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Review

Technological review on thermochemical conversion of COVID-19-related medical wastes

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ABSTRACT

COVID-19 pandemic has brought tremendous environmental burden due to huge amount of medical wastes (about 54,000 t/d as of November 22, 2020), including face mask, gloves, clothes, goggles, and sanitizer/disinfectant containers. A proper waste management is urgently required to mitigate the spread of the disease, minimize the environmental impacts, and take their potential advantages for further utilization. This work provides a prospective review on the possible thermochemical treatments for those COVID-19 related medical wastes (CMW), as well as their possible conversion to fuels. The characteristics of each waste are initially analyzed and described, especially their potential as energy source. It is clear that most of CMWs are dominated by plastic polymers. Thermochemical processes, including incineration, torrefaction, pyrolysis, and gasification, are reviewed in terms of applicability for CMW. In addition, the mechanical treatment of CMW into sanitized refuse-derived fuel (SRDF) is also discussed as the preliminary stage before thermochemical conversion. In terms of material flexibility, incineration is practically applicable for all types of CMW, although it has the highest potential to emit the largest amount of CO₂ and other harmful gasses. Furthermore, gasification and pyrolysis are considered promising in terms of energy conversion efficiency and environmental impacts. On the other hand, carbonization faces several technical problems following thermal degradation due to insufficient operating temperature.

1. Introduction

The outbreak of COVID-19 has led to extremely high global concern, and World Health Organization (WHO) has declared a global health emergency on January 30, 2020 (Fadare and Okoffo, 2020). Severe acute respiratory syndrome coronavirus (SARS-CoV-2 or COVID-19 virus) can be transmitted through direct droplet transmission (such as cough and sneeze) and contact transmission (e.g. oral, nasal, and eye mucous membrane) (Lepelletier et al., 2020). This epidemic has changed the lifestyle of people, resulting in massive job losses and threat on the economic sustenance of people and businesses (Saadat et al., 2020). Each government has tried to issue various measures and policies in order to contain the spread of the virus, as well as minimize the death risk. These measures include the lockdown to stay at home, social distancing, wearing of mask/face covering, staggered working hours,

travel restriction, isolation, disinfection, and crowd avoidance in any public space (Freedman, 2020; Chintalapudi et al., 2020). Although massive lockdown in many areas throughout the world has resulted in the improvement of air and water quality (Saadat et al., 2020), its negative impacts on economic and social aspects are very great. Furthermore, other measures such as wearing mask/face covering and using disinfection contributed to the increase of medical waste.

COVID-19 medical waste (CMW) is defined in this study as medical waste that is produced during the COVID-19 pandemic, as this pandemic generates wastes with quite unique characteristics that are discussed further, such as lower density compared with normal medical waste. CMW includes personal protective equipment (PPE), such as face mask, gloves, face shields, goggles, coverall suits, and other related wastes (such as hand sanitizer/disinfectant containers). The use of standard PPEs is an obligation for health workers (doctors, nurses, and

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caregivers), patients, and also healthy persons who have a close contact with the patients. Currently, almost all the countries around the world are enforcing their citizens to wear face masks whenever they are out from home. As the results, extremely large amount of disposable PPEs are manufactured and used that end up to a huge increase of possible contagious medical waste leading to the further health and environmental threats. Kampf et al. (Kampf et al., 2020) found that on material surfaces, including steel, plastic, and glass, COVID-19 virus can survive for about 9 days. The risks of these threats are increasing in case of under-developed or developing countries, which have limited medical waste management systems.

Huge and strong demand in the future for large amount of these medical and health-protecting goods is corresponding to the regional and global pandemic curve. The massive disruption in the supply of medical goods has created problems in their downstream disposals. In Hubei Province, the number of medical wastes generated during the outbreak of COVID-19 significantly increased to about four times of the normal condition (Joint Prevention and Control Mechanism of the State Council, 2020). In addition, the amount of CMW in Wuhan showed a peak of about 240 t/d, which is about five times of the maximum incineration capacity (Tang, 2020). Klemes et al. (2020) stated the urgent requirement of the existing treatment system to cope with the significant changes during the abnormal conditions.

Generally, plastic waste is considered as a long term environmental problem due to low degradability and its impacts in both terrestrial and marine ecosystems (Rajmohan et al., 2019). In addition, contaminated plastic wastes generated from the current pandemic needs a special treatment for disinfection that leads to the overwhelming burden for existing waste management system (Klemes et al., 2020). Therefore, the safe handling of these wastes becomes one of the highest priority among current health and environmental concerns (Liu et al., 2015).

Liu et al. (2015) stated that the selection of an optimal treatment technology for CMW treatment is very complex, including economic, technical, environmental, and social aspects. Currently, high temperature incineration has been widely used to treat them. In addition, several disinfection treatments, including gas sterilization, chemical disinfection, microwave treatment, thermal inactivation, irradiation, and autoclaving, have been generally applied to neutralize CMW for the further processes (Sharma et al., 2020). In case that the treatment facilities for biomedical waste are not well advanced, these wastes can be buried in a closed pit with a clay or geo-synthetic lining at the bottom or can be further treated as general waste after disinfection treatment (Chartier et al., 2014). Although many countries are taking active measures to treat these wastes, the technologies and strategies to effectively manage (contain and reduce the spread of the disease) are considered still very lacking. There is an urgent need for appropriate technology for safe treatment of daily accumulated CMW.

According to the literature (G Kampf et al., 2020; Chin et al., 2020), thermal disinfection is considered effective to sterilize the contaminated materials, including COVID-19 virus. Thermal treatment with temperature of 80 °C for 1 min has been able to reduce the virus infectivity by at least 4 log₁₀ (Saknimit et al., 1988). Therefore, thermal treatment and conversion higher than this temperature is considered sufficient to decontaminate and sterilize the infectious medical wastes. Fig. 1 shows the possible thermal conversion technologies to treat and recover CMW for energy-related products. Four different technologies are overviewed, including incineration (combustion), carbonization (torrefaction), pyrolysis (liquefaction), and gasification.

Before the treatment, the properties of common CMW are essential to be discussed since most of the specific waste conversion technologies will only fit to a certain waste specification. The option of CMW conversion into sanitized refuse-derived fuel (SRDF) is also worth to be considered. If CMW can be pretreated to become SRDF then it can be mixed and co-processed with general (non-hazardous) solid waste and then treated using existing facility.

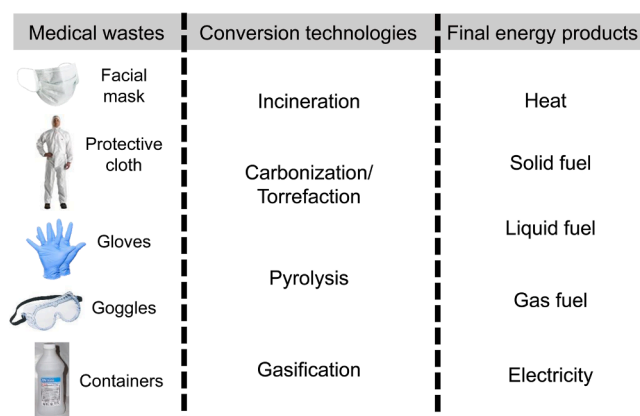


Fig. 1. Possible thermal conversion technologies to treat and convert CMW into energy-related products.

2. CMW generation

Although it is apparent that the pandemic increases the amount of generated CMW, especially in the affected countries across the world, it is difficult to find a complete data of CMW during this pandemic. Gient Heating Industry Co., Ltd, a waste treatment company located in Chongqing, China, has reported that the average medical waste amount they received was about 45 t/d before the pandemic outbreak. This number increased to 110–150 t/d in mid-February 2020, and reached a peak at 247 t/d in the beginning of March. However, it has progressively decreased since mid-March and back to normal in early May (Wei, 2020). Fig. 2 plots the correlation of generated CMW amount with the officially reported number of cases of people infected in the city of Wuhan (Liu et al., 2020). It shows that the evolution of generated CMW follows the number of COVID-19 patients with a lag of a few days.

