https://doi.org/10.1016/j.envpol.2021.116934

Valorisation of medical waste through pyrolysis for a cleaner environment: Progress and challenges

Guangcan Su[1], Hwai Chyuan Ong[2,*], Shaliza Ibrahim[3], I. M. Rizwanul Fattah[2], M. Mofijur[2], Cheng Tung Chong[4]

[1] Department of Mechanical Engineering, Faculty of Engineering, University of Malaya, 50603 Kuala Lumpur, Malaysia

[2] School of Information, Systems and Modelling, Faculty of Engineering and IT, University of Technology Sydney, NSW, 2007, Australia

[3] Institute of Ocean and Earth Sciences (IOES), University of Malaya, 50603, Kuala Lumpur, Malaysia

[4] China-UK Low Carbon College, Shanghai Jiao Tong University, Lingang, Shanghai 201306, China

*Corresponding author: E-mail addresses: hwaichyuan.ong@uts.edu.au, ong1983@yahoo.com (Hwai Chyuan Ong)

Abstract

The COVID-19 pandemic has exerted great shocks and challenges to the environment, society and economy. With the epidemic, an intractable issue appeared: a considerable number of hazardous medical wastes have been generated from the hospitals, clinics, and other health care facilities, constituting a serious threat to public health and environmental sustainability without proper management. Traditional disposal methods like incineration, landfill and autoclaving are unable to reduce environmental burden due to the issues such as toxic gas release, large land occupation, and unsustainability. While the application of clean and safe pyrolysis technology on the medical wastes treatment to produce high-grade bioproducts has the potential to alleviate the situation. Besides, medical wastes are excellent and ideal raw materials, which possess high hydrogen, carbon content and heating value. Consequently, pyrolysis of medical wastes can deal with wastes and generate valuable products like bio-oil and biochar. Consequently, this paper presents a critical and comprehensive review of the pyrolysis of medical wastes. It demonstrates the feasibility of pyrolysis, which mainly includes pyrolysis characteristics, product properties, related problems, the prospects and future challenges of pyrolysis of medical wastes.

***Keywords**:* COVID-19 pandemic; Medical wastes management; Biochar; Bio-oil; Environmental sustainability; Thermogravimetric analysis

Summaries of finding

Before the COVID-19 pandemic, medical wastes were often mixed with municipal solid waste and disposed of in waste landfills or incorrect treatment facilities. Many reviews have been devoted to the pyrolysis of plastics and other solid wastes. However, a review on the potential of pyrolysis of medical wastes has not been reported previously, prompting its publication during this pandemic. Pyrolysis of medical wastes can deal with wastes and generate valuable products like bio-oil and biochar.

Highlights

- Medical wastes are highly potent environmental hazards on public health risks.
- Pyrolysis of medical waste, together with associated problems, were reviewed.
- Prospects and future challenges of medical waste pyrolysis were discussed.
- Pyrolysis of medical wastes presents great environmental benefits.

Nomenclature

COVID-19	Coronavirus disease 2019
DAEM	Distributed activation energy model
EHI	Effective hydrogen index
Eq	Equation
FC	Fixed carbon
Fig	Figure
HDPE	High-density polyethylene
HHV	Higher heating value
LDPE	Low-density polyethylene
LHV	Lower heating value
MO	Moisture
PAHs	Polycyclic aromatic hydrocarbons
PCDDs	Polychlorinated dibenzo-p-dioxins
PCDFs	Polychlorinated dibenzofurans
PE	Polyethylene
PET	Polyethylene terephthalate
PMMA	Polymethyl methacrylate
PO	Polyolefins
PU	Polyurethanes
PP	Polypropylene
PS	Polystyrene
PVC	Polyvinyl chloride
Py-GC/MS	Pyrolysis–gas chromatography/mass spectrometry
TGA	Thermogravimetric analysis
US EPA	US Environmental Protection Agency
VM	Volatile matter
WHO	World Health Organization

1. Introduction

There is no doubt that the whole world has entered a new era since the global outbreak of Coronavirus Disease 2019 (COVID-19), as more than 109.47 million positive cases and over 2.41 million deaths have been confirmed at the moment of writing the paper (Johns Hopkins University (JHU), 2021). These numbers are increasing continuously every day because of the droplet and contact transmissions, which has an extensive impact on human lives (Wang *et al.*, 2020a). This has also resulted in a series of health, socio-economic, and environmental problems (Mofijur *et al.*, 2021). Among them, the disposal of medical wastes is a tremendous challenge for every nation. Before the global outbreak of COVID-19, it was reported that just hospitals in America produced over 5.9 million tons of medical wastes annually (Kargar *et al.*, 2020b). Meanwhile, the amount of waste continues to rise because of many reasons other than the COVID-19, such as the increase of elderly population, the improvement of health awareness, the rise in medical services expenditure, and the development of medical technology (Patrício Silva *et al.*, 2020; Peng *et al.*, 2020). The global epidemic further exacerbated the situation, especially for the most affected countries like the USA, Brazil, India, the UK, France, Italy, China, and so on (Kumar *et al.*, 2020b). For example, the generation of medical wastes explosively rose from 3.64 to 27.32 kg/day per 1000 persons in Wuhan since the outbreak of COVID-19, and the personal protective equipment like the protective suit, facemasks, nitrile gloves, safety goggles, and testing kits were the primary components of medical wastes (Di Maria *et al.*, 2020; Singh *et al.*, 2020; Yang *et al.*, 2021).

World Health Organization (WHO) defines medical waste as the waste generated in the diagnosis, treatment or immunisation of human beings or animals (Mohee, 2005). They are hazardous and infectious refuse produced by hospitals, clinics and other medical institutions (Saeidi-Mobarakeh *et al.*, 2020). The characteristics of these wastes include radioactivity, complexity, infectivity, and toxicity. These wastes have enormous potential to cause environmental pollution and health risks without proper management or treatment (Windfeld and Brooks, 2015). The novel coronavirus (SARS-CoV-2) has a high infection rate and strong survivability. People with minor symptoms or even asymptomatic infection possess the potential risk of transmitting the virus to others. Furthermore, the virus can survive for several days in numerous materials, including gloves, plastics, metal, silicon, and others, which significantly increases the risk and the difficulty of medical waste disposal (Lee *et al.*, 2020b; van Doremalen *et al.*, 2020). Therefore, considerable attention is required to be paid to every step, including medical wastes identification, collection, separation, storage, transportation, and final disposal (Sharma *et al.*, 2020; Wei *et al.*, 2020).

Due to the toxicity of medical wastes, countries worldwide have gradually enhanced the focus on the careful disposal of medical wastes. Subsequently, several technologies have been studied and developed (Moreira and Günther, 2013). **Table 1** summarises the merits and demerits of the main seven disposal methods, including incineration, landfill, chemical disinfection, autoclaving, microwave, plasma, and pyrolysis (Hoque and Rahman, 2020). The incineration is the most extensively used technique, which can significantly cut down the mass of medical wastes with admirable economy and broad applicability. Unfortunately, ashes with toxic metals and poisonous gases are generated during the process, posing a severe threat to human health and the environment (Makarichi *et al.*, 2018). Furthermore, the landfill is also widely applied due to its easy operation and low capital cost. However, it causes some undesirable effects like large land occupation, toxic gases release, and the risk of virus spread. With their pros and cons, the remaining four techniques have not been widely utilised in medical wastes disposal (Kargar *et al.*, 2020a). In contrast to those traditional treatment technologies, clean and safe pyrolysis has shown enormous potential advantages, mainly associated with the improvement of efficiency, the generation of high value-added products, and environment-friendliness (Chand Malav et al., 2020; Imtenan et al., 2014).

Pyrolysis is treated as a potential waste disposal technology and the best energy recovery method, which is thermal degradation of organic material by cracking the chemical bonds in an anaerobic environment (Sharifzadeh *et al.*, 2019). Pyrolysis can produce a series of high value products, including biochar, bio-oil and biogas. Based on the operating conditions, pyrolysis is divided into slow, fast and flash pyrolysis, and products distribution is highly affected by the type of pyrolysis (Ong *et al.*, 2020a; Zhang *et al.*, 2020). Thus, pyrolysis has been considered as a practical and cheap method to produce bio-oil and high value-added chemical products owing to the superiorities of high conversion efficiency, unstrict conditions and eco-friendly (Lee *et al.*, 2020c). Meanwhile, the addition of catalyst can considerably improve the product quality via the reduction of oxygenous and nitrogenous compounds. Moreover, many studies have illustrated that co-pyrolysis with suitable feedstocks has a remarkable promotion on the properties of bio-oil, too (Ahmed *et al.*, 2020; Sipra *et al.*, 2018).

In the past, medical wastes were often mixed with municipal solid waste and disposed of in waste landfills or incorrect treatment facilities (Jang *et al.*, 2006). However, this epidemic has shown the authorities worldwide the importance of proper management of medical wastes because of its potential in creating environmental hazards and public health risks. In consideration of the urgency of medical wastes disposal and the strengths of the pyrolysis process, pyrolysis is deemed as an optimal approach to deal with medical wastes and influence the environment positively. The literature on pyrolysis of plastics, microalgae, tire, lignocellulosic biomass and municipal solid waste have been published extensively (Anuar Sharuddin *et al.*, 2016; Arabiourrutia *et al.*, 2020; Azizi *et al.*, 2018a; Dhyani and Bhaskar, 2018; Kumar *et al.*, 2020a; Lee *et al.*, 2020a; Li *et al.*, 2019; Wang *et al.*, 2017; Yang *et al.*, 2019). However, a review on the pyrolysis of medical wastes has not been reported, even with the above-mentioned number of literature. Consequently, this paper provides a critical and comprehensive review of the medical wastes pyrolysis. The characterisation of medical wastes is presented. Moreover, the pyrolysis characteristics, products, and related problems of medical wastes pyrolysis are introduced. Finally, the prospects and future challenges of medical wastes pyrolysis are thoroughly discussed. Comprehensive analysis on the pyrolysis of medical wastes and the characteristics of products can provide the foundation for the sustainable management and scientific disposal of hazardous medical wastes.

Table 1. The merits and demerits of the main disposal methods of medical wastes.

Disposal methods	Advantages	Disadvantages
Incineration	Wide applicability, simple, mature, efficient technique, reduce the amount of waste largely	Toxic gas (especially dioxins, furans and mercury) release, produce ash with toxic metals
Landfill	Simple and mature technology, economical and convenient disposal method	Non-sustainability, risk of virus spread, large land occupation, poisonous gases emissions, dusts generation
Chemical disinfection	Small influence on the environment, broad sterilisation spectrum, high efficiency	High agent costs and equipment investment, produce toxic gases and liquids, residual disinfectants, cannot reduce the volume of medical wastes
Autoclaving	Well-established technology, good sterilisation, strong penetration	Produce toxic gases and liquids, cannot reduce the volume of medical wastes
Microwave disinfection	High efficiency, good sterilisation, low pollution	Huge capital investment, high running cost, reduce a small volume of medical wastes
Plasma	Reduce the volume of waste largely, good sterilisation	Huge capital investment and running cost, NO_x generation
Pyrolysis	High efficiency and sustainability, high value-added products, broad applicability	High pre-treatment cost and energy consumption

Sources: Zamri *et al.* (2021); Ilyas *et al.* (2020); Wang *et al.* (2020b); Ma *et al.* (2019); Hong *et al.* (2018); Zroychikov *et al.* (2018).

2. Characteristics of medical wastes

Heterogeneity is the most overriding characteristic of medical wastes because the composition of medical wastes is extremely complex and dependent on many factors, such as season, location, hospital patterns, and so on (Zroychikov *et al.*, 2018). **Table 2** lists the range of each component contents based on the literature survey. Plastics, papers and textiles are the three main components of medical wastes. They are raw materials for the most common sanitary consumables in hospital, such as medical bottles, drug packaging, bedding, and toilet papers (Chen *et al.*, 2013). Generally, the plastics existed in medical wastes are polyvinylchloride (PVC), polyurethanes (PU), polystyrene (PS), polyethylene terephthalate (PET), polyolefins (PO), and polyethylene (PE), all of them are ideal feedstocks for pyrolysis (Dash *et al.*, 2015). In addition, papers and textiles are typical lignocellulosic biomasses, which are treated as environmental-friendly, economically feasible, and potentially carbon-neutral feedstock for generating the renewable biofuels (Abraham *et al.*, 2020). Furthermore, it is reported that the bulk density of medical wastes is about 249 kg/m^3, while and the content of moisture is around 44.75 wt.% (Zhang *et al.*, 2016).

