylene up to 78.2% in the gaseous products, as a result the overall lower heating value was enhanced from 5.8 to 6.4 MJ/Nm^3. In addition, the co-gasification had also prevented the issue of defluidization and formation of slag (Pio et al. 2020). The undeniable advantages are clearly indicated by co-gasification of refuse-derived fuel and biomass in terms of product quality and process maintenance as compared with gasification of single feedstock.

Other than biomass, the refuse-derived fuel was also co-gasified with the biochar to produce 55.8 vol% of H_2 in syngas compared to co-gasification with biomass that yielded a lower H_2 of 45.2 vol% (Zaini et al. 2020). Considering that the majority of volatiles matters have been expelled from the resulted biochar after thermochemical transformation, the formation of tar could be averted when the biochar is gasified (Jia et al. 2017). Similar finding was obtained by Zaini et al. (2020) where co-gasification of refuse-derived fuel with biochar had reduced 72% of tar yield compared to co-gasification of refuse-derived fuel and biomass. The reduction of tar could be due to the tar reforming reaction occurred on the surface of biochar that involve dehydrogenation, tar adsorption, and gasification (Shen and Fu 2018). On top of that, the alkali and alkaline earth metals (AAEM) such as potassium, calcium, and magnesium that inherently present in the biochar could also serve as catalytic active sites to induce tar reforming reaction (Feng et al. 2017; Lam et al. 2015). In addition, the AAEM present as ash in refuse-derived fuel was also reported to enhance the production of light hydrocarbons (Masnadi et al. 2015c). Figure 5 shows the transformation route of municipal solid waste to gaseous fuel. Table 2 shows the existing efforts on co-gasification of different wastes.

Modelling of gasification

Numerical models have been established to estimate the optimum process parameters and outcome since trial and error will be cost-ineffective and time-intensive. (Couto et al. 2015). In tandem with advances in programming associated with high technology computational hardware, complicated numerical simulations and sophisticated calculations are easily realized over the last decades. Despite that many papers have been published on the modelling of biomass gasification (Aravind et al. 2012; Cao et al. 2020;

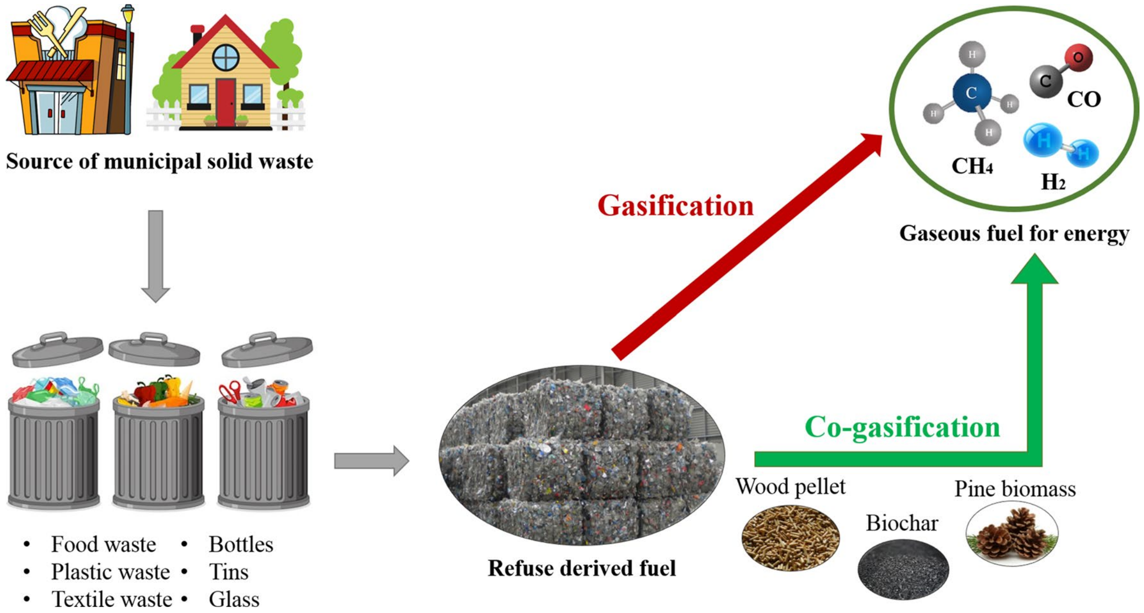


Fig. 5 Transformation route of municipal solid waste to gaseous fuel for energy purpose. The refuse-derived fuel obtained from the municipal solid waste can be converted into gaseous fuel via gasification and co-gasification. The refuse derive fuel can be co-gasified with different biomass and biochar to achieve synergistic effects, thus obtaining better quality of gaseous fuel than conventional gasification