Based on those few available data, Asian Development Bank (ADB) (2020) proposed an equation that can correlate the number of infected person with the increase of CMW, as shown in Eq. (1). Therefore, this equation can be used to predict the generated CMW which corresponds to the current pandemic.

$$\text{Amount of CMW (kg/d)} = \text{Number of infected person} \times 3.4 \quad (1)$$

Table 1 shows the predicted amount of CMW in top 25 countries with the largest active cases as of November 22, 2020 (Worldometer, 2020). USA generated the largest amount of CMW which was about 15,000 t/d. Some most affected European countries, such as France, Germany, the Netherlands, and Italy, have experienced growth of CMW as well. According to SUEZ, a 40–50% increase was seen in France, and the waste quantity has increased by 30–50% in their plant in the Netherlands during COVID-19 pandemic (Liu et al., 2020). Some South American and South Asian countries' waste generations were following those of USA and European countries, releasing more than 200 t/d of CMW.

3. Types and characteristics of COVID-related disposable solid wastes (CMW)

In general, medical wastes are defined as the solid wastes that are generated from diagnosis, treatment, and immunization of human beings and animals, covering the activities of research, testing, and production of biological products (Windfeld and Brooks, 2015). WHO has estimated that about 20% of these CMWs are categorized as infectious, toxic, and radioactive (Birchard, 2002). However, in reality, there is no clear definition and categorization for these CMWs across the countries, leading to several variation in handling and treatment (Insa et al., 2010). Rutala and Mayhall (1992) categorized the medical wastes into four types: hospital, medical, regulated medical, and infectious wastes. Windfeld and Brooks (2015) defined the infectious waste as wastes

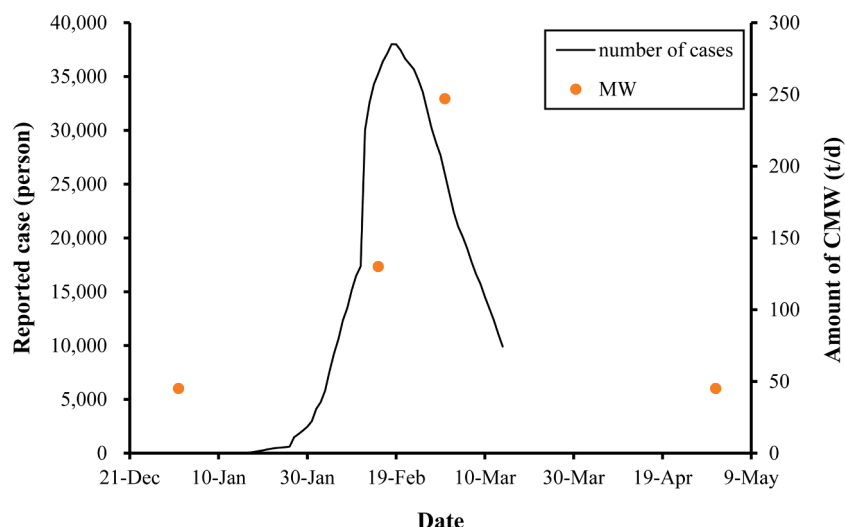


Fig. 2. COVID-19 reported case versus generated CMW amount in Wuhan.

Table 1

The calculated amount of CMW in top 25 countries with the largest active cases as of November 22, 2020 (Worldometer, 2020).

No	Country	Active cases	Calculated amount of CMW (t/d)
1	USA	4454,829	15,146
2	France	1873,049	6368
3	Italy	743,168	2527
4	Belgium	492,079	1673
5	Russia	456,528	1552
6	India	444,755	1512
7	Poland	418,489	1423
8	Brazil	390,043	1326
9	Ukraine	300,962	1023
10	Germany	294,541	1001
11	Iran	181,970	619
12	Mexico	154,176	524
13	Argentina	146,516	498
14	Hungary	118,723	404
15	Romania	112,927	384
16	Switzerland	107,783	366
17	Czech	100,970	343
18	Portugal	78,681	268
19	Bangladesh	77,732	264
20	Austria	76,896	261
21	Bulgaria	75,526	257
22	Greece	70,757	241
23	Jordan	67,061	228
24	Serbia	65,371	222
25	Indonesia	60,870	207
	Word total	15,877,048	53,982

produced from healthcare facilities that are unsuitable to be treated as municipal solid waste.

Before being discussed in detail, Table 2 shows the summary of PPE and main component for each type of PPE. In general, plastic polymers are the main ingredient of most of PPE. Mismanagement of this sort of waste not only will threat human being but also will put more burden to environment that already overwhelming with existing amount of plastic waste generated daily.

3.1. Protective disposable face mask

The easy spread of COVID-19 virus has motivated people in general to wear mask and use hand sanitizer on a daily basis as precautionary measure. Disposable medical mask (surgical mask) is basically designed and used to protect the health-care workers in order to mitigate the hazard during the medical activities. However, during the outbreak of

Table 2

PPE and its main components.

PPE	Variety	Main components
Respirator	N95	Polypropylene (PP)
Masks	Surgical mask	PP and textile
	Fabric	Cotton
Face shields		Polycarbonate (PC), polyethylene terephthalate (PET), or polyvinylchloride (PVC)
Goggles		PC
Protective gown		PP, polyester (PEs), or polyethylene (PE).
Coveralls		High density polyethylene (HDPE)
Gloves	Latex gloves	Natural rubber
	Vinyl gloves	PVC
	Nitrile gloves	Acrylonitrile and butadiene
	Neoprene gloves	Chlorine, carbon, hydrogen and sulfur

infectious diseases, such as SARS in 2003, *pdm* H1N1 in 2009, and the current SARS-CoV-2, the medical face mask has been massively worn by most of the citizen, as also has been recommended by the authorities (Elachola et al., 2020). The face mask is believed to be able to reduce the risk of person-to-person transmission. Based on the study conducted by Eikenberry et al. (2020), face masks are potential to reduce the transmission rate of the disease, leading to the illness prevention to the healthy person and prevention of asymptomatic transmission. WHO stated that the number of mask required globally for each month is about 89 million pieces to respond to the current SARS-CoV-2 (WHO, 2020a). As of April 2020, Japanese Ministry of Economy, Trade and Industry (METI) has secured the order of 600 million pieces of face mask per month (Ministry of Economy Trade and Industry (METI), 2020). In addition, as of February 2020, China has increased its daily production capacity to about 15 million pieces of face mask (Xinhuanet 2020). It has been projected that the global market of protective masks (including respirator and surgical mask) increases from about 14.6 billion units in 2019 to 33.4 billion units in 2023 (annual increase of about 23%) (Market Research, 2020).

Meanwhile, protective face masks can be categorized into three types i.e. homemade cloth mask, surgical/medical mask (including the procedure mask), and respirator. The medical mask is defined as flat/pleated mask, which is affixed to the head via straps going around the ears, head, and/or both. This kind of mask is designed to have a balanced filtration, breathability and fluid penetration resistance, and filtration capability of 3 μ m droplets. These performances are tested

using several standards, including ASTM F2100 and EN 14,683. In addition, respirator or filtering facepiece respirator (FFR) also has those required performances similar to the medical face mask, but it has the ability to filter further smaller particles, about 0.075 μm of solid particles (WHO, 2020b). Several standards for this kind of mask exists, such as EN 194 for FFP2 respirator (filtering at least 94% NaCl particles) and NIOSH 42 CFR Part 84 for N95 respirator (filtering at least 95% NaCl particles).