Table 2. The main components of medical wastes.

Components	Samples	Contents (%)
Plastics	Syringe, blood bag, drug packaging, medical bottles, infusion set, one-off medical glove, bowls	39.30–50.00
Textiles	Gauze, bedding, cotton pads, disposable diapers, absorbent cotton, towels, caps, masks	14.00–31.00
Papers	Used tissue, toilet paper, printer paper	11.15–25.10
Glass	Used slides and cover glass, glass bottles	0.30–22.70
Woodware	Bamboo stick, swab	3.17–20.00
Rubber	Nitrile gloves, rubber tourniquet, catheter	3.40–6.60
Metals	Scalpel, scissors, needles, surgical saws	0.30-5.00
Others	Food waste, medicine, human tissue, vaccines	1.40–18.60

Sources: Hong *et al.* (2018); Zroychikov *et al.* (2018); Ilyas *et al.* (2020); Zhang *et al.* (2016); Qin *et al.* (2018b); Mohseni-Bandpei *et al.* (2019); Zolfagharpour *et al.* (2020); Gerasimov *et al.* (2019); Graikos *et al.* (2010); Xie *et al.* (2009).

On the other hand, **Table 3** displays the elemental and proximate analyses of medical wastes or typical samples in the medical wastes. Plastic materials like medical bottles, infusion set, waste syringes, and packages have high carbon and hydrogen content, leading to a high calorific value. However, lignocellulosic biomasses in medical wastes, including bamboo stick, gauze, cotton, and tissues, do not show good performance on the HHV due to the high oxygen content. Furthermore, some specimens presented different characteristics. Due to the existence of nitrogen in the raw materials of butyronitrile, 12.90% nitrogen was detected in nitrile gloves. Moreover, 6.49% sulphur was determined in rubber tourniquet, mainly related to the process of vulcanisation, which is applied to improve its strength, hardness, and elasticity (Liu *et al.*, 2018).

As shown in **Fig. 1**, seven kinds of commonly used biomass materials were selected to show the differences in the properties of medical wastes and other biomass materials.

Apparently, the integral medical wastes are promising feedstocks for energy recovery. They possess better utilisation potential than most traditional biomass materials because medical wastes have the second-highest hydrogen content and relatively high carbon content. While the oxygen content is lower than many biomasses, nitrogen and sulphur content are approximately close to zero. Consequently, medical wastes have the third-highest calorific value among them. Furthermore, medical wastes possess the second-highest volatile matter, which means that more bio-oil will be generated from the pyrolysis of medical wastes. Based on the above analyses, medical wastes are indeed optimal raw materials for the production of biofuels.

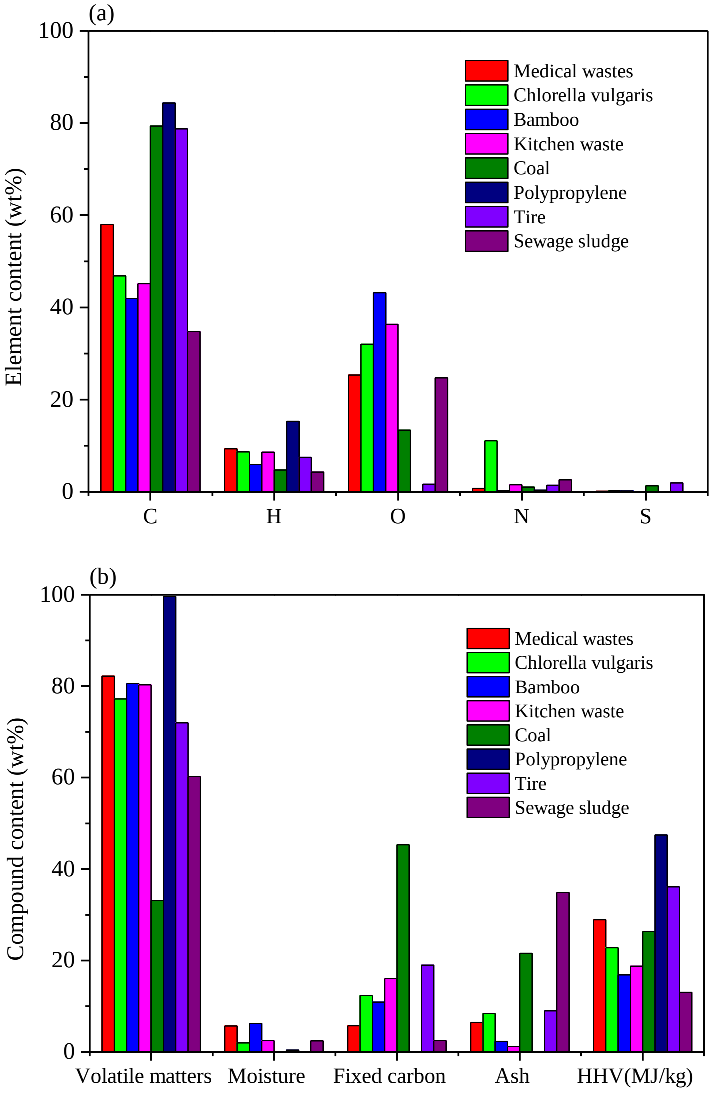

Fig. 1. (a) Elemental and (b) proximate analyses of medical wastes and other materials (Azizi *et al.*, 2018b; Chen *et al.*, 2012; Chen *et al.*, 2018a; Chen *et al.*, 2018b; Chen *et al.*, 2017; Duan *et al.*, 2015; Wang *et al.*, 2016; Yatsunthea and Chaiyat, 2020).

Table 3. Elemental and proximate analyses of samples and medical wastes.

Materials	Elemental analysis (dry basis, wt.%)					Proximate analysis (wt.%)				HHV (MJ/kg)	Reference
	C	**H**	**O**	**N**	**S**	**VM**	**MO**	**FC**	**Ash**		
Medical wastes	58.00	9.33	25.35	0.73	0.14	82.20	5.65	5.70	6.45	28.89	Yatsunthea and Chaiyat (2020)
Medical wastes	56.82	7.83	29.87	0.35	0.08	86.28	–	8.67	5.05	27.95	Xiong *et al.* (2006)
Plastic medical wastes	72.56	11.17	10.22	5.82	0.23	62.70	0.82	32.31	4.17	33.30	Som *et al.* (2018)
Cotton	44.92	9.00	45.86	0.19	0.03	96.40	6.46	3.60	0.20	15.79	Zhu *et al.* (2008)
Respirator	51.28	6.69	41.71	0.18	0.14	92.47	7.01	7.53	4.14	18.10	Zhu *et al.* (2008)
Bamboo stick	50.76	5.91	42.98	0.28	0.07	82.17	9.77	17.83	1.96	17.45	Zhu *et al.* (2008)
Paper	45.71	5.96	37.18	0.16	0.13	82.43	7.01	3.85	6.71	18.14	Zhu *et al.* (2015)
Gauze	41.93	8.40	42.81	0.18	0.03	89.99	6.46	3.36	0.19	15.82	Zhu *et al.* (2015)
Medical bottles	84.71	13.81	–	0.00	0.07	98.27	0.05	1.65	0.03	45.51	Ding *et al.* (2021)
Food waste	42.39	6.27	47.49	–	–	71.50	1.26	24.65	2.59	15.65	Gerasimov *et al.* (2019)
Tissues	47.23	6.43	45.23	–	–	78.89	0.30	19.99	0.82	17.70	Gerasimov *et al.* (2019)
Cotton wool	45.34	6.84	47.23	–	–	79.32	0.23	20.09	0.36	17.27	Gerasimov *et al.* (2019)
Bandage	44.68	6.65	48.29	–	–	79.49	0.18	20.13	0.20	16.74	Gerasimov *et al.* (2019)
Biomaterial container	84.54	15.46	–	–	–	99.82	–	0.18	–	44.56	Gerasimov *et al.* (2019)
Waste package	80.83	15.97	–	–	–	66.14	–	30.66	3.20	43.83	Gerasimov *et al.* (2019)
Nitrile gloves	77.32	8.27	–	12.90	–	87.45	–	11.05	1.50	34.72	Gerasimov *et al.* (2019)

Rubber tourniquet	54.19	8.06	–	–	6.49	67.85	–	0.89	31.26	27.37	Gerasimov *et al.* (2019)
PVC	32.78	4.11	–	–	40.88 (Cl)	62.72	–	15.04	22.24	15.34	Gerasimov *et al.* (2019)
Infusion set	81.81	12.17	–	0.15	0.11	99.13	0.32	0.55	–	42.65	Qin *et al.* (2018a)
Syringes	84.30	14.44	0.00	0.18	0.03	99.84	0.00	0.00	0.16	45.77	Yan *et al.* (2008)
Pig liver	53.66	7.96	15.21	11.62	0.33	81.54	6.68	7.24	4.54	22.12	Yan *et al.* (2008)

VM: Volatile matter; MO: Moisture; FC: Fixed carbon; HHV: Higher heating value (MJ/kg).

3. Pyrolysis characteristics of medical wastes

The heterogeneity and complexity of medical wastes result in the extreme complexity of its pyrolysis process. Furthermore, pyrolysis performance is prone to be affected by many factors such as atmosphere, heating rate, temperature range, residence time, particle size, sample dosage, and pressure. Thermogravimetric analysis has been widely used to obtain valuable pyrolysis data and explore the pyrolysis characteristics (Chong *et al.*, 2019). Thus, this section mainly discusses the pyrolysis characteristics of medical wastes in terms of thermodynamic parameters and kinetic models.

3.1. Thermogravimetric analysis

Thermogravimetric analysis is the most widely applied technology to reveal the pyrolysis characteristics of medical wastes, a ScienceDirect search on 1/1/2021 with the keywords "thermogravimetric analysis and pyrolysis" yielded 30260 articles. With the help of thermobalance, the relationship between sample mass and temperature or time can be continuously recorded under the control of temperature program. Some valuable information like initial reaction temperature, peak temperature, final temperature, weight loss, decomposition degree, and thermal stability range can be obtained during the process (Gao *et al.*, 2020). Moreover, according to the data, thermal stability, decomposition process and products of the raw materials can be evaluated, activation energy and pre-exponential factor can be calculated to investigate the reaction kinetics. Thermogravimetric analysis is fast, simple, convenient and accurate, which is the primary method to study the pyrolysis characteristics of materials (Xiao *et al.*, 2020).

Table 4 summarises the pyrolysis characteristic parameters of twenty-one typical samples. The common types of those materials are macromolecule; some are synthetic macromolecule, like PVC, syringes, and infusion set. Simultaneously, the others are natural macromolecules, such as cotton, bamboo stick, and pig liver. In this regard, the pyrolysis of medical wastes can be treated as the pyrolysis of high macromolecule compounds to a certain extent (Ding *et al.*, 2021). Based on **Table 4**, apparently, most of the typical samples such as gloves, paper, gauze presented one main weight loss stage. However, other specimens like syringes, respirator, infusion tube, urine collector, catheter, dressing displayed two decomposition stages with two weight loss peaks. Lignocellulose biomass bamboo stick showed three weight loss stages, mainly due to those materials' unique physical and chemical composition. Generally, ingredients with poor stability in the materials tend to decompose at a low temperature. In contrast, ingredients with high stability are prone to experience the degradation process at a high temperature (Wu *et al.*, 2020). For instance, PVC (Polyvinyl chloride) is the main component of urine collector and infusion tube (Deng *et al.*, 2008). Previous studies have reported that PVC pyrolysis proceeds in two stages: dehydrochlorination and hydrocarbon formation (Kim, 2001; McNeill *et al.*, 1995). In the first stage, dehydrochlorination is the primary reaction leading to the release of HCl and the formation of a volatile organic compound such as conjugated polyene (Zhou *et al.*, 2016). However, other opinions regarding the mechanism of first stage degradation also prevail (Karayildirim *et al.*, 2006). In the second stage, toluene is produced with a small number of alkyl aromatics which yields a residual char (Marcilla and Beltrán, 1995). The aliphatic hydrocarbons are formed from the decomposition of alkyl aromatics on some occasions.