Table 2 Existing efforts on co-gasification research

Feedstock	Temperature of gasification	Energy value of syngas	Reference
Pig manure and wood chip	530–700 °C	14 MJ	Xiao et al. (2011)
Sewage sludge and woody biomass	550–850 °C	5.5 MJ	Seggiani et al. (2012)
Lignite and polyethylene	850 °C	19 MJ	Kern et al. (2013)
Palm kernel shell and polyethylene	650–800 °C	46 MJ	Moghadam et al. (2014)
Coal and switchgrass	700 °C	18 MJ	Masnadi et al. (2015a, b, c)
Bituminous coal and pine sawdust	500–800 °C	11.4 MJ	Tursun et al. (2016)
Coconut shell and high-density polyethylene	600–800 °C	13.4 MJ	Esfahani et al. (2017)
Sewage sludge and residue from hydrolysis	600–800 °C	6.8 MJ	Chen et al. (2018)
Banana hydrochar and anthracite coal	850 °C	10.1 MJ	Zhu et al. (2019)
Gas-pressurized rice straw and coal	950 °C	23.8 MJ	Tong et al. (2020)

Das et al. 2020; Rahma et al. 2021; Vecchione et al. 2015) and refuse-derived fuel gasification (Barba et al. 2011; Kardaś et al. 2018; Násner et al. 2017), concerted efforts are still required to contribute new findings to the existing database since there are countless types of biomass with different chemical compositions to enhance the accuracy of modelling.

On the other hands, limited modelling work has been reported on the co-gasification especially that involving refuse-derived fuel where the only study was found as reported by Kardaś et al. (2018) for the co-gasification of beechwood and refuse-derived fuel that adopted a stationary two-fluid model to describe both solid and gas phases. A polynomial model was recently reported for the co-gasification of sugarcane bagasse with municipal solid waste adopting a steady state and one-dimensional approach using MATLAB software to describe the process outcome including heating value, composition of syngas, and energy efficiency (Lewin et al. 2020). The impact of several process parameters was then determined and optimized using central composite design. The models developed showed high accuracy as determined by its high R^2 values and verified via the literature for validation (Yucel and Hastaoglu 2016). The author concluded that the model developed with smooth functioning revealed promising exploration for co-gasification of biomass and municipal solid waste, hence providing motivation for future study to be conducted on other feedstocks.

Instead of comparing with existing studies, some of the studies reported to verify their models with real experimentation. Xu (2013) employed MATLAB for development of two phases flow model in the co-gasification of biomass with coal pellets. The models were obtained using data produced from the co-gasification experiment at bench scale which was then verified with the real data produced from a pilot-scale experiment. Jeong et al. (2017) performed a modelling study on co-gasification of wood pellet and Douglas coal using computational fluid dynamics, and then, the findings were also verified and corroborated with the real data obtained from the operating gasification plant in Spain, thus indicating the reliable accuracy of the modelling results. Despite that the research on modelling studies of co-gasification is making good progress (Ali et al. 2017; Hantoko et al. 2018; Zhang et al. 2020), huge research gap is awaiting to be filled by more studies performed with different combinations of feedstock and inclusion of underexplored material such as refuse-derived fuel.