Reuse and extended wear of face mask are expected to be able to reduce the number of wastes, as well as improve the availability of face mask due to production shortage. Celina et al. (2020) have found that thermal conditioning is effective as the option to sterilize the used face mask, therefore, it can be reused for certain cycle. Other disinfection methods include spraying using alcohol-based materials, ultraviolet radiation (Viscusi et al., 2009), and use of hydrogen peroxide (Bergman et al., 2010) and ethylene oxide (Celina et al., 2020). However, although those methods are potential to extend the lifetime of the face mask, the consumption of face mask is still very high.

The mask basically has three layers: outer, mid, and inner layers. The outer layer is usually made of non-woven fibers and relatively water resistant, while the inner layer is made of soft fibers. The mid layer is the most important layer, which provides the filtering function and is made of micro- and nano-fibers (Fadare and Okoffo, 2020). Generally, disposable face masks are made of polymeric materials, including PP, PE, and PEs (Potluri and Needham, 2005). PP, made of propylene monomers, is utilized as a filter (mid layer) which is spun-woven into the mask filter. This layer is manufactured by extrusion of melted polymer through tiny nozzles under high speed blowing gas. In addition, the fibers are then electrically charged, hence, the particles are attracted when the air is passing through the filter. A flexible and tight fitting mask sheath is made of PEs, which is basically a product of xylene. In addition, polyurethane (PU), a product of toluene, is also usually adopted as the supporting material for the nose piece, assuring a snug fit (Torrance Refining Company LLC, 2020). Cotton and other fabrics also can be adopted as inner and outer layer. Tables 3 and 4 show the typical material composition of respirator and medical masks, respectively. It is very clear that PP has the largest share as the material for masks, followed by PEs and PE.

However, it is known that polymeric materials are source of plastic pollution to the environment (Schnurr et al., 2018). The micro plastics wastes have strong implications on human existence, due to their dangerous threat to aquatic lives, and thus, significantly influences the food web, resulting in food safety concern (Fadare et al., 2020). Furthermore, the polluted aquatic environment potentially reduces its recreational worth and increases the climate concern because of carbon emission (Shen et al., 2019). Reid et al. (2019) mentioned that plastic wastes also may propagate the microbes, therefore, they potentially become the medium for the disease outbreak.

In addition, waste of protective face mask is considered potential to carry the pathogens. Hence, proper disposal of this kind of waste is urgently required. As mentioned in (Peng et al., 2020), this face mask waste is generally treated carefully and packaged in a double layer medical waste bag, which is conducted by trained staff. In addition, the wasted face masks in the terrestrial and aquatic environments are also potential source of plastic pollution, leading to serious environmental

Table 3

Typical material composition of respirator (3M™ 8210 N95 Particulate Respirator) (3 M, 2018; 3 M Personal Safety Division, 2018).

Material	Usage	Weight percentage (wt%)
PP	Filter	40–72
PEs	Shell, coverweb	10–30
Thermoplastic elastomer	Strap	10–30
Aluminum	Nose clip	7–13
Adhesive film	–	0.5–1.5
PU foam	Nose foam	0.5–1.5

Table 4

Typical material composition of medical/procedure mask (3M™ Earloop Fluid Resistant Face Mask Cat. #1820, 1820FS, 1826, 1817) (3 M, 2020).

Material	Usage	Weight percentage (wt %)
PP	Filter, inner and outer layers	65–85
Elastic-natural rubber latex free	Strap	10–20
PE-coated steel wire	Nose clip	10–20

problems if they are discarded anyway to the environment without sufficient treatment (Fadare and Okoffo, 2020). The face masks which are disposed in the landfills, dumpsites, freshwater, and ocean might break down or degrade into significantly smaller size of particles, known as micro plastics.

3.2. Medical gloves

Medical gloves are basically used by health care workers for various clinical conditions, and currently are not recommended for public use as they provide no additional protection as long as there is no contact between hand and face (WHO, 2020c). Although their usage is basically limited to the health care workers, their demand is very high and increasing due to COVID-19 pandemic. WHO predicted that about 67 million of medical gloves are required each month during this pandemic (WHO, 2020a). The reuse of medical gloves is basically not recommended (WHO, 2009). However, in case of their shortage, the use of gloves after sufficient disinfection for the ongoing care on the same patient or the patients in the same room can be taken (Kampf et al., 2020).

The medical gloves are basically made of natural rubber latex (Manhart et al., 2020) due to its properties of high barrier against blood-borne pathogens, low cost, resealing ability after punctured, and flexibility. Natural rubber latex is generated from *Hevea brasiliensis* tree, therefore, it is basically biodegradable. Moreover, non-latex materials, including polyvinyl chloride, neoprene and nitrile rubber are also utilized as the optional materials for the medical gloves. However, those synthetic materials are petroleum-based and considered difficult to be degraded, leading to serious environmental problems. In order to reduce the surface friction and facilitate donning, as well as improve the wearing comfortability, dexterity, and tactility, the surface of the gloves is modified though chlorination, polymer coating, and powder application (Manhart et al., 2020).

3.3. Medical protective clothing

Medical protective clothing is generally defined as the protective clothing worn by healthcare workers and people entering specific health areas, including the infected area and rooms for patients with infectious disease. These medical protective clothing can be categorized into surgical gown, isolation gown, and coverall (hazmat) suit, depending on the level of protection features (FDA, 2020). Surgical gown is used in order to avoid any contamination of blood, body fluids, and other infectious substances, and also protect the patient from being infected. In addition, surgical gown is also worn in order to reduce the risk during the surgery. Isolation gown is used mainly to protect the clothing of health care workers. In addition, it also protects the patients and visitors by preventing the transfer of microorganism and body fluids. Surgical and isolation gowns basically provide no whole-body protection. Gown is relatively easier to put and take off than coverall. When dealing with the patients having infectious disease (including COVID-19), the medical cloth, especially cloth-made gown, is combined together with an apron which is changed for each patient and its tightness and integrity must be guaranteed (Kampf et al., 2020). Furthermore, coverall is defined as the personal equipment worn by health care workers when they have

contact with patients having infectious disease. Because it covers the whole body (including back, lower legs, head, and feet), it can provide 360-degree protection.

Disposable medical protective clothing is generally made of PP fabric, new PE fiber, polymer-coated fabric, spunbond-meltblown-spunbond (SMS) PP, and PE-breathable film. SMS PP is a tri-laminate non-woven fabric, having three different layers: spunbond PP, melt-blown PP, and spunbond PP. Hence, strong barrier to fluids and particles can be achieved. In addition, gown made of cotton basically can be washed and disinfected for reuse using detergent and warm water (60–90 °C) (WHO, 2020c). Similar to other PPEs, the wastes of medical protective clothing are environment-pollutant. Hence, proper treatment technologies are demanded.

3.4. Protective goggles and face shields

Goggles and face shield are generally used in hospitals or high-risk area for infection control, as well as protection from any fluids and particles in research and industrial activities. It was predicted that the international demand for goggles reached about 1.6 million per month (WHO, 2020a) and its number is increasing following the increase in active cases of COVID-19. Similarly, the demand for face shield is also significantly increasing with a growth rate of 312% in 2020 (The Freedomia Group, 2020). Protective goggles are used to provide a sufficient eye protection, especially during healthcare activities. It is mainly used by healthcare workers when they are handling patients with infectious diseases. On the other hand, face shield is utilized to protect mucous membranes in the nose, mouth, and eyes from splashes of body fluid which is potential to transmit the disease (Mostaghimi et al., 2020). In reality, during this pandemic, face shield is not only used by the healthcare workers, but also by public, especially people who have direct meeting with others (such as receptionist, service counter, salesperson, and waitress).