Furthermore, syringes are mainly composed of PP, whose pyrolysis follows the free-radical irregular degradation reaction (Dash *et al.*, 2015). A bamboo stick is a typical lignocellulose material, mainly consists of cellulose, hemicellulose and lignin, while each component has different thermal decomposition temperature interval (Zhao *et al.*, 2019). The catheter mainly consists of natural rubber and $CaCO_3$ (Deng *et al.*, 2014). Reinforcing natural rubber with ultrafine calcium carbonate improved tear strength, modulus, and tensile strength of natural rubber (Cai *et al.*, 2003). The primary degradation is related to the depolymerisation of natural rubber, whereas the secondary degradation corresponds to the decomposition of $CaCO_3$ (Dollimore *et al.*, 1996). The dressing is made from various materials, including gauze, paper, and synthetic fibre. Deng *et al.* (2008) reported a two-stage degradation of filling of dressing in their work.

Due to the various pyrolysis characteristics of each material, the initial reaction temperature and peak decomposition temperature of different samples is different. With the rise of temperature, rubber, plastic, protein, cellulose, and synthetic fibre entered the pyrolysis process in succession. Subsequently, all samples got into a substantial weight loss process between 240 and 430°C successively. Furthermore, most of the samples finished the process at 600°C except syringes and catheter, whose weight loss still occurred between 660 and 800°C, all samples finished the pyrolysis process eventually up to 800°C. Correspondingly, in engineering design, the furnace temperature of the pyrolysis reactor ought to be 800°C or higher to make sure that the degradation process is able to be fully completed (Deng *et al.*, 2008).

The significant weight loss of plastics occurred between 300 and 500°C. In addition, noticeable weight loss of rubber materials took place in 240–400°C, the remarkable degradation of protein and cellulose showed up in 300–480°C and 300–350°C, respectively. Medical bottles had maximum weight loss, and only 2.4% of residues left, while catgut suture possessed the maximal residues. However, the weight loss of most samples was up to 80%, which verified that pyrolysis technology cut down the volume of medical wastes drastically. Furthermore, it is observed that the peak decomposition temperature of all samples locates in the range of 370–520°C. Correspondingly, prolonging reaction time in the above temperature interval is conducive to maximise the degree of degradation.

3.2. Kinetic analysis

According to the data from TGA, the kinetic parameters of typical samples in medical wastes can be determined via the Coats–Redfern method, which is widely applied to predict mass loss evolution (Anca-Couce, 2016). Based on the Arrhenius law, the rate of heterogeneous solid-state reactions can be described as Eq. (1):

$$\frac{dx}{dt} = A \cdot \exp(-\frac{E}{R \cdot T})(1-x)^n \tag{1}$$

where *A* represents the pre-exponential factor, *E* refers to the apparent activation energy (kJ/mol), *x* is the conversion extent and *n* represents reaction order, *t* refers to the reaction time (s), *T* and *R* represent the absolute temperature (K) and the universal gas constant [J/(mol·K)], respectively (Dai *et al.*, 2019).

The conversion degree *x* can be calculated by Eq. (2), where w_0 refers to the original mass of the sample, w_t and w_f represent the mass at time *t* and the mass at the end, respectively. For a constant heating rate k during pyrolysis, k=dT/dt, after reorganisation and integration, the following expression can be observed as Eq. (3) and Eq. (4):

$$x = \frac{w_0 - w_t}{w_0 - w_f} \tag{2}$$

$$\ln[-\frac{\ln(1-x)}{T^2}] = \ln[\frac{A\cdot R}{H\cdot E}(1-\frac{2\mathrm{R}\cdot T}{E})] - \frac{E}{R\cdot T} \qquad \text{if n=1} \tag{3}$$

$$\ln[-\frac{\ln(1-x)}{T^2(1-n)}] = \ln[\frac{A\cdot R}{H\cdot E}(1-\frac{2\mathrm{R}\cdot T}{E})] - \frac{E}{R\cdot T} \qquad \text{if n≠1} \tag{4}$$

Generally, $\frac{2\mathrm{R}\cdot T}{E}$"1 , and the expression $\ln[\frac{A\cdot R}{H\cdot E}(1-\frac{2\mathrm{R}\cdot T}{E})]$ is essentially constant in the temperature interval of pyrolysis. Thus, the line with slope and intercept can be determined by the left side of the equation. The activation energy and pre-exponential factor are obtained by this mean.

Table 5 presents the kinetic parameters of twenty-six typical samples from the literature. Most of them were calculated by Coats–Redfern. While Distributed Activation Energy Model (DAEM) was also applied to analyse the evolution of different volatile species in pyrolysis, like CO, CO_2, H_2O, hydrocarbon, ketone, acid, aldehyde, and others, it assumed the pyrolysis of specimen involves several independent chemical reactions, each one affecting the whole process (Fang *et al.*, 2018). Apparently, the correlation coefficient of the line is in the range of 0.960 to 0.999. The activation energy values of all specimens are distributed between 80.62 and 306.00 kJ/mol in the first stage. Meanwhile, the secondary process's activation energy is ranged from 206.60 to 412.92 kJ/mol, which is much higher than that of the primary process.

Table 4. Pyrolysis characteristic parameters for samples in medical wastes

Samples	K	T_1 (°C)	T_{p1} (°C)	T_{f1} (°C)	DTG_1	WL_1 (%)	T_2 (°C)	T_{p2} (°C)	T_{f2} (°C)	DTG_2	WL_2 (%)	T_3 (°C)	T_{p3} (°C)	T_{f3} (°C)	DTG_3	WL_3 %)	R (%)	Reference
Syringes	20	394.40	467.30	501.00	40.53	73.90	661.90	738.30	759.50	2.99	10.74	–	–	–	–	–	9.96	Ding *et al.* (2021)
Medicine bottles	20	417.90	477.90	517.00	62.03	97.60	–	–	–	–	–	–	–	–	–	–	2.40	Ding *et al.* (2021)
Absorbent cotton	30	291.00	384.00	432.00	–	89.19	–	–	–	–	–	–	–	–	–	–	10.81	Zhu *et al.* (2008)
Respirator	30	280.00	381.00	409.00	–	–	465.00	494.00	516.00	–	–	–	–	–	–	–	11.43	Zhu *et al.* (2008)
Bamboo stick	30	200.00	313.00	320.00	–	–	320.00	363.00	400.00	–	–	468.00	494.00	520.00	–	–	17.91	Zhu *et al.* (2008)
Infusion tube	20	288.86	320.32	342.86	25.80	72.40	461.92	470.41	491.27	6.60	14.99	–	–	–	–	–	12.70	Deng *et al.* (2008)
Urine collector	20	295.34	309.93	329.97	33.00	58.21	454.58	472.31	493.00	11.40	24.52	–	–	–	–	–	17.27	Deng *et al.* (2008)
Medical glove	20	429.40	476.81	493.99	31.20	95.14	–	–	–	–	–	–	–	–	–	–	4.86	Deng *et al.* (2008)
Operating glove	20	373.42	395.88	422.94	32.40	92.35	–	–	–	–	–	–	–	–	–	–	7.65	Deng *et al.* (2008)
Catheter	20	365.72	395.80	430.46	13.20	46.51	717.21	755.45	768.13	4.80	14.03	–	–	–	–	–	39.46	Deng *et al.* (2008)
Cotton swabs	20	327.12	382.50	394.59	20.40	69.76	–	–	–	–	–	–	–	–	–	–	30.24	Deng *et al.* (2008)
Toilet paper	20	344.72	372.51	383.81	39.60	78.94	–	–	–	–	–	–	–	–	–	–	21.06	Deng *et al.* (2008)
Gauze	20	351.41	381.75	397.51	35.40	81.01	–	–	–	–	–	–	–	–	–	–	18.99	Deng *et al.* (2008)
Absorbent cotton	20	353.21	382.57	397.20	37.80	82.89	–	–	–	–	–	–	–	–	–	–	17.11	Deng *et al.* (2008)
Catgut suture	20	309.30	351.28	382.69	11.40	48.89	–	–	–	–	–	–	–	–	–	–	51.11	Deng *et al.* (2008)
Muscle of rat	20	308.27	346.71	369.91	13.80	66.38	–	–	–	–	–	–	–	–	–	–	33.62	Deng *et al.* (2008)
Dressing filling	20	329.35	358.97	371.26	12.60	29.16	431.49	455.50	475.03	20.40	48.13	–	–	–	–	–	22.71	Deng *et al.* (2008)
Adhesive plaster	20	365.24	384.38	408.49	23.40	66.59	–	–	–	–	–	–	–	–	–	–	33.41	Deng *et al.* (2008)
Dressing	20	332.23	363.67	376.04	52.13	19.20	–	413.25	440.58	13.20	32.39	–	–	–	–	–	15.48	Deng *et al.* (2008)
Glove	20	253.81	394.79	394.79	-	92.71	–	–	–	–	–	–	–	–	–	–	7.29	Deng *et al.* (2013)

Catheter	20	240.08	394.10	513.12	-	47.59	–	769.54	799.90	–	15.50	–	–	–	–	–	36.91	Deng *et al.* (2013)

K: Heating rate (°C/min); T_n: Initial reaction temperature in stage n; T_{pn}: Peak decomposition temperature in stage n; T_{fn}: Final decomposition temperature in stage n; DTG_n: Maximum rate of weight loss in stage n (%/min); WL_n: Weight loss in stage n; R: Residues.

Table 5. Pyrolysis kinetic parameters for samples in medical wastes.

Samples	**K**	**E_1(kJ/mol)**	**A_1(min^{-1})**	**n_1**	**R_1**	**E_2(kJ/mol)**	**A_2(min^{-1})**	**n_2**	**R_2**	**Methods**	**Reference**
Syringes	20	247.03	1.00×10^{17}	2	0.998	213.84	3.47×10^{17}	2	0.999	Integral master-plots	Ding *et al.* (2021)
Medical bottles	20	269.66	5.23×10^{18}	1.2	0.994	–	–	–	–	Integral master-plots	Ding *et al.* (2021)
Absorbent cotton	30	188.50–289.00	10^{14}–10^{22}	–	0.984–0.999	–	–	–	–	DAEM	Yan *et al.* (2009)
Respirator	30	184.50–294.50	10^{13}–10^{23}	–	0.960–0.999	–	–	–	–	DAEM	Yan *et al.* (2009)
Bamboo stick	30	107.50–295.50	10^{8}–10^{25}	–	0.987–0.999	–	–	–	–	DAEM	Yan *et al.* (2009)
Infusion tube	20	110.42	3.28×10^{9}	1	0.998	246.94	9.87×10^{16}	1	0.982	Coats–Redfern	Deng *et al.* (2008)
Urine collector	20	130.62	2.09×10^{11}	1	0.975	208.27	2.19×10^{14}	1	0.982	Coats–Redfern	Deng *et al.* (2008)
Medical glove	20	181.36	2.15×10^{12}	0	0.999	–	–	–	–	Coats–Redfern	Deng *et al.* (2008)
Operating glove	20	148.81	1.74×10^{11}	1	0.993	–	–	–	–	Coats–Redfern	Deng *et al.* (2008)
Catheter	20	117.61	5.70×10^{8}	1	0.992	412.92	1.35×10^{21}	1	0.999	Coats–Redfern	Deng *et al.* (2008)
Cotton swabs	20	84.45	4.07×10^{6}	1	0.993	–	–	–	–	Coats–Redfern	Deng *et al.* (2008)
Toilet paper	20	170.11	6.91×10^{13}	1	0.992	–	–	–	–	Coats–Redfern	Deng *et al.* (2008)

Gauze	20	185.85	7.62×10^{14}	1	0.998	–	–	–	–	Coats–Redfern	Deng *et al.* (2008)
Absorbent cotton	20	198.23	7.70×10^{15}	1	0.999	–	–	–	–	Coats–Redfern	Deng *et al.* (2008)
Catgut suture	20	85.47	6.02×10^{6}	1.5	0.993	–	–	–	–	Coats–Redfern	Deng *et al.* (2008)
Rat muscle	20	80.62	2.09×10^{6}	1.5	0.992	–	–	–	–	Coats–Redfern	Deng *et al.* (2008)
Dressing filling	20	147.90	1.69×10^{12}	1	0.998	228.12	2.02×10^{16}	1	0.999	Coats–Redfern	Deng *et al.* (2008)
Adhesive plaster	20	128.60	9.45×10^{9}	1	0.994	–	–	–	–	Coats–Redfern	Deng *et al.* (2008)
Dressing	20	135.98	1.14×10^{11}	1	0.994	285.31	1.14×10^{21}	1	0.994	Coats–Redfern	Deng *et al.* (2008)
Infusion set	20	132.38	1.42×10^{9}	1	0.999	–	–	–	–	Coats–Redfern	Qin *et al.* (2018a)
PVC	20	125.50	8.07×10^{10}	1	–	206.60	2.28×10^{14}	1	–	Coats–Redfern	Dudkina *et al.* (2019)
PE	20	305.00	6.15×10^{20}	1	0.999	–	–	–	–	Coats–Redfern	Paraschiv *et al.* (2015)
PP	20	301.00	3.71×10^{20}	1	0.999	–	–	–	–	Coats–Redfern	Paraschiv *et al.* (2015)
PS	20	256.00	5.50×10^{18}	1	0.999	–	–	–	–	Coats–Redfern	Paraschiv *et al.* (2015)
Latex	20	107.00	6.72×10^{7}	1	0.990	–	–	–	–	Coats–Redfern	Paraschiv *et al.* (2015)
PMMA	20	306.00	6.72×10^{15}	1	0.999	–	–	–	–	Coats–Redfern	Paraschiv *et al.* (2015)

K: Heating rate (°C/min); E_m: Activation energy in stage m; A_m: Pre-exponential factor in stage m; n_m: Reaction order in stage m; R_m: Correlation coefficient in stage m.

