Renewable and Sustainable Energy Reviews 145 (2021) 111080

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: http://www.elsevier.com/locate/rser

Municipal solid waste-to-energy processing for a circular economy in New Zealand

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ARTICLE INFO

Keywords:
Waste-to-energy processing
Municipal solid waste
Circular economy

ABSTRACT

For the success of waste-to-energy in New Zealand, waste-to-energy processing technologies need to reduce their costs (e.g. capital and operational) by generating additional revenue in the form of fuels and other by-products. We focus on municipal solid waste (MSW), the garbage that New Zealand generates in a problematically large amount per capita, proposing that a circular economy approach can safely manage MSW while mitigating increasing energy demands when waste is converted to energy by various MSW-to-energy technologies. The present study reviews the current status of comparative MSW generation, energy deficit, and waste-to-energy processing. Various waste-to-energy technologies are reviewed, their potential and current status in New Zealand are described, and their associated challenges identified to develop a potentially promising waste-to-energy process for a circular economy in New Zealand. Waste-to-energy technologies in New Zealand can achieve commercial success and community readiness levels by using better communication strategies to inform end-users and relevant stakeholders, and adding extra safety layers around their processes. Various combinations of waste-to-energy technologies are recommended for successful waste-to-energy processing in New Zealand, as no technology can effectively serve the purpose of waste-to-energy processing alone.

1. Introduction

Municipal solid waste (MSW) management and replacement of non-renewable fossil fuels with something more sustainable are universal issues affecting communities and the environment. Poorly managed MSW contaminates the environment and endangers human and animal health. Additionally, ongoing use of fossil fuels is not sustainable due to greenhouse gas emissions. For a sustainable future, a properly managed MSW that produces non-fossil fuel energy is the gold standard. New Zealand has some way to go to achieve this.

Turning waste to energy can be a viable option to properly manage MSW, and produce sustainable non-fossil fuel energy. Waste-to-energy processes significantly reduce volume (approximately 50–90%) of MSW which is easier to manage [1]. Furthermore, MSW contains a net energy potential of about 0.13–0.38 tonnes of oil equivalent (toe) per tonne which can be extracted using waste-to-energy process [2]. MSW can be converted into various chemicals or fuels such as biogas, hydrogen, alcohol, synthesis gas, organic acids, etc., creating a circular economy [3]. The net energy potential of MSW varies with its composition and also depends on the waste-to-energy process used [4,5], so setting up systems depends on the context.

Various conventional and nonconventional waste-to-energy technologies have been reported in recent literature. Conventional waste treatment or disposal techniques include composting [6,7], anaerobic digestion [8,9], and landfilling [10,11], while incineration [12,13], pyrolysis [14,15], gasification (e.g. plasma gasification) [16,17], and hydrothermal processing [18,19] are considered nonconventional waste-to-energy technologies. In this study, waste-to-energy technologies were divided into conventional and nonconventional categories for the New Zealand context. It is worth mentioning that gasification in some countries such as Japan is relatively conventional because long-standing; however, it is not conventionally used in a majority of countries. Other technologies can treat or dispose waste to produce fuels/chemicals and create a real circular economy.

The choices of waste-to-energy technology and energy demands primarily depend on a country's income level. Waste-to-energy technologies evolve and energy demands increase as a country develops from low-income to high-income economy. The World Bank divides the world's economies into four main groups: i) high-income (e.g. Australia, Japan, New Zealand, and USA), ii) upper-middle income (e.g. Argentina, Brazil, and China), iii) lower-middle income (e.g. India, and Indonesia),

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https://doi.org/10.1016/j.rser.2021.111080
Received 19 August 2020; Received in revised form 18 March 2021; Accepted 3 April 2021
Available online 13 April 2021
1364-0321/

Nomenclature

Enthalpy of reaction (MJ/kmol) H
Food waste $(C_{18}H_{26}O_{10}N)$
Gasification stoichiometric coefficients p, q, r
Grass $(C_{23}H_{38}O_{17}N)$
Hydrocarbons C_nH_m
Mixed paper $(C_{266}H_{434}O_{210}N)$
Tars C_xH_y

Abbreviations
Greenhouse gas GHG
Kilograms of oil equivalent kgoe
Layers of protection analysis LOPA
Millions of tonnes of oil equivalent Mtoe
Municipal solid waste MSW
Organisation for Economic Co-operation and Development OECD
Tonnes of oil equivalent toe

and iv) low-income (e.g. Somalia, and Zimbabwe) countries [20]. High-income countries, mostly members of the Organisation for Economic Co-operation and Development (OECD), do no rely on a single waste-to-energy technology and use multiple technologies. That is, except a few high-income countries, and one of these is New Zealand. Furthermore, usually MSW collection systems are well placed, and significant portions of material are recycled to increase material reuse in high-income economies [21]. On the other hand, as you might expect, low to middle-income economies mostly do not have proper MSW collection systems, have insignificant amounts of material recycling, and also have open dumping of MSW with adverse effects on the environment [22].

As is true in other high-income and OECD countries, the generation of MSW is increasing in New Zealand (more details given in Section 2). New Zealand's MSW collection system is functional, and significant amounts of material are recycled. However, in contrast to other high-income and OECD countries, landfilling is New Zealand's only waste disposal method. The Ministry for Environment New Zealand website presents a list/map of various landfills in New Zealand [23]. New Zealand regional councils are governed by the Waste Minimization Act of 2008 that encourages recycling, reuse, and reduction of waste and landfills [24]. To minimise dumping in landfills, the government and regional authorities are imposing a levy on MSW disposed of in landfills, establishing product stewardship schemes, writing waste assessment reports regularly, and creating the Waste Advisory Board to give independent advice [25].

Furthermore, energy deficit (energy consumed – energy produced) in New Zealand is increasing at a significantly higher rate than in other high-income economies, see Section 2. That increased energy demand is another motivation for rethinking New Zealand's landfilling strategy.

For a country that identifies as green, then, New Zealand lags behind other high-income countries in properly managing MSW and energy deficit. Waste-to-energy technologies use in New Zealand could help to manage MSW and keep the energy deficit rate approximately constant. We believe that managing MSW is a critical foundation to sustainability. New Zealanders could do with more understanding of various conventional and nonconventional waste-to-energy technologies. These include composting, anaerobic digestion, landfilling, incineration, pyrolysis, gasification, plasma gasification, and hydrothermal processing, each of which has technical capabilities, optimum process conditions, costs, net energy potential, and environmental impacts. Knowing more about waste-to-energy technologies, their potential, current status, and associated challenges, might help New Zealand to develop MSW management success, where the best possible use of waste underpins a circular economy.

Various review articles on waste-to-energy processing have been published regarding waste-to-energy processing in India [26–28], in high-income countries (e.g. Australia, Denmark, Japan, and USA) [29–31], and in USA [32–34]. However, there seems to be nothing recent investigating waste-to-energy processing and associated key challenges for successful implementation in New Zealand (the novelty of the current study).

2. The current status of MSW generation and energy deficit

Waste generation –Currently, the world generates more than 2 billion metric tonnes per year of MSW which is expected to increase to approximately 2.5 billion metric tonnes by 2025 [35] and 3.40 billion tonnes by 2050 under a business-as-usual scenario. Globally, approximately 33% of the generated MSW on average is not managed in an environmentally safe manner [20].

Fig. 1 (a) shows current and projected MSW generation by region worldwide, showing that regions such as East Asia, the Pacific, Europe and Central Asia generate approximately 45% of the world's total MSW, which is also expected to increase in future, as shown by the projected data of 2030 and 2050. On the other hand, regions such as Sub-Saharan Africa, and Middle East and North Africa generate approximately 15% of the world's total MSW, also expected to increase in future.

Unsurprisingly, greater wealth relates to more rubbish: low-income countries generate approximately 5%, and high-income countries generate about 35% of the global MSW. In other words, there's a positive correlation between a country's income level and its MSW generation. Globally, MSW generation in high-income economies in general and low-income economies in particular is expected to increase in future. The expected increase in MSW generation is due to various factors such as population growth, swift urbanisation and the resulting change in lifestyle especially in fast-growing South Asia, Sub-Saharan Africa, the Middle East and North Africa regions [5].

In New Zealand, MSW generation has also increased during recent years and has reached to approximately 3.3 million tonnes per annum in 2016 as shown in Fig. 1 (b). Furthermore, MSW generation is expected to increase to approximately 4.0 million tonnes per annum by 2030 and 4.8 million tonnes per annum by 2050 [20]. According to the World Bank, New Zealand has the ninth-highest rate of MSW production per capita which makes New Zealand the worst in the developed world. In 2018, New Zealand generated approximately 781 kg of MSW per capita per year, which was significantly higher than the OECD total of approximately 525 kg of MSW per capita per year, Fig. 2 (a).