Protective goggles are made of PVC (the frame part), PC (the lens part), and rubber (the headband). Face shield is generally made of PET and PVC/acetate for the transparent visor, polylactic acid for the headband and bottom reinforcement bracket, and ethylene-vinyl acetate and PU for the foam pad (Mostaghimi et al., 2020; Shokrani et al., 2020). Although both protective goggles and face shields can be reused after sufficient disinfection, the amount of waste, especially the face shield is considered very high.

3.5. Hand sanitizer and other disinfectant containers

The consumption of hand sanitizer and other disinfectant has increased largely, whether in the healthcare facilities, residential, offices/working spaces, and public spaces. Basically, the disinfectant is refillable, especially for the stationary dispenser. Unfortunately, as the demand for disinfectant is very high, the number of containers, bottles, sprayers, and dispensers is also largely expanding. The main materials for these containers, bottles, sprayers, and dispensers are PET and PE for the body of the container and PP for the cap.

3.6. Other wastes

In order to avoid any further transmission, wastes from observation, isolation, examination, medical laboratory rooms, and fever clinics are also necessary to be treated and included together as COVID-19 wastes (Peng et al., 2020). These wastes cover wide range of categories, such as paper towels or wipes, swabs, syringes, needles, blades, scalpels, drug container, tubes, bandages, tapes, and disposable medical equipment. In addition, organic wastes including human tissues, organs and fluids are also necessary to be treated well. Infectious and pathological wastes are basically packaged in a double layer waste bag which is further sprayed using chlorine-based disinfectant for sterilization. The wastes can be temporarily stored in the hospital for less than 24 h.

4. CMW thermochemical treatment technology

As it can be observed from the description above, in general, PPE and medical wastes are dominantly made of plastic polymer, including PP, PE, PVC, PES, PET, and rubber latex. Therefore, the conversion technologies which are able to effectively treat those kinds of materials and provide sufficient disinfection are required. Since it is dominated by light material, the bulk density of medical waste during pandemic tends to decrease almost a half from 120 kg/m³ in normal condition to 67–85 kg/m³ during pandemic (Wei, 2020). This fluffy material could bring benefits for thermochemical conversion since it is easier to dry and co-treated with other solid fuel or waste.

Currently, those plastic-related materials are basically disposed in landfill or incinerated. Polymeric solid wastes can be recycled through re-extrusion, chemical, mechanical, and thermal processes (Al-Salem et al., 2009). Mechanical recycling is considered as the excellent way to recover the plastic materials. However, as the composition of medical wastes is complex and there is requirement for sufficient disinfection before mechanical recycling, chemical and thermal processes are considered as the appropriate options to recover the material or energy from the wastes, while it also facilitates sufficient disinfection. Chemical recovery covers pyrolysis (cracking), gasification, and depolymerization (Yu et al., 2016). However, pyrolysis and gasification also can be categorized into thermal recovery, as well as incineration (combustion) and carbonization. The recommended treatment technologies for each different CMW is summarized in Table 5.

4.1. Sanitized refuse-derived fuel (SRDF)

Utilization of CMW as an energy source is a challenging task. However, the potential of CMW is considered very high because of overwhelmed supply, relatively homogenous contents of its components, and low moisture content. Unfortunately, it might pose a substantial additional risk to the workers and surrounding. In general, refuse-derived fuel (RDF) production requires several processing stages, including sorting, size reduction, and drying. These processes are conducted in an open large space with belt conveyor and manned loader for transferring between the equipment. Indeed, the RDF plant from MSW or other non-hazardous solid waste is considered as a safe working place with no evidence of causing work-related illness (Mahar and Mahar, 2016). However, considering that COVID-19 virus is transmitted through droplets, and all the mechanical processing in the plant may produce droplets exhausted from a CMW with relatively high moisture content, there is a high risk of infection that arise with the treatment of CMW..

In general, solid fuel or solid recovered fuel (SRF) derived from municipal solid waste (MSW) or commercial waste has many drawbacks since it contains various components, including plastic, paper and cardboard, wood, organic and non-combustible with quite wide range of composition. Four major mass fractions of SRF are 15%–35% plastic, 20–50% paper and cardboard, 2–10% wood, 5–20% organics, and 5–10% non-combustibles (Rezaei et al., 2020). This large composition variable leads to a broad range of major properties, such as calorific

Table 5

Technological applicability of thermochemical treatments and conversions for each CMW.

Wastes	Incineration	Combustion (torrefaction)	Pyrolysis	Gasification
Respirator	⊙	△	○	○
Medical mask	⊙	○	⊙	⊙
Latex glove	⊙	△	△	△
Nitrile glove	⊙	×	△	△
Goggles	○	×	△	○
Hand sanitizer container	○	×	○	⊙

Symbol meanings: ⊙ highly feasible; ○ feasible; △ lowly feasible; × not feasible.

values, bulk density, and chlorine content. However, in case of SRF comes from CMW, it is expected that the waste has few compositional variations, as well as final properties since most of CMW consists of plastics and few papers.

In terms of recovery, the production of RDF from MSW mostly has reasonably low recovery. The recovery rate is usually less than 50% for high quality or high calorific product. For premium quality of high calorific SRF (i.e. LHV of 22 MJ/kg) used as primary burner fuel (PBF) in cement kilns, the recovery rate is about 20% for commercial waste input and only 7% for municipal waste input (Sarc and Lorber, 2013). The low recovery of this process still requires vast landfill area to dump the rejected solid waste. Different from RDF produced from MSW or commercial waste, SRDF produced from CMW generates very low or no rejected solid waste that has to be landfilled. The only rejected solid probably comes from specific parts, such as needles and other sharp metal objects, that can be easily recovered by magnetic separator and further recycled in other facilities.

Another potential characteristic of CMW is its low water content. RDF produced from MSW plant has an energy-intensive drying process due to high moisture content, caused by high fraction of organic materials. In tropical countries, such as Indonesia, the moisture content of mixed MSW can reach more than 66% (Tan et al., 2015). Meanwhile, to be used as RDF, the moisture should be lowered to less than 25%. Thus, drying is required and a lot of energy is consumed although it is conducted through bio-drying or other mechanical drying systems. On the other hand, CMW does not require intensive energy for drying since the moisture content is reasonably low.

The hardest part of CMW is about disinfection stage, especially when dealing with airborne or droplet containing virus from the contaminated waste. Fortunately, the technologies to treat and convert CMW to SRDF are already in the market with a size ranging from a compact one to large capacity. The sterilization stage can be done before size reduction or afterward. For small scale system, such as in small hospital or clinic, it is preferred to use a compact shredder, which is combined with sterilizer machine. One of the integrated sterilizer and shredder, coupled with the steam generator, that available in the market can handle up to 150 kg/h of medical waste and requires 110 kW electrical power (Tan et al., 2015). Meanwhile, for a large scale, sterilization is mostly done first in huge autonomous feeding autoclaves followed by shredding the waste to produce SRDF. One of the large facilities with 30 t/d treatment capacity had been operated in Wuhan during the outbreak (Wei, 2020).

There are two types of commercial RDF. The first is the simplest form called as fluff (crushed and shredded), and the second is one which is further processed from the first type to become pellet (crushed, shredded, and molded waste). Fluffy RDF is the simple form of RDF in which solid waste only undergoes segregation, size reduction, and drying. Meanwhile, this type of RDF can be further processed to become pellet. The pellet then can undergo various thermal processes, such as carbonization or torrefaction for cleaner and higher-grade solid fuel product (Nobre et al., 2019b). Otherwise, RDF is changed into other types of fuel or energy through thermal processes, such as pyrolysis or gasification (Miskolczi et al., 2011). The waste-to-energy technological options for the raw CMW and SRDF are summarized in Table 6. The heat from high temperature thermal process or its exhausted heat can be used in the sterilization stage of CMW simultaneously.