4. Characteristics of products from medical wastes pyrolysis

The production of valuable final products is the predominant characteristic and distinct superiority of the pyrolysis process, which is the main feature that distinguishes it from other technologies. Bio-oil and biochar are the main outputs of this process. Among these products, bio-oil has a considerable potential to substitute for fossil fuels and solves a series of environmental problems caused by reckless fossil fuels consumption. Besides, biochar is rich in carbon with favourable porous structure and high surface functionality, which is used as a supercapacitor, anode material, photocatalytic support, and adsorbent (Fakayode *et al.*, 2020). As such, many experimentalists tried to maximise the bio-oil yield by optimising the reaction conditions. Under optimised condition for bio-oil, very little biogas can be generated, and most of which are either released into the air or reused into the pyrolysis process (Ong *et al.*, 2019). Consequently, many researchers have explored in-depth and made numerous achievements during the pyrolysis of medical wastes. **Table 6** presents pyrolysis products characteristics of medical wastes or some typical samples.

Many studies have shown that pyrolysis of medical wastes is able to generate a considerable yield of bio-oil and biochar with high quality. Fang *et al.* (2020) selected the organic substances in the medical wastes as the experimental materials and pyrolysed them in the furnace at 500°C. 42.00 wt.% bio-oil was obtained at the optimal conditions. It contained 60% hydrocarbons and lipids, and the carbon chain length was between C_6 and C_{28}. The calorific value was as high as 37.56 MJ/kg, which was very close to gasoline. During the pyrolysis, 50.69 wt.% biochar was gained with a high HHV of 22.80 MJ/kg. In addition, the effect of vacuum degree and condensing temperature on final products were explored, the optimum vacuum degree was 0.04 MPa, and the condensing temperature was 70°C in the first stage to achieve the maximum yield of bio-oil. Mohseni-Bandpei *et al.* (2019) and Gerasimov *et al.* (2019) gained 73.40 and 50.00 wt.% bio-oil during the pyrolysis of medical wastes, respectively mainly owing to the high content of volatile matter in the medical wastes.

The pyrolysis of typical samples in medical wastes also achieved numerous remarkable results. Jung *et al.* (2020) proposed a new approach to the disposal of the used facemask during the pandemic. After analysis and pyrolysis of the disposable COVID-19 mask, they figured out that PP (73.33 wt.%), PE (13.77 wt.%), nylon (8.27 wt.%) were the main chemical constituents, and about 51.00 wt.% bio-oil was generated. As for the quality of bio-oil, long-chain hydrocarbons were the major chemical components, while the carbon chain length was between C_6 and C_{46}. Furthermore, syngas was produced too, H_2, CH_4, C_2H_6, and C_2H_4 were the chief components. While the accession of Ni/SiO_2 further promoted the formation of H_2 and CH_4, additional CO was generated in the atmosphere of CO_2. They made a conclusion that pyrolysis of disposable face mask in the presence of CO_2 was a safe and environmentally benign method to get rid of COVID-19 relevant plastic waste and produce valuable products.

As mentioned above, plastics are the main components of medical wastes. Therefore, many researchers have put attention to the pyrolysis of plastic materials in medical wastes and achieved fruitful results. Som *et al.* (2018) conducted the pyrolysis of plastic medical waste (PWM) and got a high-grade bio-oil. The properties of bio-oil were close to commercial fuel such as petrol and diesel. As the calorific value was 41.31 MJ/kg, the density was 840 kg/m^3, the flash point and pour point were 39 and 14°C, respectively. Furthermore, Paraschiv *et al.* (2015) chose several representative plastic materials in hospital solid wastes and studied their pyrolysis products. Firstly, the yield of bio-oil was in the range of 63.20 and 98.00 wt.% because the high volatiles content was favourable for the formation of liquid products. Furthermore, the obtained bio-oil was rich in hydrocarbons and led to a high calorific value ranged from 27.17 and 46.80 MJ/kg. 11.00 to 21.00 wt.% biogas with high quality were generated during the process too, and CH_4, C_2H_4, C_2H_6, C_3H_6, C_3H_8 were the chief components, the biogas LHV was between 39.16 and 69.22 MJ/Nm^3, which was close to the natural gas, and could replace the natural gas for urban and industrial utilisation. The high carbon and hydrogen content in plastic materials were the main reason. Moreover, less yield of biochar was obtained due to the low content of ash in the plastics. Qin *et al.* (2018b) pyrolysed medical plastic wastes (medicinal plastic bottles and plastic infusion bag) consisted of PS and PP and observed the thermal degradation process. Wastes started vitrifying at around 100°C, began degrading at about 300°C, and reached the maximum near 400°C. Styrene monomer, benzene, toluene, and C_1–C_4 hydrocarbons were the main products at the initial stage of pyrolysis. They held a view that the aromatic compounds were primarily originated from PP degradation, while alkanes and alkenes mainly came from PS degradation.

In addition, Ding *et al.* (2021) detected the molecular structures of gases from discarded syringes and medicine bottles by Py-GC/MS analysis. During discarded syringes pyrolysis, C_4-C_{24} alkenes (51.28% peak areas) were the chief products, diene (23.63% peak areas) and alkanes (1.04% peak areas) were also determined simultaneously. As for the medicine bottles, C_8-C_{41} alkenes (49.94% peak areas) and C_6-C_{41} (31.91% peak areas) alkanes were the major products. Moreover, the accession of a large mass of catalysts is beneficial to the production of biogas. Lin *et al.* (2010) detected that the addition of acidic cracking catalysts (FCC-R1, HUSY, ZSM-5 and SAHA) (30 wt.%) in the pyrolysis of hospital plastic wastes generated more than 82.00 wt.% biogas. This was because the secondary cracking broke the long carbon chain into a short carbon chain owing to the presence of the catalyst, and C_1–C_4 was the primary product. Meanwhile, silicalite increased the biochar yield to 85.10 wt.%.

Table 7 presents the bio-oil physicochemical characteristics from the pyrolysis of medical wastes. The typical physicochemical properties include density, viscosity, flash point, pour point, and HHV. Bio-oil can be directly used in combustors or converted into biodiesel via transesterification process (Fattah *et al.*, 2020; Ong *et al.*, 2020b; Suchocki *et al.*, 2021). In general, bio-oil physicochemical characteristics produced from the pyrolysis of medical wastes are very close to traditional fossil fuels like diesel or gasoline. As such, those can be blended with petroleum-based fuels. However, the bio-oil from PVC has low HHV due to the high content of chlorine in the PVC. The viscosity of the bio-oil originated from medical waste is a little higher than the viscosity of commercial fuels. Furthermore, the bio-oil from pyrolysis of latex and PMMA has a lower flash point than regular petroleum-based fuels.

In short, the pyrolysis of plastic-based medical wastes possesses great strengths and generates a considerable amount of bio-oil with favourable physicochemical characteristics. The oils can replace traditional fossil fuels and solve a series of ecological, environmental and social problems.

Table 6. Pyrolysis products characteristics of medical wastes or typical samples.

Samples	**Conditions**	**Liquid products**		**Solid products**		**Gas products**		**Reference**
		Yields (wt.%)	**HHV (MJ/kg)**	**Yields (wt.%)**	**HHV (MJ/kg)**	**Yields (wt.%)**	**LHV (MJ/Nm^3)**	
Medical wastes	500°C, 0.05 MPa	42.00	37.56	50.69	22.80	7.31	46.18	Fang *et al.* (2020)
Medical wastes	700°C, 145 s, N_2	73.40	–	24.10	–	2.50	–	Mohseni-Bandpei *et al.* (2019)
Medical wastes	600°C, 10°C/min, N_2	50.00	–	–	–	–	–	Gerasimov *et al.* (2019)
Plastic medical wastes	260°C, N_2	53.00	41.33	29.00	–	18.00	–	Som *et al.* (2018)
Plastic medical wastes	390°C, N_2, FCC-R1	3.80	–	11.70	–	82.40	–	Lin *et al.* (2010)
Plastic medical wastes	390°C, N_2, Silicalite	1.40	–	85.10	–	13.50	–	Lin *et al.* (2010)
Plastic medical wastes	390°C, N_2, HUSY	3.30	–	8.60	–	85.60	–	Lin *et al.* (2010)
Plastic medical wastes	390°C, N_2, ZSM-5	3.40	–	6.40	–	88.30	–	Lin *et al.* (2010)
Plastic medical wastes	390°C, N_2, SAHA	3.60	–	10.50	–	84.10	–	Lin *et al.* (2010)
Facemask	600°C, 10°C/min, CO_2	51.00	–	6.00	–	43.00	–	Jung *et al.* (2020)
Syringe	450°C, 20°C/min, He	83.30	42.54	0.00	–	16.70	–	Dash *et al.* (2015)
PE	5-7°C/min, 20 min, N_2	68.50	45.70	10.50	–	21.00	69.22	Paraschiv *et al.* (2015)
PP	5-7°C/min, 20 min, N_2	82.00	46.80	0.00	–	18.00	64.30	Paraschiv *et al.* (2015)
PS	5-7°C/min, 20 min, N_2	89.00	–	0.00	–	11.00	48.46	Paraschiv *et al.* (2015)
Latex	5-7°C/min, 20 min, N_2	63.20	46.40	25.20	–	11.60	39.16	Paraschiv *et al.* (2015)
PMMA	5-7°C/min, 20 min, N_2	98.00	27.17	0.00	–	2.00	–	Paraschiv *et al.* (2015)

PVC	800°C, 350°C/min, N_2	31.30	–	15.60	–	44.40	–	Zhou *et al.* (2015)
PET	800°C, 350°C/min, N_2	38.20	–	4.50	–	47.20	–	Zhou *et al.* (2015)

HHV: Higher heating value (MJ/kg); LHV: Lower heating value (MJ/Nm^3).

Table 7. Physicochemical characteristics of the bio-oil from pyrolysis of medical wastes or typical samples.

Materials	**Density (kg/m^3)**	**Viscosity (mPa·s)**	**Flash point (°C)**	**Pour point (°C)**	**HHV (MJ/kg)**	**Reference**
Medical wastes	–	9.10	–	–	37.56	Fang *et al.* (2020)
Plastic medical wastes	840.00	–	39.00	14.00	41.33	Som *et al.* (2018)
Waste syringe	828.10	2.97	-6.00	-18.00	42.54	Dash *et al.* (2015)
PP	740.00	5.70	-3.00	–	45.80	Paraschiv *et al.* (2015)
Latex	860.00	2.57	<-10.00	–	46.40	Paraschiv *et al.* (2015)
PMMA	900.00	0.91	<-10.00	–	27.17	Paraschiv *et al.* (2015)
HDPE	890.00	4.52	48.00	–	40.50	Anuar Sharuddin *et al.* (2016)
LDPE	780.00	4.34	41.00	–	39.50	Anuar Sharuddin *et al.* (2016)
PVC	840.00.	5.34	40.00	–	21.10	Anuar Sharuddin *et al.* (2016)
PS	850.00	1.19	26.10	–	43.00	Anuar Sharuddin *et al.* (2016)
Diesel	830.00-840.00	2.07-2.64	–	–	42.50	(Singh *et al.*, 2021)
Diesel (EU Standard)	860.00-900.00	3.00-4.50	120.00	< 0.00	–	(Samuel *et al.*, 2020)
Biodiesel	867.00-928.50	3.96-4.99	67.0-242.0	-6.00-15.00	37.5-51.5	(Rahman *et al.*, 2021)
Gasoline	750.0 - 765.0s	0.6	-45.0 - -13.0	–	47.30	(Masum *et al.*, 2014)

5. Problems associated with the pyrolysis of medical wastes

Noxious gas emission is the main problem during the pyrolysis of medical wastes, such as PAHs, HCl, SO_2, and NO_x, which posed a tremendous threat to public health and ecological security. Based on this, many researchers have concentrated on the issue and tried to limit toxic gases released.