It is worth noting in Fig. 2 (a) that MSW generation per capita per year in New Zealand has been constantly increasing since 2010 whereas other high-income countries have remained stable in this. This high amount of MSW generation per capita may be due to various factors such as an abundance of resources for approximately 5 million people in New Zealand. A recent study by Perrot and Subiantoro (2018) [25] claimed that this huge amount of waste in New Zealand is because China restricted imports of plastic waste in 2017, which has directly increased approximately 30,000 tonnes of plastic waste per annum in New Zealand who previously paid to send it to China. However, MSW generation per capita has been sharply increasing since 2012, well before China's decision, Fig. 2 (a). In contrast, other high-income countries such as Australia, USA, Sweden, and UK have maintained almost a constant rate of MSW generation per capita per year since 2010.

Energy deficit – Global energy consumption has increased significantly, reaching approximately 14,000 millions of tonnes of oil equivalent (Mtoe) with +2.3% energy consumption growth rate in 2018. Regional use in global energy consumption includes Europe (1847 Mtoe); Commonwealth of Independent States (1081 Mtoe); North America (2558 Mtoe); Latin America (822 Mtoe); Asia (5859 Mtoe); Pacific (158 Mtoe); Africa (850 Mtoe), and Middle-East (803 Mtoe) [36].

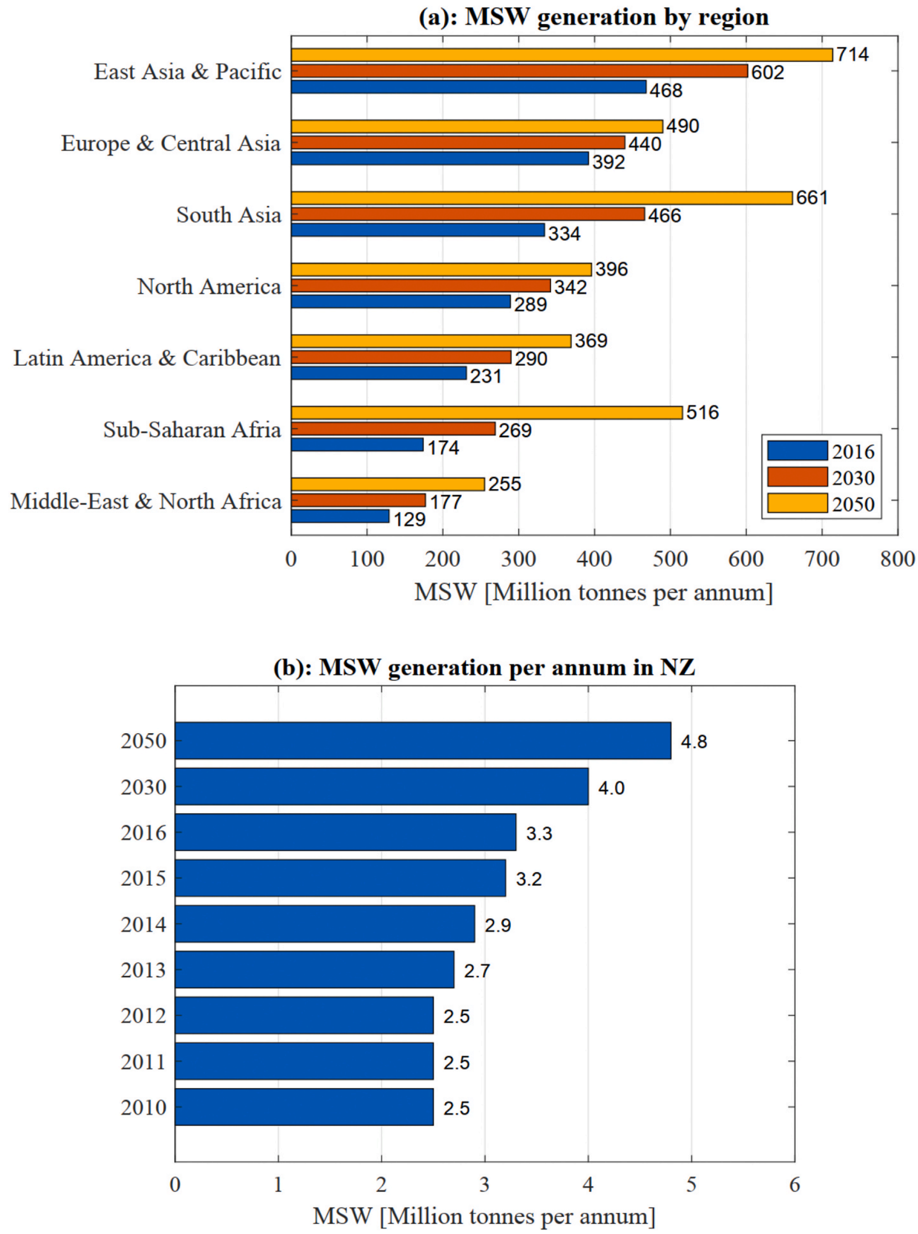

Fig. 1. (a) Current and projected MSW generation worldwide [20], and (b) MSW generation in New Zealand [20,35].

Energy consumption fluctuates (for example, 1% decrease in Europe; 3.5% increase in the USA), which may be because of unusual fluctuations in weather, reduced consumption, and improvements in energy conservation and energy efficiency. Energy data mentioned above was reported as 'Global Energy Statistics' (yearbook.enerdata.net).

Fig. 2 (b) shows recent trends of energy balance or deficit (energy consumed – energy produced) in various OECD countries such as New Zealand, Australia, USA, and Germany. Additionally, the OECD total in all 36 countries is also presented in Fig. 2 (b) which shows a decreasing trend during years. In other words, most of OECD countries, including Australia and USA, are minimising their energy deficits.

However, energy deficit in New Zealand has increased during recent years and has reached approximately 6.8 Mtoe in 2018. Increase can be attributed to New Zealand's continued economic growth, population growth, social well-being, and lack of renewable energy plants as discussed in Section 3. Currently, approximately 60% of energy in New Zealand comes from fossil fuels [39]. Under the current scenario of energy supply in New Zealand, burning more fossil fuel is likely to meet the energy deficiency shown in Fig. 2 (b), increasing New Zealand's contribution to GHG emissions. On the other hand, waste-to-energy processing in New Zealand could cope with the increasing amount of MSW and rising energy deficit without burning additional fossil fuels.

3. Global MSW collection and waste treatment methods

Municipal solid waste *collection* is a critical step in waste management and the choice of waste-to-energy technology. A country's income level and region have strong impact on MSW collection rates. For example, high-income countries nearly collect 100% of MSW in urban and rural regions. On the other hand, low-income countries collect approximately 50% of MSW in urban areas and about 26% in rural areas. Similarly, North America and Europe collect more than 90% and Sub-Saharan Africa collects approximately 45% of MSW [20,40]. We note that New Zealand's human geography and its consequences for collection, beyond the scope of this paper, would be a factor in the final solutions to MSW management.

Once collected, converting MSW to energy is challenging because the raw waste, i.e., the 'feedstock' has comparatively low energy content,

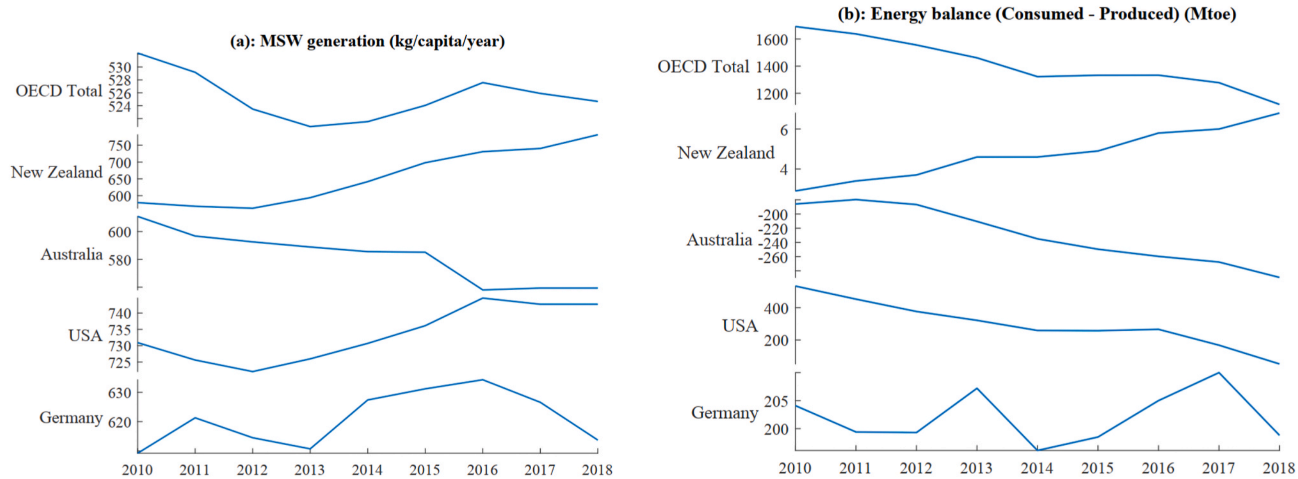

Fig. 2. OECD data: (a) MSW [37], and (b) Energy deficit [38].

heterogeneous composition, and high moisture content. However, various conventional and nonconventional waste-to-energy technologies have been used directly or indirectly to treat and dispose of MSW, and for waste-to-energy processing. Around the world, approximately 36.6% MSW is disposed of in landfills; 33% of is treated through composting; about 13.5% undergoes materials recovery through recycling; 11.1% through incineration; 5.5% is openly dumped; and 0.3% is treated using other methods such as gasification, Fig. 3 (a) [20].