Economic analysis

Economic analysis is an important aspect to determine the feasibility of a technology for commercialization. Although gasification plant has been existing for waste treatment (San Miguel et al. 2012), the economic analysis is still performed and reported in some recent studies to further explore its potential for commercialization with optimum benefit (Salkuyeh et al. 2018; Thunman et al. 2019). Luz et al. (2015) present the economic feasibility of municipal solid waste gasification involving the estimation of costs for commercialization and potential revenues. The estimation of commercialization cost covers process operation and maintenance, installation, and design of equipment, associated with the interest rate of the investment. For the estimation of potential revenues, the income from electricity sale and recyclable materials including glasses, metals, and plastics, the profit of gasification by-product such as char, and stipend paid by the local government in Brazil for the demolition of municipal solid waste were considered. The economic feasibility was assessed under equipment lifetime of 20 years via two economic indicators which are internal rate of return and net present value. It was revealed that the larger capacity of the installation will gain more benefits at lower costs, thus more economic feasible. It was anticipated by the author that the financial support from the Brazilian municipalities is essential to realize the commercialization, otherwise the overall profit might not convince the investors. On the other hands, a straightforward cost estimation considered only the materials and energy required in post-treatment was reported by Goswami et al. (2019) on the product of biochar obtained from gasification instead of the technology used. Despite that the estimated cost of 1.89 USD/kg was comparatively lower than the average cost at 2.85 USD/kg according to the International of Biochar Initiative, the value obtained will be different when other expenses such as equipment capital, process operation and maintenance are included, thus suggesting that the economic analysis would be useful and representable only if complete costing details are taken into consideration.

Economic analysis was also reported in co-gasification study (Carvalho et al. 2018; Jia et al. 2018). A thorough cost–benefit analysis was reported by Ng et al. (2017) using Monte Carlo simulation to evaluate the profit feasibility of implementing a co-gasification plant in chicken farm. The cost analysis included an initial investment on land and equipment required, materials, process operation and maintenance, uncertainties occurred at present and future, and potential damage caused during the process (You et al. 2016). The benefit analysis mainly constituted of the income from energy via electricity sale, by-product such as biochar, and disposal of chicken manure. The authors estimated the standard deviation of net present value distribution to be about 22 million USD over 20 years. They also concluded that there was about 42% of chances to generate profit for the farm via the proposed co-gasification system. Interestingly, the chances could be increased to over 90% if either the price of feedstock is discounted by half, or the price of electricity or biochar is doubled. In fact, the price of biochar could be varied according to its used in different applications such as heterogeneous catalysis (Balajii and Niju 2019; Foong et al. 2020b), agriculture (Lam et al. 2019; Wan Mahari et al. 2020), wastewater remediation (Cai et al. 2020; Klasson et al. 2013), aquaponics (Su et al. 2020), and synthesis of activated carbon (Heidarinejad et al. 2020; Liew et al. 2018a).

Conclusion

The future of refuse-derived fuel application at global scale seems to be a promising prospect considering the accuracy and reliability of modelling design and real-time experimental/industrial output which is further supplemented by the urgency in solving one of mankind's impending environmental crisis. However, there are several challenges that need to be tackled to ensure proper and equitable adoption of this technology worldwide. Currently, the development of refuse-derived fuel facilities is concentrated in major countries such as the USA, Europe, China, Japan, and India. The economic and social transformation occurring at other nations also brought about increased municipal solid waste issues to respective nations. For instance, Sub-Saharan Africa nations have both the need for cements and rapidly increasing municipal solid waste output volume which prompted interest in studying the benefits of refuse-derived fuel facilities being established (Larionov and Demir Duru 2017). Sub-Saharan Africa nations are projected to achieve substantially higher population count compared to the rest of the world which places them in a unique position to fully take advantage of establishing refuse-derived fuel facilities to solve the upcoming municipal solid waste management nightmare. Furthermore, development of refuse-derived fuel technology and subsequent commercialization of said technology plays a crucial role in establishing concept of circular economy in the aspects of waste management. Circular economy is defined as transformation of goods with completed service life into resources for reuse thus closing loop in industrial ecosystems while minimizing waste (Stahel 2016). As such, development of refuse-derived fuel facilities in developed and developing nations and between urban and rural regions poses unique set of challenges.

Figure 6 Future of refuse-derived fuel. In order to realize the promising future of refuse-derived fuel, further research work should include investigations on more process parameters and co-gasification with different types of feedstock. Then, optimization study using modelling software, life cycle assessment, and circular economy is inevitable. Finally, sufficient funding is required for commercialization.