5.1. PAHs generation

Based on the US Environmental Protection Agency (US EPA), 16 kinds of polycyclic aromatic hydrocarbons (PAHs), including anthracene, acenaphthene, fluorene, phenanthrene, fluoranthene, pyrene, were confirmed to be hazardous to the environment and healthiness considering their carcinogenic, mutagenic, teratogenic and genotoxic potentials (Kim *et al.*, 2013). In addition, PAHs are possibly involved in the formation of polychlorinated dibenzo-p-dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) in the fly ash as intermediate reactants (Chin *et al.*, 2012). The persistent toxicity and threat to the circumstance are mainly related to the molecular structure of PAHs, which may include nitro, chlorinated and oxy groups (Imtenan *et al.*, 2014; Zhou *et al.*, 2019).

Many studies have indicated that plastics, lignocellulose biomass or other macromolecule organic compounds in pyrolysis are conducive to the generation of PAHs. Font *et al.* (2003) studied the pyrolysis of PE and found the formation of PAHs in the bio-oil at a high temperature. Small molecules were formed firstly during the pyrolysis; then, PAHs were produced by the rapid cyclic reaction of small molecules. Onwudili *et al.* (2009) identified naphthalene in the bio-oil during the pyrolysis of low-density polyethylene (LDPE). They figured out that the rise of reaction temperature and residence time exerted a positive impact on the formation of naphthalene. Furthermore, Li *et al.* (2013) pointed out that the pyrolysis of cellulose (3.87%) produced more naphthalene than LDPE (0.79%) with the help of ZSM-5 at 650°C. However, plastics, lignocellulose biomass are the major components of medical wastes; the release of PAHs during the pyrolysis should not be overlooked.

Many researchers have focused on the issue and reported that the operating conditions greatly influenced the production of PAHs. Mohseni-Bandpei *et al.* (2019) detected that the concentration of PAHs was 121–29440 mg/lit in the bio-oil, 223–1610 mg/kg in the biochar via the pyrolysis of medical wastes. Additionally, particles size, reaction temperature and residence time had a huge impact on the yield of PAHs. The maximum PAHs yield was detected at 2 cm and 145 s. The rising particles size increased the formation of PAHs in the liquid products significantly, whereas more PAHs were absorbed in the biochar with the high temperature and long residence times. Zhou *et al.* (2015) pyrolysed a series of medical typical solid wastes including cellulose, xylan, lignin, pectin, starch, PS, PVC, PE, and PET and observed the formation of PAHs. A high concentration of PAHs was determined from the pyrolysis of plastic materials, and most of the PAHs were produced by the pyrolysis of PS, followed by PVC, PET, and lignin. As for the composition of PAHs, the content of naphthalene was the highest.

In addition, many studies have shown that the accession of catalysts possesses a negative effect on the PAHs generation. Wu *et al.* (2013) detected naphthalene during the pyrolysis of cellulose, xylan and lignin, and the pyrolysis of lignin gained the highest concentration of naphthalene without any catalyst. In comparison, the addition of nickel-based catalysts hinders the production of PAHs effectively. This result is supported by the research of Wang *et al.* (2018). They pyrolysed polyethylene and corn stover with the addition of nickel-modified HZSM-5 and determined Ni-HZSM-5 reduced the content of PAHs and increased the production of aromatics effectively. Therefore, the concentration of PAHs can be cut down effectively by reducing particles size, lessening the residence time, controlling the reaction temperature and adding the proper catalysts.

5.2. HCl generation

In general, chlorine mainly originated from an organic form like PVC or inorganic form such as physiological saline in medical wastes, while participating in the chemical reaction and generate HCl usually. HCl is another hazardous gaseous pollutant during the pyrolysis of medical wastes, which is corrosive and harmful and can lead to acid rain. Also, the HCl in the bio-oil is prone to cause several problems like high acidity, low stability and HHV, damage the gasoline engine, and cut down the value of bio-oil dramatically. In addition, some reports have demonstrated that Cl might lead to the generation of highly toxic dioxins and furans during the pyrolysis (Hunsinger *et al.*, 2002).

Thus, the fixation of HCl or Cl is a critical research topic, and the addition of alkaline additives like $Ca(OH)_2$, ZnO, CaO, and Fe_2O_3 during the pyrolysis is the main approach to remove the HCl. Kaminsky and Kim (1999) pyrolysed the mixed plastics in a fluidised reactor and observed the evolution of chlorine. In the bio-oil, most of the chlorine existed in the form of calcium chloride with the addition of $Ca(OH)_2$. This was because $Ca(OH)_2$ converted the HCl into $CaCl_2$ with the reaction as Eq (5):

$$Ca(OH)_2 + 2HCl = CaCl_2 + 2H_2O \tag{5}$$

Zhu *et al.* (2015) conducted an experiment on the pyrolysis of simulative medical wastes with PVC or NaCl to explore the evolution route of chlorine. Firstly, no HCl was detected during the pyrolysis of medical wastes with NaCl because ionic bond energy of NaCl was too high to reach. As for the addition of PVC, HCl emitted in both thermal degradation stage. Furthermore, the accession of Ca-based additives ($CaCO_3$, CaO, $Ca(OH)_2$) inhibited the concentration of HCl, a remarkable negative correlation between Ca/Cl molar ratio and HCl concentration was observed, and $Ca(OH)_2$ had the highest HCl removal efficiency among those additives.

Apart from that, some researchers tried to figure out the relationship between the experimental conditions and the emission of HCl. Dudkina *et al.* (2019) studied the pyrolysis of chlorine-containing medical wastes and found that most of the HCl (88.5%) were released at temperatures above 350°C. Lin *et al.* (2010) pyrolysed hospital plastic wastes with five kinds of catalysts (FCC-R1, silicalite, HUSY, ZSM-5, SAHA) and explored the catalytic effect on the yield of HCl. It was detected that the catalyst hindered the yield of HCl, and silicalite decreased the content of HCl to 1.4 wt.%. However, with the addition of additives or the adjustment of operation conditions, the inhibition to the generation of toxic gases, including PAHs, HCl, NO_x, SO_2, is still limited. In this regard, a gas cleaning system is necessary to be fixed at the end of the pyrolysis equipment, which can remove those hazardous gaseous pollutants and protect the environment or human beings (Roy *et al.*, 1992).

6. Prospects and future challenges

In contrast to the traditional medical wastes treatment method, pyrolysis is an environmentally friendly treatment method for disposing of medical wastes. In view of the large number of medical wastes produced in the world since the outbreak, the application of pyrolysis to reduce the medical waste amount and generate various value-added products has huge potentials (Al-Salem *et al.*, 2017). Bio-oil obtained from the pyrolysis of medical wastes is used to replace fossil fuels. Biochar holds wide application in many fields as a catalyst, adsorbent, anode material, and photocatalytic support. Furthermore, the emission of toxic gases can be solved by an additional gas cleaning system (Isahak *et al.*, 2012).

Consequently, pyrolysis has presented a remarkable economic and environmental performance on the disposal of solid waste. For instance, Elkhalifa *et al.* (2019) compared several treatment methods, including landfilling, composting, incineration, gasification and pyrolysis, to deal with food waste and concluded that pyrolysis process manifested significant economic superiorities owing to the production of biofuel and biochar efficiently. Additionally, Al-Salem *et al.* (2017) analysed the disposal means of plastic solid waste such as incineration, landfilling, gasification and pyrolysis, then pointed out pyrolysis possessed distinct environmental advantages, which was conducive to the reduction of the emission of toxic gases, including dioxins, carbon monoxide, and dioxide emissions. Microwave-assisted pyrolysis presented a better economic benefit due to the decrease in operational costs and heating time. Hong *et al.* (2018) conducted a life-cycle economic and environmental assessment of medical waste pyrolysis. Investment, electricity cost, labour cost, and human health protection were considered. Pyrolysis scenario had a net profit of $189.96/t.

Fig. 2 presents the workflows of medical wastes recovery and recycling systems. The entire workflows are divided into three main processes. The first one is the preliminary collection and classification, then metal, glass, and other recycled materials will be regulated by transportation and stored for the application in the downstream industries after disinfection. Biomass materials will be transported to the related factory as raw materials for pyrolysis, producing valuable bioproducts after condensation.

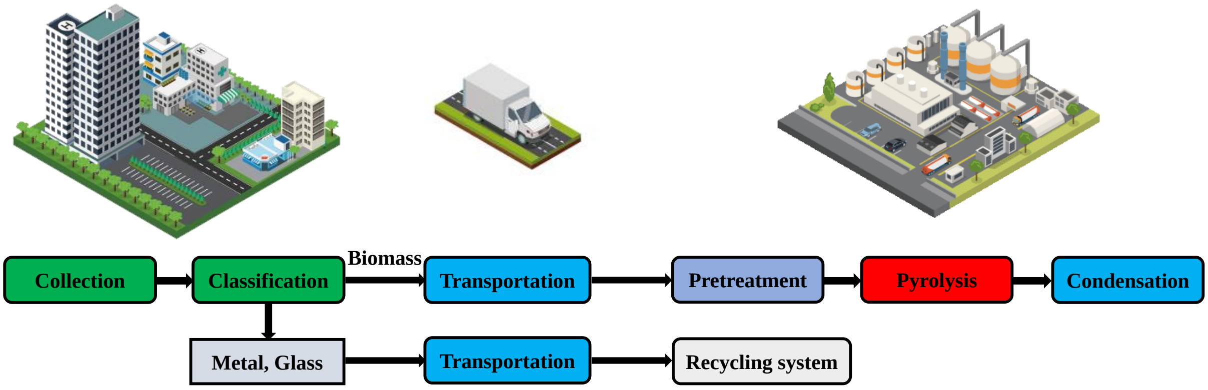

Fig. 2. Workflows of medical wastes recovery and recycling systems.

There are many challenges associated with the medical wastes recovery and recycling systems. Usually, medical wastes are broadly divided into domestic wastes, pathological wastes, infectious wastes, pharmaceutical wastes, chemical wastes, radioactive wastes, and sharp wastes. Most of them do not require disinfection or particular disposal treatment due to its nontoxicity. However, disinfection or special treatment is needed when the toxic medical wastes are mixed with those nontoxic ones. In this regard, the classifying medical wastes and preventing secondary pollution are quite important. In addition, high infectious and strong survivable virus possesses significant risks for the associated workers. Therefore, the cost of disinfection, personnel protection and training is massive. Furthermore, the collection fee and transportation cost are tremendous because of the wide distribution of hospitals (Klemeš *et al.*, 2020).

Since the complex nature and structure of medical wastes, pre-treatment methods are quite important. As mentioned above, high water content does not favour the production of high-grade bio-oil. Furthermore, on the basis of surface chemistry, small particles size is beneficial to improve the reaction efficiency, reduce the yield of PAHs, and promote the production of biofuels (Zhu *et al.*, 2019). Hence, drying and grinding are required to be conducted before pyrolysis. However, pre-treatment is the most expensive process because of the massive energy consumption, which means that energy cost will be huge during the process (Liu *et al.*, 2020).

As shown in **Table 5**, the whole pyrolysis reaction is endothermic. Thus, the energy content of the final products ought to exceed that of the raw material owing to the endothermic characteristics of pyrolysis. At the same time, synergism between different materials in medical waste is significant to reach the exergy surplus. However, in highly heterogeneous mixture environments, the main barrier of synergism is the lack of knowledge in a multi-component complex reaction network of medical waste pyrolysis. The synergistic mechanism of medical wastes pyrolysis needs to be further explored (Lee *et al.*, 2020a).

Fig. 3 shows the primary input and output of the whole recycling systems. However, the high cost is still the main barrier to the promotion and application of the integral medical wastes recovery and recycling systems. Generally, capital-related costs are the chief cost contributed with 30–40% of the input (Sipra *et al.*, 2018). Furthermore, transportation cost is exceptionally high due to the wide distribution of each medical facilities. Many studies have indicated that pyrolysis is an energy-intensive technology, especially for the pre-treatment process, which has been explained before. Reusing the generated biogas has the potential to alleviate the situation. Moreover, labour cost cannot be ignored, which accounts for 12–15% of the entire cost based on some researches (Meyer *et al.*, 2020).