The choice of waste treatment varies significantly by a country's income level. Fig. 3 (a) shows waste treatment methods comparison between countries based on their income. Notably, high-income countries have significantly higher amounts of material recycling, landfilling, and incineration than average or low-income countries. Furthermore, high-income countries have very little open waste dumping (around 2%) as compared to average or low-income countries, which can have up to 93% of open dump. High-income countries are also using new waste treatment or waste-to-energy technologies such as gasification and pyrolysis, though these only contribute 2% of waste treatment methods [20,37].

Fig. 3 (b) compares New Zealand's waste treatment or waste-to-energy technologies with other high-income countries. Current waste treatment methods in New Zealand and their percentages are significantly different from other high-income countries. In New Zealand, material recycling (28%) and landfilling (72%) are mainly used. However, other high-income countries are also significantly using incineration (22%), composting (6%), and other new waste treatment methods (2%) which are rare in New Zealand. Fig. 3 (c) compares waste composition in New Zealand and other high-income countries that have organics, and inorganics such as glass, metals, paper & cardboard, plastics, rubber & leather, wood, and other materials in their MSW. There are also significant differences in between MSW composition in New Zealand and in other high-income countries.

These comparative figures raise the question of why New Zealand differs. Reasons include.

i. A relatively low population number, so a lower pool of funding for civic work;
ii. Historic context, such as an island nation's desire for more land produced by landfill;
iii. Political reluctance to spend public money on MSW management, an expenditure that is perhaps less appealing to the public than health or education spending;
iv. Consumption habits and attitudes; and,
v. Lack of knowledge of and attention to the potentials offered by change.

This article is addressing the fifth item hoping to contribute to the way forward into a sustainable future.

4. Waste-to-energy processing technologies

4.1. An overview of waste-to-energy technologies

Municipal solid waste can be converted into energy directly or indirectly using various types of processes such as biological (e.g. composting, anaerobic digestion), thermochemical (e.g. incineration, pyrolysis, gasification, and plasma gasification), and hydrothermal (e.g. wet oxidation) processes. Table 1 shows a comprehensive comparison of MSW-to-energy technologies in terms of different performance criteria such as process plant service life and technical capabilities, costs, net energy production, environmental impacts, and readiness levels.

It is worth mentioning that composting and landfilling are conventionally considered waste disposal methods and are not considered among conventional waste-to-energy technologies. Composting was considered a conventional technology in this study because it can extract a certain amount of energy during the composting process (heat released due to bio-oxidation of carbohydrates). Still, the energy produced is relatively low compared to other waste-to-energy technologies. Also, landfilling is not always considered among conventional waste-to-energy technologies because there are many landfills where landfill gas collection and use for energy is not applied. Usually, it is not economically viable to apply this technology for smaller landfills (lower quantities of disposed waste).

As shown in Table 1, each waste-to-energy technology mentioned above has advantages and disadvantages. However, it is evident from recent studies such as Young (2010) [41], Munir et al. (2018) [42], and Munir et al. (2019) [43] that nonconventional technologies of waste-to-value processing such as pyrolysis, gasification, plasma gasification, and hydrothermal processing have more advantages than conventional technologies. They perform better than conventional methods in terms of technical capabilities, net income, net energy production, and environmental impacts as shown in Table 1. However, no waste-to-energy technology is effectively universal because of various technical, economic, environmental, and social limitations [44–46]. Therefore, mostly multiple combinations of conventional and nonconventional waste-to-energy technologies are recommended for best results. It is worth mentioning that in the presence of proper waste sorting at the household level, only the organic fraction should be treated through an anaerobic treatment, while the dry fraction (MSW-organic fraction), after the bulk separation of glasses, metals, paper, and plastic should be submitted to thermochemical processes.

As evident in Table 1, thermochemical methods, as a whole, have

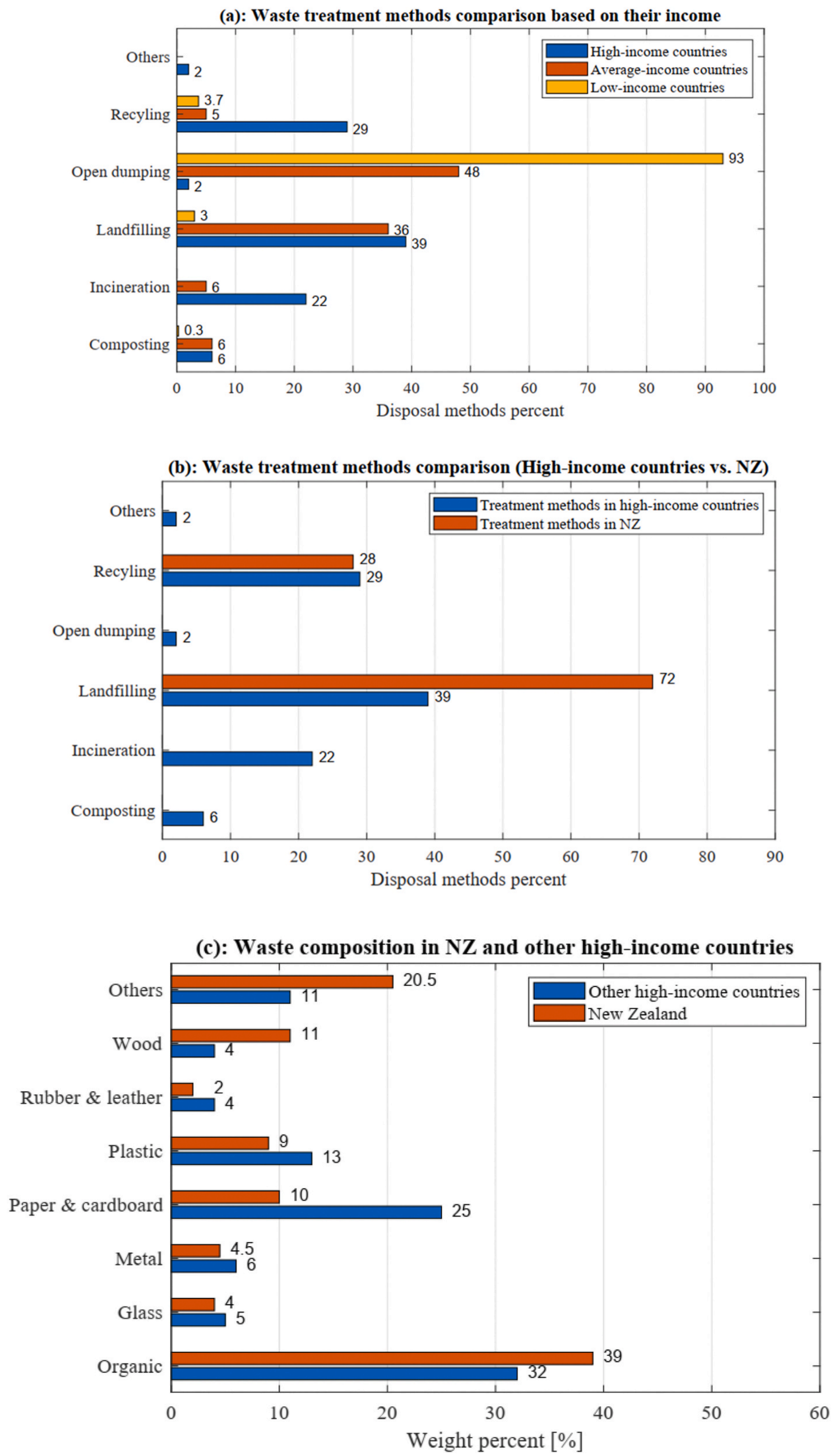

Fig. 3. Waste treatment methods and composition comparisons.

better plant service life and technical capabilities than biological or landfilling methods. Thermochemical or hydrothermal methods produce higher net energy or income than biological or landfilling methods. Biological or landfilling methods recover less value than thermochemical or hydrothermal processes, but are cheaper, well established and their readiness levels (society and technology) are higher than thermochemical or hydrothermal processes [47–49].