4.2. Incineration

High-temperature incineration (combustion) is the most commonly adopted technology to effectively treat various medical wastes and kill infectious pathogens (Windfeld and Brooks, 2015). However, this treatment leads to relatively high environmental concerns, due to high CO₂ emission and also high consumption of additional fuel to reach and be stable at the temperature higher than 800 °C. For the region having no medical incineration or proper medical waste treatment, sanitary landfill is also considered as an option to treat medical wastes. However,

Table 6
Technological options to convert raw CMW and/or CMW-based RDF.

Thermochemical conversion or upgrading	Main product features	Oxidizing agent	Temp. range (°C)	Ref
Torrefaction	Heat and high calorific char with low calcium and chlorine content	Basically in the absence of oxygen	300–400	(Nobre et al., 2019b; Nobre et al., 2019c)
Hydrothermal carbonization	Heat and high calorific char with low ash and chlorine content		200–300	(Nobre et al., 2019)
pyrolysis (with or without catalyst)	gasses (H ₂ , CH ₄ , C _n H _m , CO, and CO ₂), pyrolytic oil, and solid (charcoal, char)	Absence of oxygen and/or steam	350–600	(Miskolczi et al., 2011)
Gasification	Synthetic gasses (CO, H ₂ , CH ₄ , C _n H _m , and CO ₂)	The oxygen is less than its stoichiometric value, steam as very potential oxidizing agent (adjusting H ₂ /CO ratio)	800–850	(Nobre et al., 2020)
Plasma gasification	Flammable/synthetic natural gasses (CO, H ₂ , CH ₄ , C _n H _m , and CO ₂)	Steam is generally used as oxidant and adjuster of H ₂ /CO ratio	700–1200	(Materazzi et al., 2016; Kabalina et al., 2016)
Incineration (combustion)	Heat, CO ₂ , and H ₂ O	Oxygen is higher than its stoichiometric value	Higher than 800	

before the wastes are disposed to the landfill, the wastes need to be sterilized using steam or they are boiled at temperature of 150 °C or higher (Peng et al., 2020).

PE, PP, PET, and PS show similar thermal degradation curve, having one degradation step (Yu et al., 2016). Thermal degradation of PE (HDPE and low density polyethylene (LDPE)) starts when the temperature approaches 430 °C, and ends at temperature of 500 °C (Matsuzawa et al., 2004; Aboulkas et al., 2010), generating several types of gasses, including H₂ and C₁–C₆ hydrocarbons with average molecular weight of 35–37 (Murata and Makino, 1973). Furthermore, PP basically have similar degradation temperature with PE but in slightly lower manner, ranges 420 to 480 °C (Abdullah and Wu, 2009). The produced gasses are also similar to PE, such as H₂ and C₁–C₅ hydrocarbons (especially propylene and isobutene), with average molecular weight of 41–44 (Murata and Makino, 1975). PS has the lowest degradation temperature, which is 380–440 °C (Matsuzawa et al., 2004), releasing H₂ and C₁–C₄ hydrocarbons with average molecular weight of 27 (Murata and Makino, 1975). PET starts to degrade when the temperature approaches 400 °C and stops at temperature of about 500 °C, producing CO, CO₂, methane, and light hydrocarbons (Martín-Gullón et al., 2001).

Different to above-mentioned materials, PVC degrades in two continuous steps. The first degradation step starts at a temperature of 250 °C and ends at 350 °C, resulting in about 65% of mass loss (Yu et al., 2016). In this step, a polymer dehydrochlorination occurs, generating de-HCl and other volatiles (hydrocarbons), including hydrochloride, benzene, and toluene (Jordan et al., 2001). Furthermore, the second degradation occurs at temperature higher than 350 °C to about 525 °C,

in which de-HCl is further decomposed or cracked. PVC is the main source of chlorine during the formation of chlorinated dioxin during the combustion (incineration). Therefore, when PVC-included wastes are combusted, a lot of hydrochloric acid (HCl) might be generated, resulting in generation of harmful gasses to the atmosphere and technical problems, such as corrosion of boiler tubes and other auxiliaries (Yu et al., 2016). The combustion of PVC is potential to form charred residues, airborne particles, smoke, and compounds of polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins (PCDD), polychlorinated dibenzofurans (PCDF), chlorophenols, and chlorobenzenes (McKay, 2002; Font et al., 2010).

All of those possible emission from CMW burning should be controlled by proper flue gas treatment. Almost half of operating cost of incinerator is used for air pollution treatment. Mostly the gas cleaner unit consist of a series of equipment which are gas quencher, water or alkali scrubber, catalytic converter, carbon filter, and bag filter. This equipment line is necessary to treat the flue gas before it can be released to atmosphere through a tall stack. The product that can be utilized is only the heat of combustion that can be used for steam and electricity generation. Meanwhile, this technology is still producing solid waste in the form of ash that should be carefully checked for possible heavy metal content.

4.3. Carbonization

In general, carbonization results in the release of volatile matter, producing homogeneous solid carbonized (coal-like, char) products. The solid product has higher energy density, due to the increase of carbon content and decrease of oxygen content, excellent grindability, hydrophobicity, and stability (possibility for stable and long storage) (Nunes et al., 2014). Smaller ratio of oxygen to carbon is obtained due to the release of volatile matter, resulting in the decrease of self-ignition during grinding (Akbari et al., 2020). Carbonization sometimes is also called as torrefaction. Some researchers distinguished their definition based on the operating temperature, which are 200–300 °C and 300–500 °C, respectively (Du et al., 2014; Sabil et al., 2014; Abdullah and Wu, 2009). However, both of them are intermingled as the solid product refers to the similar carbonized material. For simplification and clear understanding, in this work, both carbonization and torrefaction are considered as the same process. Carbonization can be divided into two different processes: dry and wet processes. Fig. 3 shows the different routes of carbonization to produce solid carbonized products. Both dry and wet techniques have

advantages and disadvantages.

4.3.1. Dry carbonization (torrefaction)

Dry carbonization is generally called as torrefaction, dry torrefaction, mild pyrolysis, and slow pyrolysis (Akbari et al., 2020). It is a thermochemical process, conducted at almost inert atmosphere and the materials are heated slowly under ambient pressure and temperature of 200–300 °C. Although the main product of torrefaction is solid carbonized product, the released volatile matter (such as water and acetic acid) in the gaseous form can be trapped and condensed at low temperature, resulting in an oily liquid product (Acharya et al., 2015). Compared to wet carbonization, torrefaction is simpler and mature technology, which can be adopted for small to large scale (Babinszki et al., 2020). Torrefaction requires raw material with low moisture content (such as lower than 15 wt% wb) (Koppejan et al., 2012). Therefore, as general medical wastes, especially the above-mentioned wastes, are basically dry, they can be torrefied directly without the necessity of drying. Torrefaction is initially started with evaporation of moisture at temperature of about 100 °C, followed by the evaporation of moisture content, leading to large mass loss.

Rago et al. (Rago et al., 2020) have performed torrefaction of mixed solid wastes, including LDPE at temperature of 300 °C for 30 min. They found that co-torrefaction of biomass waste with LDPE resulted in higher char yield, as well as higher energy content. Regarding the torrefaction of PVC, it seems that thermal degradation following the reaction during torrefaction is potential to produce hydrocarbons, including hydrochloride, benzene, naphthalene, and anthracene (Xu et al., 2020). Therefore, it is important to trap and captured the evaporated gasses, including these hydrocarbons, during torrefaction. Hanoglu et al. (Hanoğlu et al., 2019) have investigated the torrefaction of textile fibers, including PEs and acrylic, under the temperature of 300–400 °C. They found that temperature plays very important role in defining the solid product. In addition, the torrefaction could produce solid product (char) having high-energy density (18–25 MJ/kg), but low ash and sulfur (less than 10 wt%) (Mohd Faizal et al., 2018). Moreover, torrefaction of blended cotton and PEs potentially results in high quality of solid fuel which can substitute the coal.