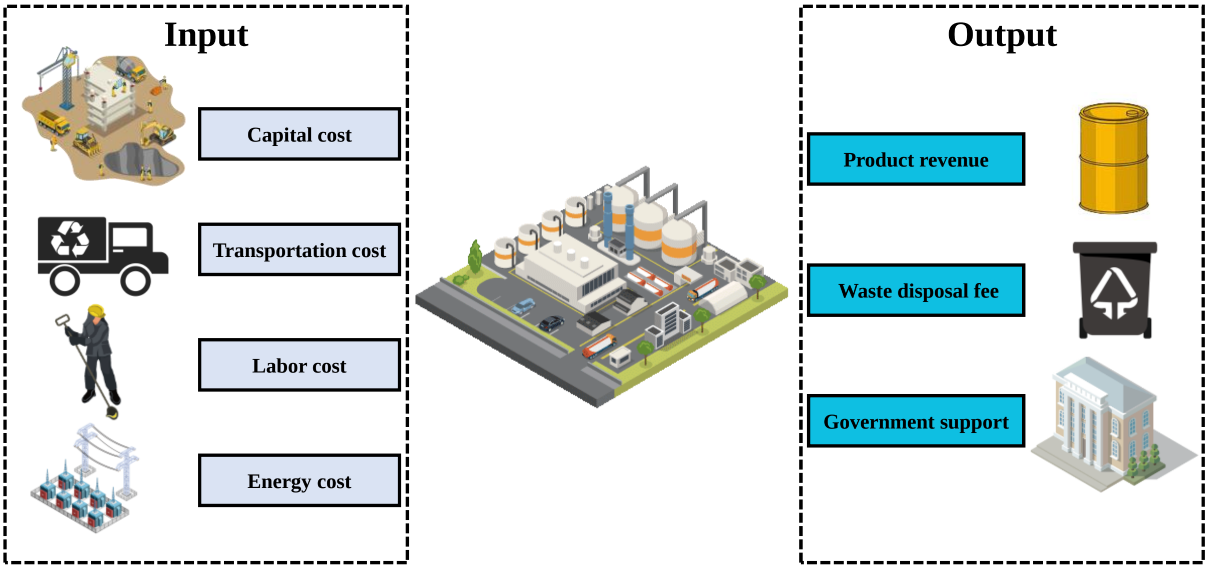

Fig. 3. Input and output of medical wastes recovery and recycling systems.

As for the output of the system, firstly, the product revenue is the major proceeds sources, and the quality and yield of target products are particularly important to ensure and increase the income. Furthermore, the treatment of medical wastes during the pyrolysis can bring the waste disposal fee from the government (Chen *et al.*, 2021). The pyrolysis of medical wastes also produces numerous social, economic and environmental benefits, which will benefit from government support like economic support, tax break, and subsidies for production and infrastructure. Those supports will stimulate the development of relevant industries significantly. In addition, the improvement of equipment, the new design of process and the application of new catalysts are required to maximise economic and environmental benefits via the maximum production of valuable products and the minimum emission of toxic gases (Goh *et al.*, 2019). Furthermore, increasing the scalability and duplication of the facility is also critical to reduce the cost of production by large-scale production. A comprehensive design framework is required to combine many proposals for pyrolysis synergy into the whole synthesis and analysis. All efforts ought to develop an energy-saving medical wastes pyrolysis process, treating medical wastes at low cost, produce valuable products mostly as much as possible, recover valuable resources, and minimise the impacts on the environment (Lu *et al.*, 2020).

Moreover, enhancing the quality and yield of target products is significant too. Catalytic pyrolysis or co-pyrolysis is an effective route to reach the goal. Many catalysts like HZSM-5, CaO, MgO, biochar, and activated carbon have been widely applied into the pyrolysis of plastics, microalgae, lignocellulosic biomass and made remarkable achievements (Chen *et al.*, 2015). Numerous researches have already proved that the accession of catalysts can lower the activation energy, reduce the oxygenous and nitrogenous compounds, decrease the toxic gases emission, and enhance the production of the desired product (Ooi *et al.*, 2019). In addition, the presence of co-feedstocks has a great positive influence on the properties of bio-oil. The addition of raw materials with high volatile matter content is favourable to the enhancement of the formation of bio-oil. In contrast, co-feedstock with high effective hydrogen index (EHI) is conducive to the improvement of the quality of bio-oil (Ahmed and Hameed, 2020). However, more studies need to be conducted to search for the optimal catalyst and co-feedstock for the pyrolysis of medical wastes.

7. Conclusions

This review focuses on the pyrolysis of medical wastes to produce the bioenergy. The literature survey has illustrated that medical wastes possess tremendous potential to be ideal feedstocks for biofuel production by analysing its characteristics and pyrolysis characteristics. Meanwhile, safe and clean pyrolysis technology is an emerging optimal way to reduce the number of medical wastes. It is also one of the possible responses to manage the medical wastes in this global epidemic situation due to its potential advantages of high efficiency, extensive applicability and the generation of high value-added products. The bio-oil from medical wastes pyrolysis possess remarkable properties and great potentials to substitute for fossil fuels. Furthermore, the problem of toxic gases emissions, PAHs and HCl in particular, cannot be overlooked. Proper experiment conditions, appropriate catalysts and gas cleaning system are essential to handle the issue mentioned above. However, the entire medical wastes recovery and recycling systems' cost is still the main bottleneck which inhibited the promotion and application. This can be solved by the improvement in equipment, the design of process, the increase in scalability, duplication of the facility and the enhancement of target products properties via catalytic pyrolysis or co-pyrolysis. Furthermore, it is notable that pyrolysis is an optimal solution to realise the valorisation of medical wastes.

Acknowledgement

We acknowledge the contribution of research development fund of School of Information, Systems and Modelling, Faculty of Engineering and IT, University of Technology Sydney, Ultimo, 2007 NSW, Australia.

References

Abraham, A., Mathew, A.K., Park, H., Choi, O., Sindhu, R., Parameswaran, B., Pandey, A., Park, J.H., Sang, B.-I., 2020. Pretreatment strategies for enhanced biogas production from lignocellulosic biomass. Bioresource Technology 301, 122725.

Ahmed, M.H.M., Batalha, N., Mahmudul, H.M.D., Perkins, G., Konarova, M., 2020. A review on advanced catalytic co-pyrolysis of biomass and hydrogen-rich feedstock: Insights into synergistic effect, catalyst development and reaction mechanism. Bioresource Technology, 123457.

Ahmed, M.J., Hameed, B.H., 2020. Insight into the co-pyrolysis of different blended feedstocks to biochar for the adsorption of organic and inorganic pollutants: A review. Journal of Cleaner Production, 121762.

Al-Salem, S.M., Antelava, A., Constantinou, A., Manos, G., Dutta, A., 2017. A review on thermal and catalytic pyrolysis of plastic solid waste (PSW). Journal of Environmental Management 197, 177-198.

Anca-Couce, A., 2016. Reaction mechanisms and multi-scale modelling of lignocellulosic biomass pyrolysis. Progress in Energy and Combustion Science 53, 41-79.

Anuar Sharuddin, S.D., Abnisa, F., Wan Daud, W.M.A., Aroua, M.K., 2016. A review on pyrolysis of plastic wastes. Energy Conversion and Management 115, 308-326.

Arabiourrutia, M., Lopez, G., Artetxe, M., Alvarez, J., Bilbao, J., Olazar, M., 2020. Waste tyre valorization by catalytic pyrolysis – A review. Renewable and Sustainable Energy Reviews 129, 109932.

Azizi, K., Keshavarz Moraveji, M., Abedini Najafabadi, H., 2018a. A review on bio-fuel production from microalgal biomass by using pyrolysis method. Renewable and Sustainable Energy Reviews 82, 3046-3059.

Azizi, K., Keshavarz Moraveji, M., Abedini Najafabadi, H., 2018b. Simultaneous pyrolysis of microalgae C. vulgaris, wood and polymer: The effect of third component addition. Bioresource Technology 247, 66-72.

Cai, H.-H., Li, S.-D., Tian, G.-R., Wang, H.-B., Wang, J.-H., 2003. Reinforcement of natural rubber latex film by ultrafine calcium carbonate. Journal of Applied Polymer Science 87, 982-985.

Chand Malav, L., Yadav, K.K., Gupta, N., Kumar, S., Sharma, G.K., Krishnan, S., Rezania, S., Kamyab, H., Pham, Q.B., Yadav, S., Bhattacharyya, S., Yadav, V.K., Bach, Q.-V., 2020. A review on municipal solid waste as a renewable source for waste-to-energy project in India: current practices, challenges, and future opportunities. Journal of Cleaner Production, 123227.

Chen, C., Ma, X., He, Y., 2012. Co-pyrolysis characteristics of microalgae Chlorella vulgaris and coal through TGA. Bioresource Technology 117, 264-273.

Chen, D., Yin, L., Wang, H., He, P., 2015. Reprint of: Pyrolysis technologies for municipal solid waste: A review. Waste Management 37, 116-136.

Chen, L., Yu, Z., Fang, S., Dai, M., Ma, X., 2018a. Co-pyrolysis kinetics and behaviors of kitchen waste and chlorella vulgaris using thermogravimetric analyzer and fixed bed reactor. Energy Conversion and Management 165, 45-52.

Chen, L., Yu, Z., Liang, J., Liao, Y., Ma, X., 2018b. Co-pyrolysis of chlorella vulgaris and kitchen waste with different additives using TG-FTIR and Py-GC/MS. Energy Conversion and Management 177, 582-591.

Chen, W.-H., Lin, B.-J., Lin, Y.-Y., Chu, Y.-S., Ubando, A.T., Show, P.L., Ong, H.C., Chang, J.-S., Ho, S.-H., Culaba, A.B., Pétrissans, A., Pétrissans, M., 2021. Progress in biomass torrefaction: Principles, applications and challenges. Progress in Energy and Combustion Science 82, 100887.

Chen, W., Chen, Y., Yang, H., Xia, M., Li, K., Chen, X., Chen, H., 2017. Co-pyrolysis of lignocellulosic biomass and microalgae: Products characteristics and interaction effect. Bioresource Technology 245, 860-868.

Chen, Y., Zhao, R., Xue, J., Li, J., 2013. Generation and distribution of PAHs in the process of medical waste incineration. Waste Management 33, 1165-1173.

Chin, Y.-T., Lin, C., Chang-Chien, G.-P., Wang, Y.-M., 2012. PCDD/F Formation Catalyzed by the Metal Chlorides and Chlorinated Aromatic Compounds in Fly Ash. Aerosol and Air Quality Research 12, 228-236.

Chong, C.T., Mong, G.R., Ng, J.-H., Chong, W.W.F., Ani, F.N., Lam, S.S., Ong, H.C., 2019. Pyrolysis characteristics and kinetic studies of horse manure using thermogravimetric analysis. Energy Conversion and Management 180, 1260-1267.

Dai, M., Yu, Z., Fang, S., Ma, X., 2019. Behaviors, product characteristics and kinetics of catalytic co-pyrolysis spirulina and oil shale. Energy Conversion and Management 192, 1-10.

Dash, A., Kumar, S., Singh, R.K., 2015. Thermolysis of Medical Waste (Waste Syringe) to Liquid Fuel Using Semi Batch Reactor. Waste and Biomass Valorization 6, 507-514.

Deng, N., Cui, W.-q., Wang, W.-w., Zhang, Q., Zhang, Y.-f., Ma, H.-t., 2014. Experimental study on co-pyrolysis characteristics of typical medical waste compositions. Journal of Central South University 21, 4613-4622.

Deng, N., Wang, W.-w., Chen, G.-w., Zhang, Y., Zhang, Y.-f., Ma, H.-t., 2013. Pyrolysis characteristics of rubber compositions in medical waste. Journal of Central South University 20, 2466-2471.

Deng, N., Zhang, Y.-f., Wang, Y., 2008. Thermogravimetric analysis and kinetic study on pyrolysis of representative medical waste composition. Waste Management 28, 1572-1580.

Dhyani, V., Bhaskar, T., 2018. A comprehensive review on the pyrolysis of lignocellulosic biomass. Renewable Energy 129, 695-716.

Di Maria, F., Beccaloni, E., Bonadonna, L., Cini, C., Confalonieri, E., La Rosa, G., Milana, M.R., Testai, E., Scaini, F., 2020. Minimization of spreading of SARS-CoV-2 via household waste produced by subjects affected by COVID-19 or in quarantine. Science of The Total Environment 743, 140803.