Table 1
Comparison of various technologies for waste-to-energy processing [1,42,50–64].

Criteria	Conventional technologies				Nonconventional technologies			
	Composting	Anaerobic digestion	Landfilling	Incineration	Pyrolysis	Gasification	Plasma gasification	Wet oxidation
	Plant service life and technical capabilities comparison							
Plant life (years)	10–15	15–20	30	30	20	30	20	20
Waste sorting required	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No
Wet waste handling	Limited	Limited	Limited	No	Limited	Limited	Limited	Yes
Automation level	Low	Low	Low	Medium	Medium	Medium	High	High
Hazardous waste handling	Low	Low	Low	Medium	High	High	High	High
	Cost comparison (Plant capacity: 1000 tonne MSW per day)							
Average capital costs (US$M)	Low (10)	Medium (50)	Medium (70)	Medium (116)	High (87)	High (80)	High (100)	High (80)
Compliance costs	Medium	Low	Low	High	Medium	High	High	High
Average operational costs (US$M)	Low (1)	Low (2)	Low (2)	Low (8.2)	High (7.2)	High (6.8)	High (8.5)	High (8)
Net income (US$M)	Low (−0.1)	Medium (+0.5)	Medium (+0.5)	Medium (+0.5)	Medium (+0.5)	High (+3.1)	High (+3.2)	High (+2)
	Net energy comparison							
Net energy production (kgoe/tonne of MSW)	−2.7–3.2	9–13.5	4.5–9	36–45	45–50	36–63	63–81	–
	Environmental impact comparison							
MSW volume reduction (%)	Low (50)	Medium (60)	Medium (60)	High (75)	High (84)	High (82)	High (90)	High (90)
Value recovery	Low	Low	Low	Low	Medium	Medium	High	High
Residue remaining	High	High	Medium	Medium	Medium	Medium	Low	Low
NOx (mg/m^3)	–	–	–	Less than 400	Less than 50	Less than 200	Less than 200	–
SOx (μg/Nm^3)	–	–	–	40	35	19	26	–
Particles (μg/Nm^3)	–	–	–	20	5.7	14.1	12.5	–
HCl (μg/Nm^3)	–	–	–	–	10–50	3–26	1–8	–
CO_2 tonne per tonne MSW	1.61	1.19	1.97	1.67	0.7–1.2	1.3–1.5	1.3–1.5	–
	Readiness levels comparison							
Society readiness level	Medium	Medium	High	Low	Low	Low	Low	Low
Customer readiness level	High	High	Medium	High	Medium	Medium	Medium	Medium
Technology readiness level	High	High	High	High	Medium	Medium	Low	Low

4.2. Conventional waste-to-energy technologies

Fig. 4 shows process flow schematics of conventional technologies such as composting, anaerobic digestion, landfilling, and incineration processes presenting the main steps involved in the waste-to-energy processing. The main steps of each process include MSW receiving, waste sorting if required, waste transformation process (e.g. anaerobic digester), product separation (e.g. gas separator), and energy production (e.g. generator). It is worth mentioning that composting, and anaerobic digestion mainly process organic MSW, while landfilling waste feed can have both organic and inorganic portions. More details about each conventional technology are given below.

Composting is aerobic biological process in which organic MSW such as biomass, e.g. food waste ($C_{18}H_{26}O_{10}N$), grass ($C_{23}H_{38}O_{17}N$), and mixed paper ($C_{266}H_{434}O_{210}N$) naturally degrades into a humus-like material (i.e. compost). A typical composting process and its main steps are shown in Fig. 4 (a). Compost is rich in nutrients and useful microbes, so is used as fertilizer and soil conditioner. During composting, principal components of organic MSW (e.g. proteins, lipids, carbohydrates, lignin, and ash) are oxidized in the presence of suitable nutrients and microbes to make compost, water (H_2O), carbon dioxide (CO_2), nitrate (NO_3^-), sulphate (SO_4^{2-}), ammonia (NH_3), organic acids, and heat, Equation (1) [65]. Furthermore, oxidation of carbohydrates such as starch or cellulose that are mineralised in the waste produces water (H_2O), carbon dioxide (CO_2), and heat, Equation (2), and (3) below [66].

$$\left\{\begin{matrix} Proteins \\ Lipids \\ Carbs \\ Lignin \\ Ash \end{matrix}\right\} + O_2 \rightarrow Compost + CO_2 + H_2O + NO_3^- + SO_4^{2-} + NH_3 + Organic\ acids + Heat \tag{1}$$

$$C_6H_{10}O_5\ (Starch) + 6O_2 \rightarrow 6CO_2 + 5H_2O + Heat \tag{2}$$

$$C_6H_{10}O_5\ (Cellulose) + 6O_2 \rightarrow 6CO_2 + 5H_2O + Heat \tag{3}$$

Optimum composting performance can be achieved by manipulating compost feed formulation (e.g. pH, porosity, particle size, moisture, and nutrient balance in terms of the carbon (C)–nitrogen (N) ratio), and process parameters (e.g. temperature, oxygen concentration, and water content). A pH of 5.5–8.0 [67], a porosity of 35–50% [68], a medium particle size (approximately 15 mm) [69], a moisture of 50–60% [70], a C/N ratio of approximately 25–30 [65], a temperature range of 40–65 °C [71], and a concentration of O_2 between 15 and 20% [72] are considered optimum feed formulation and process parameters for composting.

During composting, approximately 38% of heat is released due to the bio-oxidation of carbohydrates present in organic solid waste [73]. At the beginning of the composting process, carbohydrates decompose much faster than other organic contents such as lignin, fats, and *N*-compounds [74]. Some authors such as Klejment and Rosiński (2008) [66] claimed that composting can release 3–18 MJ of ultimate energy per kg of organic waste depending upon waste composition. It is worth mentioning that the ultimate energy is the amount of energy released when one unit of waste is completely burned in the presence of oxygen.

Composting of organic MSW has many advantages and disadvantages. Advantages of composting include that composting is an eminent