Matsuzawa et al. (Matsuzawa et al., 2004) have studied the torrefaction of PE, PP, PS, and PVC which are mixed with cellulose. According to their study, there is no significant change in the degradation pattern of PE, PP, and PS which are mixed with cellulose compared to when no cellulose is mixed. Therefore, it can be stated that there is no

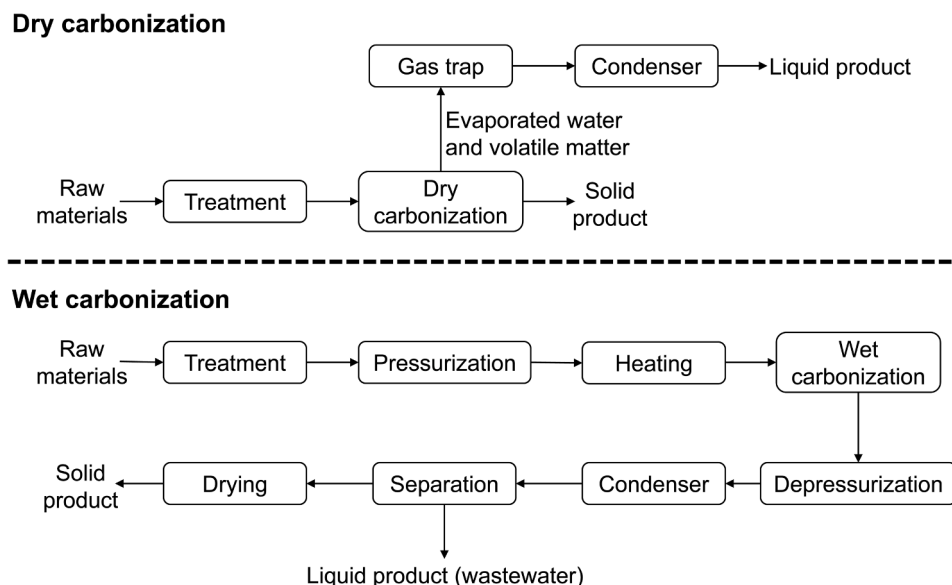


Fig. 3. Different routes of carbonization to produce solid carbonized products.

interaction or reaction which can influence their degradation pattern. However, when cellulose is mixed with PET, the degradation patterns of both PET and cellulose change, resulting in larger amount of residual char.

4.3.2. Wet carbonization (hydrothermal carbonization)

Wet carbonization is also called as hydrothermal carbonization and wet torrefaction (Aboulkas et al., 2010; Du et al., 2014; Sabil et al., 2014). Hydrothermal carbonization is one of hydrothermal processing adopted in order to produce uniformly carbonized material at elevated temperature (typically ranges from 180 to 280 °C) and saturated pressure of 2–10 MPa (Shen et al., 2017; Zaini et al., 2017). This process is favorable for the material having relatively high moisture content, as the drying step can be bypassed. The subcritical water acts as solvent and reagent during the reaction, accelerating the reaction (Kuhlmann et al., 1994). The solid product of hydrothermal carbonization is usually called as hydrochar (Tremel et al., 2012). Based on the product and operating conditions, hydrothermal processing can be categorized into: sterilization/hydrolysis (temperature of 80–180 °C, saturated pressure), hydrothermal carbonization, liquefaction (temperature of 280–370 °C, saturated pressure), hydrothermal catalytic gasification (temperature less than 550 °C, pressure less than 22 MPa), high-temperature hydrothermal gasification (temperature range of 550–700 °C, pressure less than 22 MPa), and supercritical gasification (temperature of 370–700 °C, pressure higher than 22 MPa) (Kieseler et al., 2013).

Hydrothermal carbonization has relatively high energy yield of about 80% (pilot scale with woody biomass) (Tremel et al., 2012), representing the ratio of calorific values of solid product and raw materials. Hydrothermal carbonization has been widely applied to convert biomass-related materials, including wastes-to-solid products (Triyono et al., 2019; Mu'min et al., 2017). The first step of decomposition reactions occurred during hydrothermal carbonization is hydrolysis. Further decompositions steps include dehydration, decarboxylation, recondensation, and aromatization (Poerschmann et al., 2015; Libra et al., 2011). Although the hydrothermal carbonization is advantageous in terms of elimination of drying and solid product with less ash content, the energy for pressurization and heating is considered high. In addition, it requires high-pressure reactor and faces difficulty for continuous process (Darmawan et al., 2017).

As medical wastes are generally dry, hydrothermal carbonization of these medical wastes requires addition water (including wastewater). Ma et al. (2019) have conducted hydrothermal carbonization for PVC and medical wastes model, under operating temperature of 220–300 °C and duration of 30 min. They stated that chlorine from both PVC and medical wastes can be removed effectively, especially when the temperature is higher than 240 °C. Moreover, according to Kubatova et al. (2002) and Poerschmann et al. (2015), hydrothermal carbonization can effectively convert the organic chlorine of PVC to inorganic one under sub and supercritical pressure and temperature of higher than 250 °C. In addition, Shen et al. (2017) have studied the effect of hydrothermal carbonization to the mixed medical waste (containing PVC medical products, clothes, organs, and papers) and wood chip, which has components of lignin, cellulose, and hemicellulose. They found that lignin potentially increases the dechlorination efficiency of PVC during hydrothermal carbonization, followed by cellulose and hemicellulose. Moreover, particle agglomeration also can be inhibited by these lignocellulosic materials (Shen et al., 2017).

Poerschmann et al. (2015) also have studied the hydrothermal carbonization of PVC and they found that dechlorination increases following the increase of hydrothermal temperature, with a significant increase at temperature higher than 230 °C. However, as the temperature increases, the organic carbon fraction included in the solid product decreases accordingly, numerically from 93 to 75 wt% when the temperature is increased from 180 to 250 °C. Furthermore, PAH compounds were found to be dissolved in the liquid phase, separated from the solid product, while PCDD and PCDF compounds were not found.

Lokahita et al. (2017) have conducted hydrothermal carbonization for a compound of PE (20 wt%), paper (75 wt%), and aluminum (5 wt%) under temperature of 200–240 °C. They found that although this temperature is insufficient to decompose PE, both aluminum and PE can be separated well, while other materials are decomposed forming a coal-like char.

After the main process of hydrothermal carbonization and separation, a washing might be required for the solid product in order to remove the soluble chlorine (Shen et al., 2017). The separated solid product usually has moisture content of about 20–30 wt% wb (Akbari et al., 2020), therefore, drying is required to obtain low water content solid product which is ready to be utilized as fuel.

4.4. Pyrolysis

Pyrolysis is thermal degradation of long-chain polymeric molecules into shorter and less complex molecules under inert or oxygen-deficient atmosphere, with or without the presence of catalysts. The products of pyrolysis can be a mixture of solid, liquid, and gas, and the ratio between those products may vary depending on the feedstock and conditions used. In this review, we will focus mainly on pyrolysis with high ratio of liquid products. The waste conversion processes to solid as main products were already discussed in the previous section (Carbonization), while the conversion to gas as main products will be discussed in the next section (Gasification). Pyrolysis has several advantages which make it an interesting option to valorize polymeric wastes. First, it is able to produce high amount of liquid products at wide range of temperature. Furthermore, it is a flexible process to produce valuable products, because the conditions of the process, such as temperature, pressure, and residence time can be optimized to obtain products with specific properties. Based on their properties, those products are not only suitable to be used as fuels, but can also be used as chemical feedstock. Moreover, it has low carbon emission due to lower carbon monoxide (0.8–3.9 vol%) and carbon dioxide (1.0–9.1 vol%) generation compared to combustion (Chen et al., 2014; Singh and Ruj, 2016), which make it an environmentally friendly process. Lastly, one study showed that investment of pyrolysis process as waste management system could result in internal rate of return up to 43%, which supported its economic feasibility (Al-Salem et al., 2014).