Ding, Z., Chen, H., Liu, J., Cai, H., Evrendilek, F., Buyukada, M., 2021. Pyrolysis dynamics of two medical plastic wastes: Drivers, behaviors, evolved gases, reaction mechanisms, and pathways. Journal of Hazardous Materials 402, 123472.

Dollimore, D., Tong, P., Alexander, K.S., 1996. The kinetic interpretation of the decomposition of calcium carbonate by use of relationships other than the Arrhenius equation. Thermochimica Acta 282-283, 13-27.

Duan, P., Jin, B., Xu, Y., Wang, F., 2015. Co-pyrolysis of microalgae and waste rubber tire in supercritical ethanol. Chemical Engineering Journal 269, 262-271.

Dudkina, L.M., Gerasimov, G.Y., Khaskhachikh, V.V., 2019. Thermogravimetric and Kinetic Study of Pyrolysis of Chlorine-Containing Medical Waste. IOP Conference Series: Earth and Environmental Science 272, 022117.

Elkhalifa, S., Al-Ansari, T., Mackey, H.R., McKay, G., 2019. Food waste to biochars through pyrolysis: A review. Resources, Conservation and Recycling 144, 310-320.

Fakayode, O.A., Aboagarib, E.A.A., Zhou, C., Ma, H., 2020. Co-pyrolysis of lignocellulosic and macroalgae biomasses for the production of biochar – A review. Bioresource Technology 297, 122408.

Fang, S., Jiang, L., Li, P., Bai, J., Chang, C., 2020. Study on pyrolysis products characteristics of medical waste and fractional condensation of the pyrolysis oil. Energy 195, 116969.

Fang, S., Yu, Z., Ma, X., Lin, Y., Chen, L., Liao, Y., 2018. Analysis of catalytic pyrolysis of municipal solid waste and paper sludge using TG-FTIR, Py-GC/MS and DAEM (distributed activation energy model). Energy 143, 517-532.

Fattah, I.M.R., Ong, H.C., Mahlia, T.M.I., Mofijur, M., Silitonga, A.S., Rahman, S.M.A., Ahmad, A., 2020. State of the Art of Catalysts for Biodiesel Production. Frontiers in Energy Research 8.

Font, R., Aracil, I., Fullana, A., Martín-Gullón, I., Conesa, J.A., 2003. Semivolatile compounds in pyrolysis of polyethylene. Journal of Analytical and Applied Pyrolysis 68-69, 599-611.

Gao, N., Sipra, A.T., Quan, C., 2020. Thermogravimetric analysis and pyrolysis product characterization of municipal solid waste using sludge fly ash as additive. Fuel 281, 118572.

Gerasimov, G., Khaskhachikh, V., Kornilieva, V., Tarasov, G., 2019. Study of pyrolysis of components and mixture of medical waste. Chemical Engineering Transactions 76, 1423-1428.

Goh, B.H.H., Ong, H.C., Cheah, M.Y., Chen, W.-H., Yu, K.L., Mahlia, T.M.I., 2019. Sustainability of direct biodiesel synthesis from microalgae biomass: A critical review. Renewable and Sustainable Energy Reviews 107, 59-74.

Graikos, A., Voudrias, E., Papazachariou, A., Iosifidis, N., Kalpakidou, M., 2010. Composition and production rate of medical waste from a small producer in Greece. Waste Management 30, 1683-1689.

Hong, J., Zhan, S., Yu, Z., Hong, J., Qi, C., 2018. Life-cycle environmental and economic assessment of medical waste treatment. Journal of Cleaner Production 174, 65-73.

Hoque, M.M., Rahman, M.T.U., 2020. Landfill area estimation based on solid waste collection prediction using ANN model and final waste disposal options. Journal of Cleaner Production 256, 120387.

Hunsinger, H., Jay, K., Vehlow, J., 2002. Formation and destruction of PCDD/F inside a grate furnace. Chemosphere 46, 1263-1272.

Ilyas, S., Srivastava, R.R., Kim, H., 2020. Disinfection technology and strategies for COVID-19 hospital and bio-medical waste management. Science of The Total Environment, 141652.

Imtenan, S., Varman, M., Masjuki, H.H., Kalam, M.A., Sajjad, H., Arbab, M.I., Rizwanul Fattah, I.M., 2014. Impact of low temperature combustion attaining strategies on diesel engine emissions for diesel and biodiesels: A review. Energy Conversion and Management 80, 329-356.

Isahak, W.N.R.W., Hisham, M.W.M., Yarmo, M.A., Yun Hin, T.-y., 2012. A review on bio-oil production from biomass by using pyrolysis method. Renewable and Sustainable Energy Reviews 16, 5910-5923.

Jang, Y.-C., Lee, C., Yoon, O.-S., Kim, H., 2006. Medical waste management in Korea. Journal of Environmental Management 80, 107-115.

Johns Hopkins University (JHU), 2021. COVID-19 Dashboard by the Center for Systems Science and Engineering (CSSE) at Johns Hopkins University (JHU). https://coronavirus.jhu.edu/map.html. Date accessed: 13th January, 2021.

Jung, S., Lee, S., Dou, X., Kwon, E.E., 2020. Valorization of disposable COVID-19 mask through the thermo-chemical process. Chemical Engineering Journal, 126658.

Kaminsky, W., Kim, J.-S., 1999. Pyrolysis of mixed plastics into aromatics. Journal of Analytical and Applied Pyrolysis 51, 127-134.

Karayildirim, T., Yanik, J., Yuksel, M., Saglam, M., Vasile, C., Bockhorn, H., 2006. The effect of some fillers on PVC degradation. Journal of Analytical and Applied Pyrolysis 75, 112-119.

Kargar, S., Paydar, M.M., Safaei, A.S., 2020a. A reverse supply chain for medical waste: A case study in Babol healthcare sector. Waste Management 113, 197-209.

Kargar, S., Pourmehdi, M., Paydar, M.M., 2020b. Reverse logistics network design for medical waste management in the epidemic outbreak of the novel coronavirus (COVID-19). Science of The Total Environment 746, 141183.

Kim, K.-H., Jahan, S.A., Kabir, E., Brown, R.J.C., 2013. A review of airborne polycyclic aromatic hydrocarbons (PAHs) and their human health effects. Environment International 60, 71-80.

Kim, S., 2001. Pyrolysis kinetics of waste PVC pipe. Waste Management 21, 609-616.

Klemeš, J.J., Fan, Y.V., Tan, R.R., Jiang, P., 2020. Minimising the present and future plastic waste, energy and environmental footprints related to COVID-19. Renewable and Sustainable Energy Reviews 127, 109883.

Kumar, R., Strezov, V., Weldekidan, H., He, J., Singh, S., Kan, T., Dastjerdi, B., 2020a. Lignocellulose biomass pyrolysis for bio-oil production: A review of biomass pre-treatment methods for production of drop-in fuels. Renewable and Sustainable Energy Reviews 123, 109763.

Kumar, V., Singh, S.B., Singh, S., 2020b. COVID-19: Environment concern and impact of Indian medicinal system. Journal of Environmental Chemical Engineering 8, 104144.

Lee, D.-J., Lu, J.-S., Chang, J.-S., 2020a. Pyrolysis synergy of municipal solid waste (MSW): A review. Bioresource Technology, 123912.

Lee, S., Kim, T., Lee, E., Lee, C., Kim, H., Rhee, H., Park, S.Y., Son, H.-J., Yu, S., Park, J.W., Choo, E.J., Park, S., Loeb, M., Kim, T.H., 2020b. Clinical Course and Molecular Viral Shedding Among Asymptomatic and Symptomatic Patients With SARS-CoV-2 Infection in a Community Treatment Center in the Republic of Korea. JAMA Internal Medicine 180, 1447-1452.

Lee, X.J., Ong, H.C., Gan, Y.Y., Chen, W.-H., Mahlia, T.M.I., 2020c. State of art review on conventional and advanced pyrolysis of macroalgae and microalgae for biochar, bio-oil and bio-syngas production. Energy Conversion and Management 210, 112707.

Li, F., Srivatsa, S.C., Bhattacharya, S., 2019. A review on catalytic pyrolysis of microalgae to high-quality bio-oil with low oxygeneous and nitrogenous compounds. Renewable and Sustainable Energy Reviews 108, 481-497.

Li, X., Zhang, H., Li, J., Su, L., Zuo, J., Komarneni, S., Wang, Y., 2013. Improving the aromatic production in catalytic fast pyrolysis of cellulose by co-feeding low-density polyethylene. Applied Catalysis A: General 455, 114-121.

Lin, H.-T., Huang, M.-S., Luo, J.-W., Lin, L.-H., Lee, C.-M., Ou, K.-L., 2010. Hydrocarbon fuels produced by catalytic pyrolysis of hospital plastic wastes in a fluidizing cracking process. Fuel Processing Technology 91, 1355-1363.

Liu, S., Yu, J., Bikane, K., Chen, T., Ma, C., Wang, B., Sun, L., 2018. Rubber pyrolysis: Kinetic modeling and vulcanization effects. Energy 155, 215-225.

Liu, Y., Zhai, Y., Li, S., Liu, X., Liu, X., Wang, B., Qiu, Z., Li, C., 2020. Production of bio-oil with low oxygen and nitrogen contents by combined hydrothermal pretreatment and pyrolysis of sewage sludge. Energy 203, 117829.

Lu, J.-S., Chang, Y., Poon, C.-S., Lee, D.-J., 2020. Slow pyrolysis of municipal solid waste (MSW): A review. Bioresource Technology, 123615.

Ma, D., Feng, Q., Chen, B., Cheng, X., Chen, K., Li, J., 2019. Insight into chlorine evolution during hydrothermal carbonization of medical waste model. Journal of Hazardous Materials 380, 120847.

Makarichi, L., Jutidamrongphan, W., Techato, K.-a., 2018. The evolution of waste-to-energy incineration: A review. Renewable and Sustainable Energy Reviews 91, 812-821.

Marcilla, A., Beltrán, M., 1995. Thermogravimetric kinetic study of poly(vinyl chloride) pyrolysis. Polymer Degradation and Stability 48, 219-229.

Masum, B.M., Kalam, M.A., Masjuki, H.H., Palash, S.M., Fattah, I.M.R., 2014. Performance and emission analysis of a multi cylinder gasoline engine operating at different alcohol–gasoline blends. RSC Advances 4, 27898-27904.

McNeill, I.C., Memetea, L., Cole, W.J., 1995. A study of the products of PVC thermal degradation. Polymer Degradation and Stability 49, 181-191.

Meyer, P.A., Snowden-Swan, L.J., Jones, S.B., Rappé, K.G., Hartley, D.S., 2020. The effect of feedstock composition on fast pyrolysis and upgrading to transportation fuels: Techno-economic analysis and greenhouse gas life cycle analysis. Fuel 259, 116218.

Mofijur, M., Fattah, I.M.R., Alam, M.A., Islam, A.B.M.S., Ong, H.C., Rahman, S.M.A., Najafi, G., Ahmed, S.F., Uddin, M.A., Mahlia, T.M.I., 2021. Impact of COVID-19 on the social, economic, environmental and energy domains: Lessons learnt from a global pandemic. Sustainable Production and Consumption 26, 343-359.

Mohee, R., 2005. Medical wastes characterisation in healthcare institutions in Mauritius. Waste Management 25, 575-581.

Mohseni-Bandpei, A., Majlesi, M., Rafiee, M., Nojavan, S., Nowrouz, P., Zolfagharpour, H., 2019. Polycyclic aromatic hydrocarbons (PAHs) formation during the fast pyrolysis of hazardous health-care waste. Chemosphere 227, 277-288.

Moreira, A.M.M., Günther, W.M.R., 2013. Assessment of medical waste management at a primary health-care center in São Paulo, Brazil. Waste Management 33, 162-167.

Ong, H.C., Chen, W.-H., Farooq, A., Gan, Y.Y., Lee, K.T., Ashokkumar, V., 2019. Catalytic thermochemical conversion of biomass for biofuel production: A comprehensive review. Renewable and Sustainable Energy Reviews 113, 109266.

Ong, H.C., Chen, W.-H., Singh, Y., Gan, Y.Y., Chen, C.-Y., Show, P.L., 2020a. A state-of-the-art review on thermochemical conversion of biomass for biofuel production: A TG-FTIR approach. Energy Conversion and Management 209, 112634.