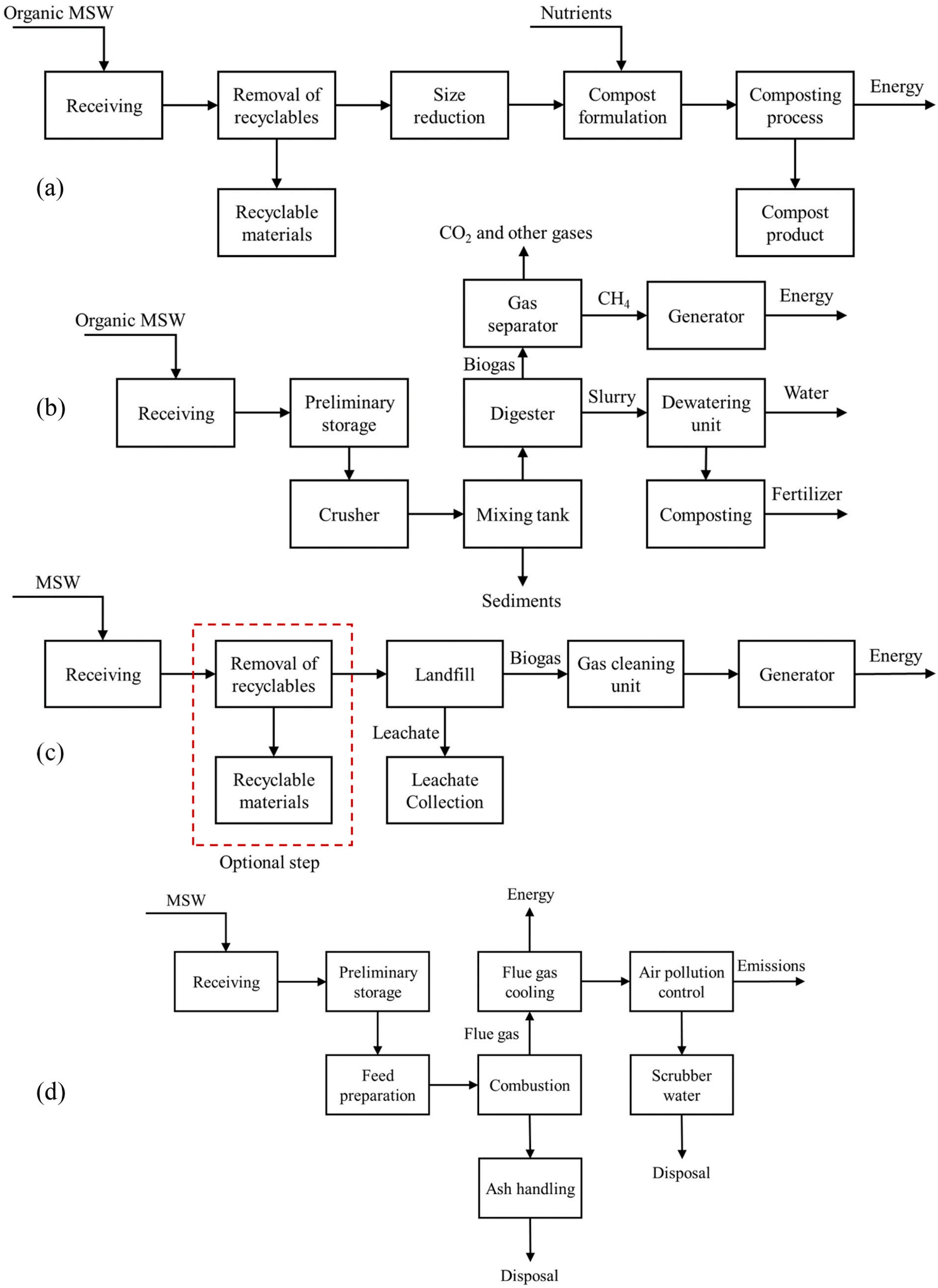

Fig. 4. Process flow schematics: (a) composting, (b) anaerobic digestion, (c) landfilling, (d) incineration.

soil regulator; requires lower initial capital investment and medium compliance cost; requires limited process automation; lowers pollution risks; has medium-high society, customer, and technology readiness levels; and increases income from compost products, Table 1. On the other hand, composting is a time-consuming process that occupies land, has limited capabilities to handle hazardous waste, and MSW volume reduction is low (approximately 40%). Furthermore, composting consumes approximately −2.7–3.2 kg of oil equivalent (kgoe) per tonne of waste [75,76].

Anaerobic digestion is anaerobic biological process in which microbes (e.g. mesophilic and thermophilic) decompose organic MSW under oxygen-free conditions to produce biogas that contains approximately 55–75% methane (CH_4), 30–45% carbon dioxide (CO_2), 1–2% hydrogen sulphide (H_2S), 0–1% nitrogen (N_2), 0–1% hydrogen (H_2), and an organic residue [77]. A typical anaerobic digestion process and its main steps are shown in Fig. 4 (b).

During anaerobic digestion, principal components of organic MSW are converted through four main reactions: hydrolysis, fermentation, acetogenesis, and methanogenesis, Fig. 5 [9].

Anaerobic digestion of organic MSW is influenced by various feed formulation and process parameters such as organic loading rate, C/N ratio, pH, temperature, moisture content, and retention time. Optimum anaerobic digestion conditions include an organic loading rate of approximately 10.1 g COD/L per day [78]; C/N ratio of 30:1 [77]; pH range of 6.8–7.2 [79]; temperature ranges of mesophilic (30–40 °C) and thermophilic (45–65 °C) [80]; about 85 wt percent of moisture content; and retention time of around 15 days [81].

Anaerobic digestion of organic MSW can produce a net energy (i.e. the amount of energy produced in biogas – total heat demand) of approximately 9–13.5 kgoe per tonne of MSW under optimum conditions [75,76]. Most of anaerobic digestion configurations such as mesophilic, and thermophilic digestion produce more energy output than they consume. However, batch pre-treatment configuration produces the most net energy output [82]. More advantages of anaerobic digestion include additional valuable products such as fertilizer; limited process automation; low compliance and operational costs; environment-friendliness; medium-high society, customer, and technology readiness levels; and waste odour level reduction. On the other hand, anaerobic digestion of MSW requires a high level of capital investment at a commercial scale and limited handling of hazardous waste. It is able to give volume reduction of organic MSW of approximately 60%, Table 1. Furthermore, it is time-consuming and arguably relatively inefficient [75].

Landfilling is a waste disposal method rather than waste-to-energy process that involves burying MSW while preventing contamination (e.g., unwanted leachate) of the environment. There are various types of landfills such as MSW landfills, industrial waste landfills, and hazardous waste landfills [83]. A typical landfilling process of MSW is shown in Fig. 4 (c). It is worth mentioning that not all landfills have integrated removal of recyclables. Removal of recyclables is an optional step and is usually done in (often dislocated) sorting plants.

Methane production during landfilling of MSW can be enhanced up to 25% by using various process parameters and their optimum values such as.

- Gravel mixing of 0.38 kg gravel per kg dry waste;
- Aeration rate of 0.66 m^3 per day per kg dry solids for 5% of total time;
- Approximately 10–13.5% (v/v) of MSW leachate recirculation;
- Approximately 1 cm intermediate soil layer; and,
- About 0.42% (v/v) of MSW digested slurry mixing in recirculated leachate [84].

It is worth mentioning that biogas produced during landfilling of MSW is approximately half (i.e. approximately 4.5–9 kgoe per tonne of MSW) of that produced during anaerobic digestion from a given volume of organic waste [85]. This difference may be because anaerobic digestion occurs under optimum conditions, whereas, landfills are often not optimised.

Landfilling, the most commonly used waste disposal method, can convert marshy lands to useful areas, produce biogas which can be used for power generation, and it does not require skilled personnel to operate. Furthermore, landfilling has 30–50 years plant service life, compliance, low operation costs, and medium-high society, customer, and technology readiness levels, Table 1. On the other hand, landfilling requires a large land area which is expensive when new landfilling sites

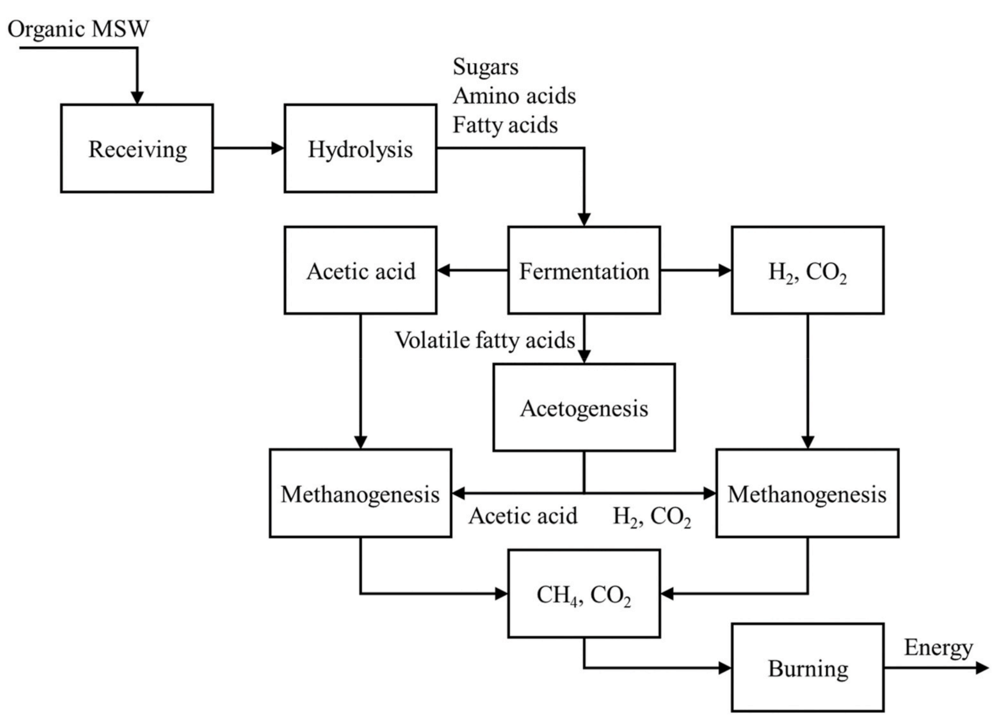

Fig. 5. Main reactions involved during anaerobic digestion of MSW [9].

are decreasing. The product yield and net energy production is low, transportation cost is significant, soil or groundwater may be polluted by leachate and hazardous waste, and volume reduction is medium, Table 1 [86].

Incineration involves the combustion of MSW in the presence of air or oxygen to produce flue gas, ash, and heat. During incineration, MSW is burned in a controlled incinerator environment and energy is recovered [87]. A typical MSW-incineration facility schematic is shown in Fig. 4 (d).

The incineration process depends on parameters such as furnace/reaction chamber type or configuration, incineration temperature, gas-residence time, air flow, and mixing of MSW and oxygen. For efficient incineration of MSW, temperature ranges (540–980 °C for primary chamber, and 980–1200 °C for secondary chamber), gas-residence time of more than 2 s, an access air flow of 140–200%, and adequate mixing of MSW and air are recommended [88].