Generally, pyrolysis can be divided into two categories, thermal pyrolysis and catalytic pyrolysis. Each of those types will be discussed in the following sub section.

4.4.1. Thermal pyrolysis

Thermal pyrolysis is a pyrolysis that valorize material using thermal energy without the presence of catalyst. Because the process is endothermic, energy must be supplied to the process. Thermal pyrolysis is a complex process comprising of polymer chain breaking, cross-linking formation, side chain elimination, and side chain crystallization (Beyler and Hirschler, 2002). Studies on thermal pyrolysis of plastics that often being used in the medical and protective equipment such as PE and PP had been performed, therefore, enough knowledge related to the valorization of these plastics had been amassed. Need to be noted that the configurations of the reactors also influence the properties of the products obtained, and those influences will not be discussed here. For more details on the influences of those reactor configurations, readers can refer to review paper by Sharuddin et al. (2016).

HDPE was reported as a good feedstock for pyrolysis (Al-Salem et al., 2017). The products obtained were highly dependent on operating conditions such as temperature, residence time, feedstock composition, and presence of moisture or other impurities. The results mentioned below are only those of optimized results. Ahmad et al. (2015) demonstrated that high liquid product yield of around 80 wt% can be obtained at a temperature as low as 350 °C. Study by Kumar and Singh (2011) showed that a higher pyrolysis temperature of 400–550 °C could reduce the residence time required for conversion, however, it also

slightly reduced the liquid product yield, while an even higher temperature caused the generation of waxes. The liquid product by Kumar and Singh (2011) had no visible residual and the boiling point was between 82 and 352 °C, suggesting that the oil was a mixture of various components such as gasoline and diesel. Bridgwater (2012) suggested that these oil products could be used for fuel in multiple application such as boiler, turbines, and furnace. Study on pyrolysis of LDPE showed that it could produce a higher liquid product yield than HDPE up to 95 wt% when pyrolysis is done at 500 °C (Bagri and Williams, 2002; Marcilla et al., 2009). Pyrolysis at a lower temperature of 430 °C resulted in a lower liquid product yield of around 75 wt% (Aguado et al., 2007). However, study conducted by Onwudili et al. (2009) showed that this problem could be solved by application of high pressure.

Research of pyrolysis of PP showed that a lot of factors influenced the obtained products, which translated to the variety of results among various researchers. However, generally pyrolysis of PP requires a lower temperature than that of PE to obtain product with acceptable liquid yield. A liquid product yield of around 70 wt% was obtained at a pyrolysis temperature of 300 °C, which is a significantly lower temperature than those achieved when using PE as feedstock (Ahmad et al., 2015). Meanwhile, research by Fakhrhoseini and Dastanian (2013) showed that a higher liquid yield of 82 wt% could be attained at a temperature of 500 °C.

Pyrolysis of PS could result in liquid product yield that could be considered as the highest among plastics, and the value could reach more than 95 wt%. Onwudili et al. (2009) obtained an oil yield of around 97 wt% when performing hydrolysis at 425 °C, while Liu et al. (2000) demonstrated a liquid yield of 98.7 wt% at 600 °C. They also achieved a high liquid yield of 97.6 wt% at a considerably lower temperature of 430 °C.

The possibility of treating PE, PP, and PS using pyrolysis as shown in the discussion above showed that this technology was feasible to treat medical equipment containing those plastics such as disposable masks and some parts of hand sanitation containers.

Meanwhile, researches on pyrolysis of PET had also been done, even though they were not as many as PE, PP, and PS. One of the reasons is the low liquid product yield of PET by pyrolysis, which often could even be lower than the gas product yield (Fakhrhoseini and Dastanian, 2013; Yoshioka et al., 2004). Fakhrhoseini and Dastanian (2013) showed a low result of 40 wt% of liquid product yield compared to 52 wt% gas product yield. Furthermore, almost half of the oil was comprised of benzoic acid, which is unfavorable to be used as fuel due to its corrosiveness. Similar to PET, PVC was also not often being studied for pyrolysis. One of the reasons for this is that it contains higher amount of chloride (57 wt%) compared to carbon (43 wt%), which can lead to the production of hydrochloric acid or chlorine gas. Pyrolysis of PVC also produced low liquid product yield less than 15 wt% (Miranda et al., 2001). Most of the content of the liquid product was hydrochloric acid, which made it unsuitable to be used as fuel. From these facts, it can be concluded that pyrolysis is not suitable to treat PET and PVC if the desired product is liquid, and therefore, it is not feasible to treat goggles and some part of hand sanitation containers that often use PET and PVC.

Studies on pyrolysis of rubber waste had been performed, however, it mainly focused on the waste tire, while on the other hand waste rubber from gloves was hardly performed. Hazan et al. (2019) performed pyrolysis on waste nitrile butadiene rubber (NBR) latex sludge, and found that it contained considerable amount of nitrogen (0.16 wt%) and sulfur (0.73%), which made it unsuitable to be converted into fuel. Thus, even though it is possible to treat those kinds of waste with pyrolysis, it is not highly feasible because the product has low value and need further processing to be properly used.

4.4.2. Catalytic pyrolysis

Catalytic pyrolysis is basically similar in process and conditions to thermal pyrolysis; the main difference is in the presence of catalyst. Catalyst is used to increase the reaction rate by lowering the activation

energy of the reaction. Therefore, by using catalyst, a high reaction rate can be obtained at a lower temperature, thus in the end reduce the energy requirement and operating cost of the process. Acid solid catalyst such as various type of zeolites (H-ZSM-5, H-MOR, and H-USY) were often utilized (Marcilla et al., 2009; Garforth et al., 1998), as well as clays (De Stefanis et al., 2013). However, for some cases, the use of catalyst also promoted the production of gas products and therefore increased the gas product yield (Seo et al., 2003; Lin and Yen, 2005). For this reason, the influence of catalyst on the desired final product should be considered first before it is being applied in the pyrolysis.

4.5. Gasification

Gasification is a process that convert carbon materials into a mix of carbon monoxide, hydrogen, carbon dioxide, methane, and longer chain of hydrocarbon gasses, by heating the materials at high temperature under controlled atmosphere. Catalyst might be used to lower the energy and direct the yield of products. The products of gasification can be used as a fuel or as chemical feedstock (syngas), depending on their composition. Sansaniwal et al. mentioned that the feasibility of producing energy, energy carriers, and chemical from syngas produced make gasification an attractive choice for revalorizing plastic wastes (Sansaniwal et al., 2017). Furthermore, gasification has the advantage in the flexibility of the feedstock, in which it can use various type of plastics, including mixture of plastics and mixture of plastic(s) and other feedstock without drastically altered the products (Lopez et al., 2018). Moreover, even though the interest in plastics gasification had only been observed recently, the technology for gasification of other type of feedstock such as coal had already matured, therefore the knowledge obtained from gasification of those other feedstock can be applied in plastics gasification. These advantages make it a more interesting option compared to pyrolysis. However, gasification, especially that of plastics, has the disadvantage of high content of tar in gas products, which can be as high as 160 g/Nm³ (Mastellone et al., 2010; Pinto et al., 2009). Nonetheless, this drawback can be addressed by developing gas cleaning system after the production or before the usage of gas products (Guan et al., 2016; Anis and Zainal, 2011).

There are several ways to classify plastic gasification processes, however, because the atmosphere is highly influential to the products, in this review, we classify the processes based on the atmosphere used, which is air gasification and steam gasification.