Ong, H.C., Tiong, Y.W., Goh, B.H.H., Gan, Y.Y., Mofijur, M., Fattah, I.M.R., Chong, C.T., Alam, M.A., Lee, H.V., Silitonga, A.S., Mahlia, T.M.I., 2020b. Recent advances in biodiesel production from agricultural products and microalgae using ionic liquids: Opportunities and challenges. Energy Conversion and Management, 113647.

Onwudili, J.A., Insura, N., Williams, P.T., 2009. Composition of products from the pyrolysis of polyethylene and polystyrene in a closed batch reactor: Effects of temperature and residence time. Journal of Analytical and Applied Pyrolysis 86, 293-303.

Ooi, X.Y., Gao, W., Ong, H.C., Lee, H.V., Juan, J.C., Chen, W.H., Lee, K.T., 2019. Overview on catalytic deoxygenation for biofuel synthesis using metal oxide supported catalysts. Renewable and Sustainable Energy Reviews 112, 834-852.

Paraschiv, M., Kuncser, R., Tazerout, M., Prisecaru, T., 2015. New energy value chain through pyrolysis of hospital plastic waste. Applied Thermal Engineering 87, 424-433.

Patrício Silva, A.L., Prata, J.C., Walker, T.R., Campos, D., Duarte, A.C., Soares, A.M.V.M., Barcelò, D., Rocha-Santos, T., 2020. Rethinking and optimising plastic waste management under COVID-19 pandemic: Policy solutions based on redesign and reduction of single-use plastics and personal protective equipment. Science of The Total Environment 742, 140565.

Peng, J., Wu, X., Wang, R., Li, C., Zhang, Q., Wei, D., 2020. Medical waste management practice during the 2019-2020 novel coronavirus pandemic: Experience in a general hospital. American journal of infection control 48, 918-921.

Qin, L., Han, J., Zhao, B., Chen, W., Xing, F., 2018a. The kinetics of typical medical waste pyrolysis based on gaseous evolution behaviour in a micro-fluidised bed reactor. Waste Management & Research 36, 1073-1082.

Qin, L., Han, J., Zhao, B., Wang, Y., Chen, W., Xing, F., 2018b. Thermal degradation of medical plastic waste by in-situ FTIR, TG-MS and TG-GC/MS coupled analyses. Journal of Analytical and Applied Pyrolysis 136, 132-145.

Rahman, S.M.A., Fattah, I.M.R., Maitra, S., Mahlia, T.M.I., 2021. A ranking scheme for biodiesel underpinned by critical physicochemical properties. Energy Conversion and Management 229, 113742.

Roy, V., de Caumia, B., Roy, C., 1992. Development of a gas-cleaning system for a scrap-tire vacuum-pyrolysis plant. Gas Separation & Purification 6, 83-87.

Saeidi-Mobarakeh, Z., Tavakkoli-Moghaddam, R., Navabakhsh, M., Amoozad-Khalili, H., 2020. A bi-level and robust optimization-based framework for a hazardous waste management problem: A real-world application. Journal of Cleaner Production 252, 119830.

Samuel, O.D., Okwu, M.O., Oyejide, O.J., Taghinezhad, E., Afzal, A., Kaveh, M., 2020. Optimizing biodiesel production from abundant waste oils through empirical method and grey wolf optimizer. Fuel 281, 118701.

Sharifzadeh, M., Sadeqzadeh, M., Guo, M., Borhani, T.N., Murthy Konda, N.V.S.N., Garcia, M.C., Wang, L., Hallett, J., Shah, N., 2019. The multi-scale challenges of biomass fast pyrolysis and bio-oil upgrading: Review of the state of art and future research directions. Progress in Energy and Combustion Science 71, 1-80.

Sharma, H.B., Vanapalli, K.R., Cheela, V.R.S., Ranjan, V.P., Jaglan, A.K., Dubey, B., Goel, S., Bhattacharya, J., 2020. Challenges, opportunities, and innovations for effective solid waste management during and post COVID-19 pandemic. Resources, Conservation and Recycling 162, 105052.

Singh, N., Tang, Y., Zhang, Z., Zheng, C., 2020. COVID-19 waste management: Effective and successful measures in Wuhan, China. Resources, Conservation and Recycling 163, 105071.

Singh, T.S., Rajak, U., Samuel, O.D., Chaurasiya, P.K., Natarajan, K., Verma, T.N., Nashine, P., 2021. Optimization of performance and emission parameters of direct injection diesel engine fuelled with microalgae Spirulina (L.) – Response surface methodology and full factorial method approach. Fuel 285, 119103.

Sipra, A.T., Gao, N., Sarwar, H., 2018. Municipal solid waste (MSW) pyrolysis for bio-fuel production: A review of effects of MSW components and catalysts. Fuel Processing Technology 175, 131-147.

Som, U., Rahman, F., Hossain, S., 2018. Recovery of pyrolytic oil from thermal pyrolysis of medical waste. Journal of Engineering Sciences 5, H5-H8.

Suchocki, T., Witanowski, Ł., Lampart, P., Kazimierski, P., Januszewicz, K., Gawron, B., 2021. Experimental investigation of performance and emission characteristics of a miniature gas turbine supplied by blends of kerosene and waste tyre pyrolysis oil. Energy 215, 119125.

van Doremalen, N., Bushmaker, T., Morris, D.H., Holbrook, M.G., Gamble, A., Williamson, B.N., Tamin, A., Harcourt, J.L., Thornburg, N.J., Gerber, S.I., Lloyd-Smith, J.O., de Wit, E., Munster, V.J., 2020. Aerosol and Surface Stability of SARS-CoV-2 as Compared with SARS-CoV-1. New England Journal of Medicine 382, 1564-1567.

Wang, J., Pan, L., Tang, S., Ji, J.S., Shi, X., 2020a. Mask use during COVID-19: A risk adjusted strategy. Environmental Pollution 266, 115099.

Wang, J., Shen, J., Ye, D., Yan, X., Zhang, Y., Yang, W., Li, X., Wang, J., Zhang, L., Pan, L., 2020b. Disinfection technology of hospital wastes and wastewater: Suggestions for disinfection strategy during coronavirus Disease 2019 (COVID-19) pandemic in China. Environmental Pollution 262, 114665.

Wang, S., Dai, G., Yang, H., Luo, Z., 2017. Lignocellulosic biomass pyrolysis mechanism: A state-of-the-art review. Progress in Energy and Combustion Science 62, 33-86.

Wang, S., Lin, X., Li, Z., Yi, W., Bai, X., 2018. Thermal and Kinetic Behaviors of Corn Stover and Polyethylene in Catalytic Co-pyrolysis. BioResources; Vol 13, No 2 (2018).

Wang, X., Zhao, B., Yang, X., 2016. Co-pyrolysis of microalgae and sewage sludge: Biocrude assessment and char yield prediction. Energy Conversion and Management 117, 326-334.

Wei, Y., Cui, M., Ye, Z., Guo, Q., 2020. Environmental challenges from the increasing medical waste since SARS outbreak. Journal of Cleaner Production, 125246.

Windfeld, E.S., Brooks, M.S.-L., 2015. Medical waste management – A review. Journal of Environmental Management 163, 98-108.

Wu, C., Wang, Z., Huang, J., Williams, P.T., 2013. Pyrolysis/gasification of cellulose, hemicellulose and lignin for hydrogen production in the presence of various nickel-based catalysts. Fuel 106, 697-706.

Wu, L., Jiang, X., Lv, G., Li, X., Yan, J., 2020. Interactive effect of the sorted components of solid recovered fuel manufactured from municipal solid waste by thermogravimetric and kinetic analysis. Waste Management 102, 270-280.

Xiao, R., Yang, W., Cong, X., Dong, K., Xu, J., Wang, D., Yang, X., 2020. Thermogravimetric analysis and reaction kinetics of lignocellulosic biomass pyrolysis. Energy 201, 117537.

Xie, R., Li, W.-j., Li, J., Wu, B.-l., Yi, J.-q., 2009. Emissions investigation for a novel medical waste incinerator. Journal of Hazardous Materials 166, 365-371.

Xiong, Z., Li, H., Zhao, Z., Wu, C., Chen, Y., 2006. An expermiental study on pyrolysis and incineration of medical wastes. Techniques and Equipment for Environmental Pollution Control 7, 92-95.

Yan, J., Zhu, H., Jiang, X., Shen, X., Cen, K., 2008. Pyrolysis and gasification characteristic of multi-component medical waste. Journal o f Zhejiang University 42, 885-889.

Yan, J.H., Zhu, H.M., Jiang, X.G., Chi, Y., Cen, K.F., 2009. Analysis of volatile species kinetics during typical medical waste materials pyrolysis using a distributed activation energy model. Journal of Hazardous Materials 162, 646-651.

Yang, C., Li, R., Zhang, B., Qiu, Q., Wang, B., Yang, H., Ding, Y., Wang, C., 2019. Pyrolysis of microalgae: A critical review. Fuel Processing Technology 186, 53-72.

Yang, L., Yu, X., Wu, X., Wang, J., Yan, X., Jiang, S., Chen, Z., 2021. Emergency response to the explosive growth of health care wastes during COVID-19 pandemic in Wuhan, China. Resources, Conservation and Recycling 164, 105074.

Yatsunthea, T., Chaiyat, N., 2020. A very small power plant – Municipal waste of the organic Rankine cycle and incinerator from medical and municipal wastes. Thermal Science and Engineering Progress 18, 100555.

Zamri, M.F.M.A., Hasmady, S., Akhiar, A., Ideris, F., Shamsuddin, A.H., Mofijur, M., Fattah, I.M.R., Mahlia, T.M.I., 2021. A comprehensive review on anaerobic digestion of organic fraction of municipal solid waste. Renewable and Sustainable Energy Reviews 137, 110637.

Zhang, L., Wu, L., Tian, F., Wang, Z., 2016. Retrospection-Simulation-Revision: approach to the analysis of the composition and characteristics of medical waste at a disaster relief site. PLOS ONE 11, e0159261.

Zhang, Y., Cui, Y., Liu, S., Fan, L., Zhou, N., Peng, P., Wang, Y., Guo, F., Min, M., Cheng, Y., Liu, Y., Lei, H., Chen, P., Li, B., Ruan, R., 2020. Fast microwave-assisted pyrolysis of wastes for biofuels production - A review. Bioresource Technology 297, 122480.

Zhao, R., Wang, X., Liu, L., Li, P., Tian, L., 2019. Slow pyrolysis characteristics of bamboo subfamily evaluated through kinetics and evolved gases analysis. Bioresource Technology 289, 121674.

Zhou, H., Wu, C., Onwudili, J.A., Meng, A., Zhang, Y., Williams, P.T., 2015. Polycyclic aromatic hydrocarbons (PAH) formation from the pyrolysis of different municipal solid waste fractions. Waste Management 36, 136-146.

Zhou, J., Gui, B., Qiao, Y., Zhang, J., Wang, W., Yao, H., Yu, Y., Xu, M., 2016. Understanding the pyrolysis mechanism of polyvinylchloride (PVC) by characterizing the chars produced in a wire-mesh reactor. Fuel 166, 526-532.

Zhou, Y., Liu, Y., Jiang, W., Shao, L., Zhang, L., Feng, L., 2019. Effects of pyrolysis temperature and addition proportions of corncob on the distribution of products and potential energy recovery during the preparation of sludge activated carbon. Chemosphere 221, 175-183.

Zhu, H., Chen, W., Jiang, X., Yan, J., Chi, Y., 2015. Study on HCl removal for medical waste pyrolysis and combustion using a TG-FTIR analyzer. Frontiers of Environmental Science & Engineering 9, 230-239.

Zhu, H.M., Yan, J.H., Jiang, X.G., Lai, Y.E., Cen, K.F., 2008. Study on pyrolysis of typical medical waste materials by using TG-FTIR analysis. Journal of Hazardous Materials 153, 670-676.

Zhu, X., Luo, Z., Diao, R., Zhu, X., 2019. Combining torrefaction pretreatment and co-pyrolysis to upgrade biochar derived from bio-oil distillation residue and walnut shell. Energy Conversion and Management 199, 111970.

Zolfagharpour, H.R., Nowrouz, P., Mohseni-Bandpei, A., Majlesi, M., Rafiee, M., Khalili, F., 2020. Influences of temperature, waste size and residence time on the generation of polycyclic aromatic hydrocarbons during the fast pyrolysis of medical waste. Caspian Journal of Environmental Sciences 18, 47-57.

Zroychikov, N.A., Fadeev, S.A., Bezruky, P.P., 2018. Development of an environmentally safe process for medical waste disposal based on pyrolysis. Thermal Engineering 65, 833-840.