Incineration efficiently reduces waste volume 70–80%, produces energy as heat, can produce good quality slag with some heavy metals, can be used to treat hazardous waste (e.g. waste from hospitals), is less time-consuming than biological processes, and cost is low while technology readiness level is high, Table 1. The energy efficiency of incineration process is about 20–25%, producing approximately 36–45 kgoe net energy per tonne of MSW [89]. On the other hand, capital and compliance costs are medium-high because of heavy equipment (e.g., furnace) and skilled staff. Furthermore, residues from ash handling, flue gas cleaning, and uncontrolled emissions (e.g. dioxins and acidic gases (NOx, SOx, and HCl) can contaminate the environment, as noted in Table 1 [90,91].

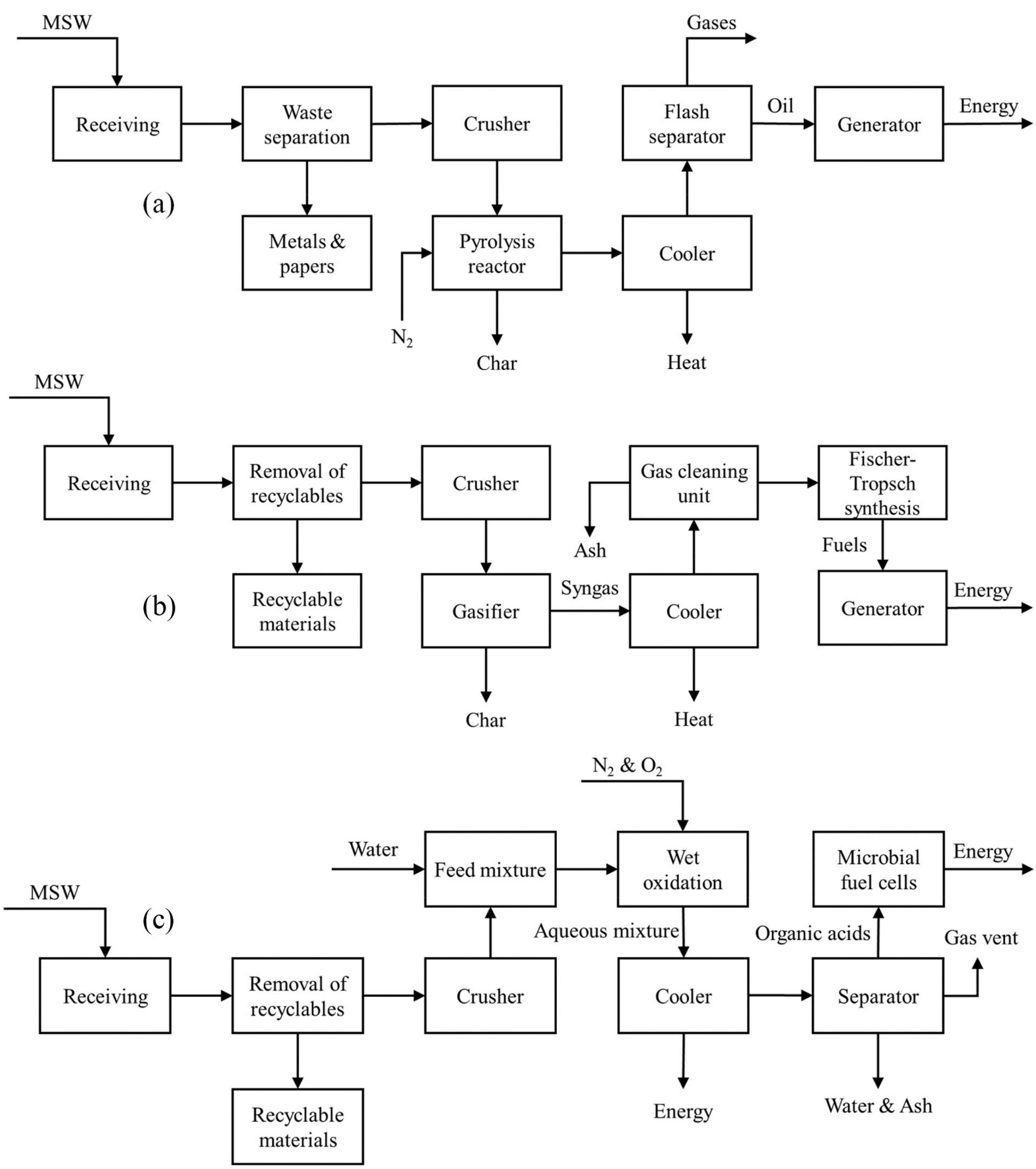

Fig. 6. Process flow schematics: (a) pyrolysis, (b) gasification, and (c) wet oxidation or hydrothermal process.

4.3. Nonconventional waste-to-energy technologies

Fig. 6 presents process flow schematics of nonconventional waste-to-energy technologies which include pyrolysis, gasification, plasma gasification, and hydrothermal processing. Nonconventional technologies can handle organics or inorganics; however, except for hydrothermal processes, feedstock may need drying. Nonconventional technologies are discussed in detail as follows.

Pyrolysis is a thermochemical treatment process in which MSW is degraded at approximately 300–800 °C in the absence of oxygen or air to produce pyrolysis-oil, syngas, and solid reside (e.g. biochar), Equation (4) [92,93]. A typical pyrolysis process of MSW is shown in Fig. 6 (a). Types of pyrolysis include slow, fast, flash, intermediate, vacuum, and hydro pyrolysis processes [94]. Tripathi et al. (2016) [94] describe each different pyrolysis type's operation.

$$C_xH_yO_z(MSW) + Heat \rightarrow Pyrolysis\ oil + Syngas + Biochar + H_2O \quad (4)$$

Various process parameters such as pyrolysis reaction temperature (300–800 °C), residence time (0.01–550 s), heating rate (0.1 – more than 100 °C per min), and particle size (less than 0.5–5 mm) influence the pyrolysis process and product quality. During pyrolysis of MSW, optimum performance can be achieved at temperatures above 500 °C, residence time of at least 2 min, heating rate of approximately 3.5 °C per s, and particle size of approximately 0.5 mm. Pyrolysis of MSW can produce net energy of approximately 45–50 kgoe per tonne of MSW [94,95]. Pyrolysis is a flexible technology which can treat different types of feedstocks (e.g. dry, wet, biomass, sludge) and operate under wide range of operating conditions. The product quality during pyrolysis can be changed by manipulating its process conditions. For example, fast pyrolysis (temperature: 400–800 °C, heating rate: 10–200 °C per s, and residence time: 0.5–10 s) is suitable for higher pyrolysis-oil yield, while slow pyrolysis (temperature: 300–700 °C, heating rate: 0.1–1.0 °C per s, and residence time: 300–550 s) is recommended for high biochar production [96]. Furthermore, pyrolysis can significantly reduce MSW volume (approximately 84%), and has high customer and technology readiness levels, Table 1. On the other hand, pyrolysis products usually require further treatment before use or vent in the environment. Other disadvantages of pyrolysis include higher capital and operational costs, requirement of skilled staff to operate, high viscosity of pyrolysis-oil, and low society readiness level [86].

Gasification is a thermochemical waste treatment method in which MSW is heated at extreme temperature 600–1700 °C with a controlled (i.e. one-fifth to one-third of the theoretical oxidant) amount of oxygen, steam, or air to produce syngas as major product and CO_2 as a minor product. There are various types of gasifiers such as updraft, downdraft, fluidized-bed, entrained flow, and plasma gasifiers. Also, plasma gasification is emerging as an effective waste treatment method due to its technical capabilities [17,43]. In plasma gasification, MSW is exposed to extremely high temperature 2000–14,000 °C of plasma [43]. During gasification or plasma gasification, four main processes take place: dehydration or drying of MSW; pyrolysis or devolatilization in the absence of oxygen to release volatiles from MSW and produce char; combustion with oxygen to release energy; and reduction to produce syngas. Partial oxidation of MSW provides most energy required for the other endothermic gasification reactions, Table 1 [43,97]. A typical gasification process schematic is shown in Fig. 6 (b). Main reactions taking place during gasification or plasma gasification are shown in Table 2.

During gasification process, operating parameters such as MSW particle size, equivalent ratio (i.e. actual amount of O_2 to stoichiometric amount of O_2 required for complete combustion), reaction temperature, and residence time are mainly responsible for performance. A particle size range of 2–60 mm [98], an equivalent ratio of 0.2–0.4, a temperature between 850 and 1200 °C, and residence time of 20–30 min are optimum conditions for MSW gasification [99,100]. Conventional gasification can produce a net energy of approximately 36–63 kgoe per tonne of MSW. On the other hand, plasma gasification can produce more net energy than conventional gasification: approximately 63–81 kgoe per tonne of MSW as mentioned in Table 1 [43,101].