4.5.1. Air gasification

Air gasification is the process of gasification using air, or a mixture between oxygen and inert gas (usually nitrogen) as the atmosphere. Due to the presence of inert gas, the calorific value of the gas product is low, which is ranging from 6 to 8 MJ/m³, because of its diluting effect (Lopez et al., 2018). However, it has advantages in the form of relative simple process and relative low tar contents (less than 61.9 g-tar/kg-fuel) (Gil et al., 1999).

Study on PE and PP wastes as feedstock for air gasification had been done and showed a promising result, therefore, air gasification is a promising method to treat masks and hand sanitation containers waste from medical application. Research by Arena et al. (2010) showed that air gasification of PE using sand as bed material could yield product gas with low heating value (LHV) up to 7.9 MJ/m³. However, this process also produced high tar content in the gas, up to 160 g/m³. The change of bed material from sand to olivine was able to reduce the tar content to zero, while keeping LHV in the value of 7.6 MJ/m³. On the other hand, air gasification of PP using sand as bed material yielded a gas product with LHV of 2.9 MJ/m³ and tar content of 17 g/m³ (Sancho et al., 2008). The shift of bed material to olivine successfully increased LHV to 6 MJ/m³, while reduced tar content to 2 g/m³. A better result obtained by changing the bed material to a mixture of sand and dolomite (7:3 ratio), in which the product gas had a LHV of 7.4 MJ/m³ and tar content as low as 1.5 g/m³.

Researches on pyrolysis of PET showed a relative high gas product yield (up to 49%), therefore it can be viewed as gasification of PET (Fakhrhoseini and Dastanian, 2013; Yoshioka et al., 2004). However, the gasification resulted in low production of hydrogen (less than 0.8%), which made it unsuitable for syngas. Furthermore, various sources reported air gasification of PET mixed with other feedstock (Yoshioka et al., 2004; Kim et al., 2011; Pohořelý et al., 2006), although the ratio of PET usually low (less than 23%). Despite it was shown that PET can be used as feedstock for air gasification, the result was not as promising as those of PE and PP, thus rendered air gasification as unsuitable treatment process for wastes such as goggles and hand sanitation containers.

4.5.2. Steam gasification

Steam gasification includes steam in the gasification atmosphere, therefore make it possible to produce gas rich in hydrogen. Due to this property, the products of this process are more suitable to be used as chemical feedstock. On the other hand, one of the disadvantages of this process is that it requires energy for endothermic hydrogen production, thus, compared to air gasification, consumes higher amount of energy.

Similar to air gasification, steam gasification of PE and PP showed a promising result to be applied for treatment of medical equipment wastes such as masks, and also labels and caps from hand sanitizer containers. Wilk and Hofbauer (2013) showed that using PE and PP wastes as feedstock for steam gasification would produce gas products with high LHV, which were 25.8 and 27.2 MJ/m³, respectively. However, as had been mentioned previously regarding the disadvantages of steam gasification, it also produced significant amount of tar, which were in the value of 190 and 180 g/m³, respectively. Cleaning processes need to be applied before further utilization of these gas products.

Utilization of PVC as feedstock of steam gasification had been reported. Van Kasteren and Slapak (2001) reported that steam gasification

of PVC successfully yielded a gas product with a heating value of 8.6 MJ/m³. Furthermore, half of the chlorine contained in the feed was also being recovered as hydrochloric acid. On the other hand, utilization of PET as feedstock of steam gasification was also being reported (Li, 2019). The process resulted in a product gas with LHV of 8.67 MJ/m³ when the process was done at 800 °C. Those findings showed the potential of steam gasification for treating goggles and hand sanitation containers from medical usage.

Similar to pyrolysis, study on gasification of rubber waste had been reported, however, the focus was mainly on the waste tire and not on the waste rubber from gloves. Finding by Hazan et al. (2019) on waste NBR latex sludge showed that the content of sulfur was up to 0.73 wt%, made it not feasible to be used as feedstock in gasification process.

4.6. Technological challenges

Table 7 shows the summary of advantages, disadvantages, and challenges of carbonization/torrefaction, pyrolysis, gasification, and incineration. Overall, during the selection of technology to be applied for CMW treatment, it is important to consider the desired final product and the availability of the technology required to solve the challenges posed by each process.

Conclusions

The number of CMW from PPE used during the current pandemic COVID-19 is believed to be very large, and those wastes are considered potential as energy source. There are many options to safely convert CMW to a usable fuel or heat available. Since this type of waste has contagious properties, a disinfection stage should be added or integrated with the selected technology. In this study, several main

Table 7
Advantages, disadvantages, and challenges among carbonization/torrefaction, pyrolysis, gasification, and incineration.

Treatment methods	Advantages	Disadvantages	Challenges
RDF (without further processing)	<ul style="list-style-type: none"> High recovery and low rejection rate (due to high plastic and paper contents of CMW) Low drying cost (due to low moisture content of CMW) 	<ul style="list-style-type: none"> Risk of infection for operator Requirement for disinfection stage 	<ul style="list-style-type: none"> Suitable disinfection method
Incineration	<ul style="list-style-type: none"> Simple process and mature technology High material flexibility No requirement for disinfection stage Low fuel requirement (due to high calorific value of CMW) 	<ul style="list-style-type: none"> High carbon emission Possibility of producing harmful or corrosive gasses Only able to recover heat 	<ul style="list-style-type: none"> Flue gas treatment technology CO₂ capture and storage technology
Dry carbonization	<ul style="list-style-type: none"> Higher energy density product No requirement for disinfection stage Suitable moisture content for CMW Low ash and sulfur content Low carbon emission 	<ul style="list-style-type: none"> Insufficient operating conditions to facilitate further degradation Possibility of producing harmful or corrosive gasses 	<ul style="list-style-type: none"> Gas treatment technology
Wet carbonization	<ul style="list-style-type: none"> Higher energy density product No requirement for disinfection stage Low carbon emission Low ash product Able to remove chlorine content from PVC efficiently 	<ul style="list-style-type: none"> Requires addition of water to CMW Requires washing and drying of product the energy for pressurization and heating is considered high requires high-pressure reactor Difficulty for continuous process 	<ul style="list-style-type: none"> Development of continuous process to increase efficiency
Pyrolysis	<ul style="list-style-type: none"> Possibility to produce chemical feedstock Flexibility of product based on condition Low carbon emission Suitable for PE and PP, which is the major constituent of CMW No requirement for disinfection stage 	<ul style="list-style-type: none"> Need further research (developing technology) Not suitable for PVC, PET, and rubber 	<ul style="list-style-type: none"> Development of technology to maturity
Air gasification	<ul style="list-style-type: none"> Simple process Suitable for PE and PP, which is the major constituent of CMW No requirement for disinfection stage 	<ul style="list-style-type: none"> Not suitable for PVC, PET and rubber 	<ul style="list-style-type: none"> Tar removal technology
Steam gasification	<ul style="list-style-type: none"> Suitable for PE and PP, which is the major constituent of CMW High hydrogen yield, suitable for syn-gas generation Able to treat PVC (Able to recover chlorine form PVC) No requirement for disinfection stage 	<ul style="list-style-type: none"> Not suitable for PET and rubber Requires high amount of energy High tar formation 	<ul style="list-style-type: none"> Heat integration system to increase energy efficiency of the process Tar removal technology

thermochemical conversion technologies are reviewed, especially their suitability to treat CMW. These include incineration, carbonization/torrefaction, pyrolysis, and gasification. Among those thermochemical conversion technologies, incineration is considered able to facilitate wide range of medical waste types, followed by gasification and pyrolysis. In addition, torrefaction is considered suitable for pretreatment, before being further converted through other conversion methods. Furthermore, the possibility of coprocessing with ordinary solid waste is still open if CMW can be disinfected first by using several methods including SRDF. The tremendous volume of this waste, high calorific content and an urgent need for fast conversion match with the nature of thermal conversion technology.

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.

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