Entry barrier for establishing refuse-derived fuel facilities in developing countries tends to be higher due to lack of investment funding available, proper municipal solid waste management by consolidation or privatization, lacking or non-existent government policies, and lack of public awareness. As such governments of these nations need to proactively formulate necessary policies and induce public awareness while directing required investment funds to establish refuse-derived fuel facilities. However, the stakeholders of municipal solid waste and refuse-derived fuel technology need to engage properly to avoid being left out as the technology rapidly evolves. In most low- and middle-income countries, existence of informal waste sector can be a challenge in streamlining municipal solid waste management as it represents as source of income to significant part of the population (Aparcana 2017; Sandhu et al. 2017).

Meanwhile, the difference in population size between urban and rural region has its own set of prospects and challenges. Urban regions with high population tend to have higher amount of municipal solid waste generated where the prospect of developing refuse-derived fuel facilities is brighter for both government and private sector compared to rural regions. However, changes in municipal solid waste management and high-level investment needed could pose a challenge. Lack of sizeable population in

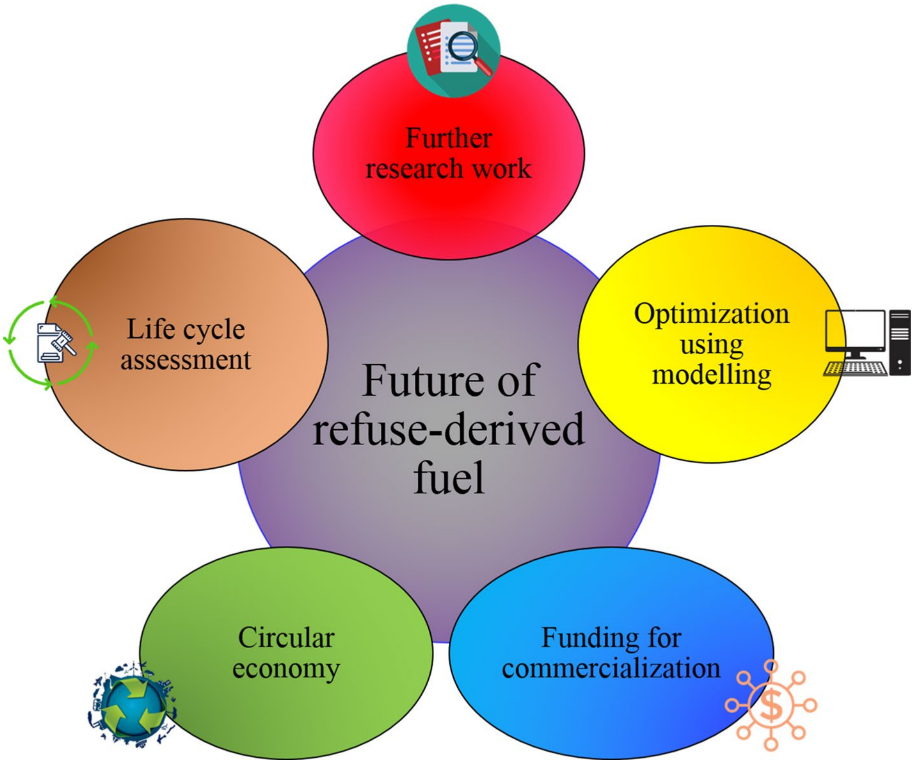


Fig. 6 Depicts the overview for the future of refuse-derived fuel

rural area meanwhile could not attract refuse-derived fuel facilities development for factors including low amount of generated waste to be supplied as feedstock. In order to develop refuse-derived fuel facilities in regions with different demands and conditions, experimental designs together with modelling works will play a crucial role. Development of refuse-derived fuel including gasification technology can pave way to reach a goal where municipal solid waste will no longer be viewed as waste material but instead as energy source that is sustainable. In regard to co-gasification, more research especially in modelling aspect is needed to advocate refuse-derived fuel co-gasification with other materials to sufficiently prove the benefits in order to attract government and private investments. Furthermore, life cycle assessment of refuse-derived fuel feedstock application in waste-to- energy conversion is necessary to substantiate the sustainability and environmentally friendly nature of this energy production. Currently life cycle assessment of energy produced from refuse-derived fuel feedstock is scarcely studied especially co-gasification which is needed to gain an edge for commercialization efforts.

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