Table 2
Main reactions occurring during gasification process.

	Oxidation reactions – (Exothermic)		ΔH = – 1030 MJ/kmol
1	$C + 0.5\,O_2 \rightarrow CO$	Partial oxidation of C	– 111 MJ/kmol
2	$CO + 0.5\,O_2 \rightarrow CO_2$	Oxidation of CO	– 283 MJ/kmol
3	$C + O_2 \rightarrow CO_2$	Oxidation of C	– 394 MJ/kmol
4	$H_2 + 0.5\,O_2 \rightarrow H_2O$	Oxidation of H_2	– 242 MJ/kmol
	Steam gasification reactions – (Endothermic)		**ΔH = + 296 MJ/kmol**
5	$C + H_2O \rightarrow CO + H_2$	Steam gas reaction	+131 MJ/kmol
6	$CO + H_2O \rightarrow CO_2 + H_2$	Steam gas shift reaction	– 41 MJ/kmol
7	$CH_4 + H_2O \rightarrow CO + 3H_2$	Steam gas reforming reaction	+206 MJ/kmol
	Hydrogen gasification reactions – (Exothermic)		**ΔH = – 302 MJ/kmol**
8	$C + 2H_2 \rightarrow CH_4$	Hydrogasification reaction	– 75 MJ/kmol
9	$CO + 3H_2 \rightarrow CH_4 + H_2O$	Methanation reaction	– 227 MJ/kmol
	Carbon dioxide gasification reactions – (Endothermic)		**ΔH = + 172 MJ/kmol**
10	$C + CO_2 \rightarrow 2CO$	Boudouard reaction	+172 MJ/kmol
	Decompositions of tars & hydrocarbons – (Endothermic)		**ΔH = + MJ/kmol**
11	$pC_xH_y \rightarrow qC_nH_m + rH_2$	Hydrogasification reaction	+ve MJ/kmol
12	$C_nH_m \rightarrow nC + 0.5mH_2$	Carbonization reaction	+ve MJ/kmol
	where, C_xH_y : Tars, C_nH_m : *Hydrocarbons*		

Gasification of MSW has many advantages including that controlled oxygen limits the formation of dioxins (e.g. NOx, and SOx). Mostly, it produces higher net energy (e.g. 36–63 kgoe, and 63–81 kgoe using gasification and plasma gasification respectively) per tonne of MSW than incineration and pyrolysis, produces a fuel gas that can be integrated with reciprocating engines or with fuel cells to efficiently convert fuel gas to electric power, and reduces significant MSW volume (approximately 80–90%), Table 1. However, fuel gas produced during gasification contains tars, ash, particulates, and heavy metals which can agglomerate in the gasifier and are hazardous for the environment, and the process has low-medium society, customer, and technology readiness levels, Table 1. It is worth mentioning that tar and other heavy hydrocarbons result from operating at a temperature range of 850–900 °C. At a temperature higher than 1100 °C, tar will not be present. Gas cleaning after the gasification is not unexpansive considering the MSW pollutants, because gas cleaning also requires syngas quenching, removal of tar and particulates, metals, HCl and H_2S [101,102].

Wet oxidation is a hydrothermal waste treatment method in which an aqueous mixture of MSW is heated to a sub-critical temperature (~150–350 °C) with oxygen or air [103]. Extreme pressure (20–150 bar) of nitrogen and oxygen mixture is also used during wet oxidation in order to keep the reaction mixture in liquid phase [104]. During wet oxidation, MSW degrades into peroxides, alcohols, ketones, and carboxylic acids (e.g. acetic acid and other organic acids) which are subsequently converted into CO_2, H_2O, and ash, Equations (5)–(9). With wet oxidation, MSW degrades under extreme conditions of temperature and pressure because water exhibits decrease in viscosity, surface tension, dielectric constant, and increase in diffusion rate which make water an excellent solubilisation and extraction solvent [105]. Organic acids can be used for a wide range of applications such as in wastewater treatment as an organic source and in microbial fuel cells for power generation [106,107]. A typical wet oxidation process of MSW is shown in Fig. 6 (c).

$$C_xH_yO_z(MSW) + O_2 + N_2 + Heat \rightarrow Peroxides \quad (5)$$

$$Peroxides \rightarrow Alcohols + Ketones + Carboxylic\ acids \quad (6)$$

$$Alcohols \rightarrow Ketones \rightarrow Carboxylic\ acids \quad (7)$$

$$Alcohols \rightarrow N_2 + CO_2 + H_2O + Ash \quad (8)$$

$$Carboxylic\ acids \rightarrow N_2 + CO_2 + H_2O + Ash \quad (9)$$

Various process parameters such as reaction temperature, residence time, oxygen pressure, and mixing speed affect the performance of wet oxidation process [108]. Reaction temperature of approximately 230–280 °C, residence time of 30–60 min, oxygen pressure of 30–40 bar, and mixing speed of 300–500 rpm are considered optimum conditions for wet MSW oxidation [19,42,104].

Wet oxidation can significantly reduce the volume of MSW (up to 90–95%), can treat wet waste without needing to dry it (an expensive step), and is less time-consuming than conventional technologies such as anaerobic digestion and landfilling, while net income is high, and the process is environmentally friendly, Table 1 [63,64]. Yet, wet oxidation is an energy-intensive process, requiring additional safety measures because of extreme conditions of temperature and pressure, and it has low society and technology readiness levels [19,109].

5. Waste-to-energy processing in New Zealand

5.1. Potential and current status of waste-to-energy processing

As shown in Fig. 1 (b), New Zealand generates around 4 million tonnes of MSW per annum. This amount has a net energy potential of approximately 0.5–1.5 Mtoe per annum, given MSW's net energy potential of about 0.13–0.38 toe per tonne, as mentioned in Section 1. As a result, appropriate MSW-to-energy technologies in New Zealand could offset 10–25% of its total energy deficit, approximately 6.8, 8.5, and 11 Mtoe in 2018, 2030, and 2050 respectively as mentioned in Section 2 and shown in Fig. 7.

A net energy potential of 0.35 toe per tonne of MSW and approximately 90% waste volume reduction after waste treatment was used to plot Fig. 7 (see Table 2 for waste-to-energy technologies such as plasma gasification or hydrothermal processing). Promisingly, waste-to-energy processing can reduce the energy deficit approximately 20% with significant reduction in waste landfilling as shown in Fig. 7.

However, currently landfilling is the main MSW disposal method (72%) in New Zealand with remaining MSW (28%) recycled as shown in Fig. 3 (b). In other words, MSW in New Zealand is mostly either being dumped in landfills or being recycled without significant use of waste-to-energy technologies practiced in other high-income or OECD countries. In New Zealand, there have been small-scale waste-to-energy projects using anaerobic digestion, incineration, pyrolysis, and gasification. However, their contribution is negligible as compared to other high-income or OECD countries. Another important fact is that the number of available landfill sites in New Zealand is decreasing–their recent estimate is fewer than 50–because of greater demand for land as the population increases, higher land cost and associated challenges [20,25].

5.2. Challenges associated with waste-to-energy processing in New Zealand

In New Zealand, various challenges are associated with the application of waste-to-energy technologies, especially for better performing nonconventional technologies or for various combinations of conventional and nonconventional technologies to get additional benefits, as mentioned in Section 4. The challenges include higher costs; limited process understanding of nonconventional technologies and their integration with conventional technologies; limited commercial success of nonconventional waste-to-energy technologies so far in New Zealand; low-to-moderate community and technology readiness levels; complex processes; and policy uncertainty about waste-to-energy processing.

As shown in Table 1, nonconventional technologies of waste-to-energy processing have higher capital, compliance, and operational costs compared to conventional methods. For a same plant capacity (e.g. 1000 tonne MSW per day), nonconventional methods such as plasma gasification require approximately 100 million US$ to build a waste treatment plant, much higher than the cost of conventional methods [43]. Furthermore, New Zealand labour costs for skilled staff are high which makes operational costs of nonconventional methods higher than conventional methods. Nonconventional methods of waste treatment have limited process understanding, fundamental and thermodynamic data, and understanding of reaction kinetics. Furthermore, limited studies reporting combining conventional and nonconventional

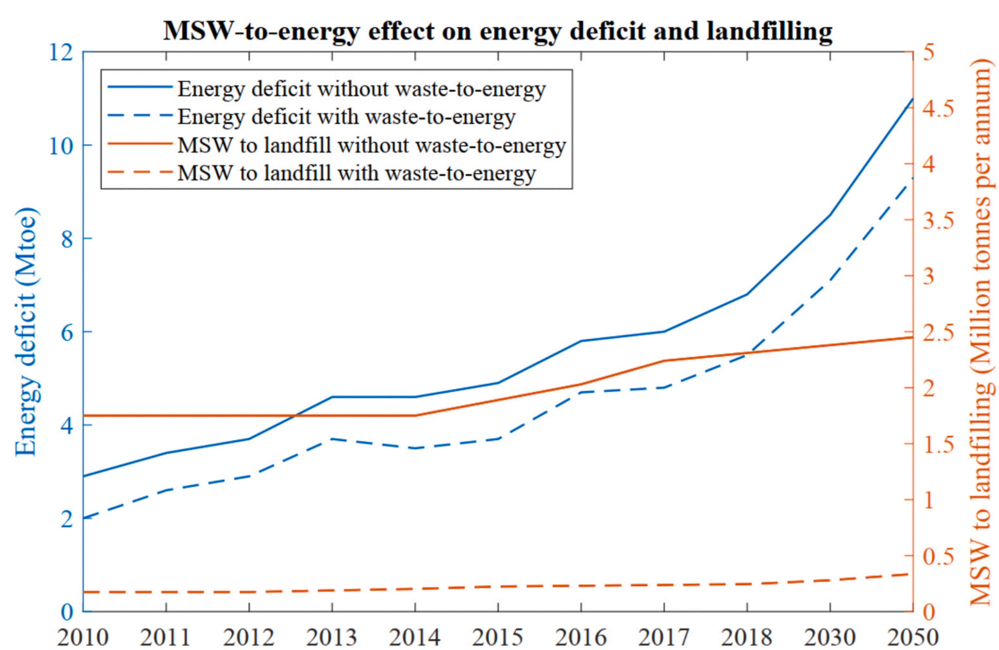

Fig. 7. Effect of waste-to-energy on the energy deficit and landfilling in New Zealand.

waste-to-energy technologies have higher technical risks to achieve reliable operation, and therefore are less popular in New Zealand. However, conventional methods produce much lower net income compared to nonconventional methods, fail to contribute energy, and are therefore limited in terms of sustainability.

Another challenge associated with the application of nonconventional methods for waste-to-energy processing in New Zealand is their limited commercial success worldwide. In spite of the various advantages discussed in Section 4, nonconventional methods have not been commercially very successful. There are only five commercial plants of plasma gasification (e.g. Mihama-Mikata Japan, and Wuhan Kaidi/Alter NRG China), and four of wet oxidation (e.g. Terax New Zealand, Athos France, Orbe Italy, and Zimpro USA). This limited commercial success may be because of safety concerns and high costs. As a result, nonconventional technologies are less appealing for investment.

As shown in Table 1, nonconventional technologies have low-to-medium society, community, and technology readiness levels. Since most of nonconventional technologies use extreme conditions, they have mostly low society readiness level. Customer readiness level for nonconventional technologies is medium because of their effective waste treatment and higher net energy production capabilities. Furthermore, nonconventional methods have low-to-medium technology readiness level due to fact that these technologies are relatively new and lack fundamental data. As a result, low-to-medium society, community, and technology readiness levels of nonconventional technologies are discouraging for investment in such technologies in New Zealand.

Policy uncertainty around waste management is another barrier, perhaps because waste-to-energy plants need a constant supply of MSW which contradicts the recycling policy of New Zealand. Furthermore, getting a consistent supply of MSW is challenging because New Zealand has only a few densely populated areas such as Auckland.

6. Possible roadmap for the circular economy in New Zealand using waste-to-energy technologies

Fig. 8 shows a holistic view of a circular economy action plan in New Zealand. The circular economy action plan aims to recycle materials where possible, to use conventional and nonconventional technologies for waste-to-energy processing, and to minimise MSW landfills. Furthermore, this plan proposes to segregate organics and inorganics after material recycling as shown in Fig. 8.

Organics are sent to conventional technologies such as composting, and anaerobic digestion, and inorganics that cannot be recycled are sent to nonconventional technologies such as gasification and hydrothermal processing. For a consistent supply of MSW, perhaps smaller distributed (decentralized) waste-to-energy plants can be considered too.

Useful products and energy from waste-to-energy technologies can be recycled back to households and businesses. As a result, materials used can be kept in the economy for a longer time, energy produced from MSW can minimise energy deficit in New Zealand, MSW can be safely managed, and significantly reduced volume of MSW would be sent to landfills as the landfill option becomes unsustainable.

In New Zealand, costs of nonconventional technologies for waste-to-energy processing can be reduced with efficient plant facilities generating additional revenue from their products such as pyrolysis oil, synthesis gas, and organic acids. End high-value products include fuels, chemical compounds, and hydrogen. Other strategies to reduce cost include lowering the tipping fee to attract MSW, increasing plant capacity, utilizing by-products such as vitrified slag in plasma gasification, using lean manufacturing practices such as 5S methodology, and integrating energy to decrease energy costs.

More study is needed both within engineering and beyond it into social geography. Various feasibility studies are required to analyse the effects of critical process parameters, and design configurations on the yield and economy of such processes. These studies are essential for efficient process design, optimisation, critical decision making, and for improving technology readiness level. Such fundamental studies need to be conducted through industry-academia collaborations at laboratory and pilot scales before their implementations at industrial scale.

Society and community readiness levels need to be improved for successful commercialisation of nonconventional technologies in New Zealand, with a better communication strategy to inform the end-users about the capabilities of nonconventional technologies, and extra safety layers using layers of protection analysis (LOPA). Furthermore, different stakeholders such as local government, local community, industry, and investment companies need to work together at laboratory to industrial scales for a proposed waste-to-energy technology to develop community and customer acceptance for the technology. Then there is the matter of finding political leaders who will take the project into practice.

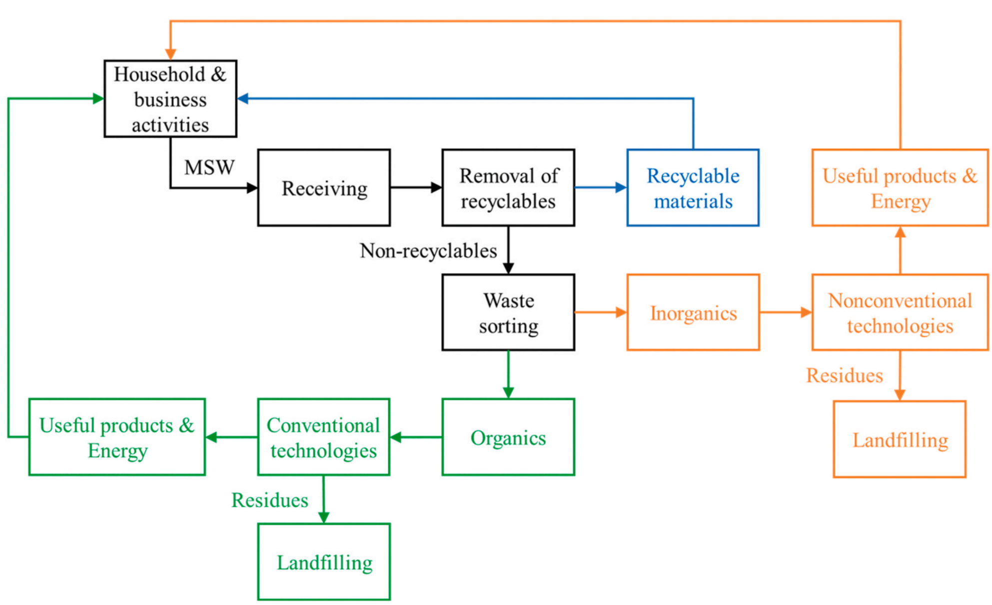

Fig. 8. Towards the circular economy in New Zealand using waste-to-energy technologies.

7. Conclusions

Nonconventional technologies integrated with conventional technologies can be suitable options for waste-to-energy processing and achieving the circular economy in New Zealand. However, various challenges such as higher costs, limited process understanding, limited commercial success, low-to-moderate community and technology readiness levels, and policy uncertainty require attention for their success in New Zealand. Costs related to nonconventional technologies can be reduced by efficient plant design, generating revenue from products, increasing plant capacity, using lean manufacturing practices, and energy integration. Commercial success of nonconventional technologies can be achieved by improving customer, society, and technology readiness levels. Better understanding, education and extra layers of process safety could take New Zealand into a sustainable circular energy economy. Persuading New Zealanders that effective MSW management is an environmental responsibility and that they should rectify the fact that they are out of kilter with other high income nations might be possible once an ideal multiple approach is designed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgement

The authors gratefully acknowledge the University of Auckland New Zealand, and the University of Canberra Australia for their support.

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