Journal of Cleaner Production 174 (2018) 65–73

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Life-cycle environmental and economic assessment of medical waste treatment

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A R T I C L E   I N F O

Article history:
Received 21 July 2017
Received in revised form
14 October 2017
Accepted 18 October 2017
Available online 21 October 2017

Keywords:
Medical waste
Life cycle assessment
Life cycle costing
Pyrolysis
Chemical disinfection
Steam sterilization

A B S T R A C T

The environmental and economic impacts of three medical waste disposal scenarios (i.e., pyrolysis, steam sterilization, and chemical disinfection) were quantified via a cost-coupled life cycle assessment to quantify the effective technique for medical waste disposal. Results show that steam sterilization and chemical disinfection scenarios exhibit the highest overall environmental and lowest economic impacts, respectively, because of the differences in energy consumption. The overall economic burden is attributed to the cost of investment, labor, electricity, and human health protection for each scenario, whereas the environmental burden comes from energy and chemical production processes. The contribution of hydrogen chloride emission to the overall environmental burden is relatively low, although the direct hydrogen chloride emission is significantly higher when generated from medical waste pyrolysis than from municipal solid waste and industrial hazardous waste incineration. However, opposite results are observed for direct mercury emission. Effective measures to reduce the environmental burden include improving electricity and diesel consumption efficiency, reducing the use of chemicals (e.g., sodium hydroxide, lime, and chlorine oxide), selecting clean energy, and providing medical waste incineration with energy recovery. Similarly, effective measures to reduce the economic impact include optimizing labor and investment costs and electricity consumption.

1. Introduction

Medical waste (MW) refers to various potentially infectious materials that can pose potential health risks to the public (Hossain et al., 2011). The improper management of MW is common in China due to the high cost of MW disposal, although people are well aware of the potential health risk. Approximately two-thirds of MW is currently disposed in unsafe ways (China Statistical Yearbook, 2016; MEPC, 2016). Therefore, decision makers have recently focused on building MW disposal plants to meet the requirements for MW management. In this study, a cost-coupled life cycle assessment on commonly used MW treatment technologies in China were conducted to provide useful information regarding the establishment, reconstruction, or technological transformation of MW disposal plants.

To date, MW disposal is primarily implemented worldwide using landfill, microwave, chemical disinfection, incineration, shredding, compacting, and steam sterilization technologies (PATH, 2005; Windfeld and Brooks, 2015). However, these methods cause several undesirable effects (PATH, 2005) as follows: 1) a variety of toxic substances (e.g., pathogens and radioactive substances) may penetrate the soil or underground water in landfill; 2) certain volatile chemicals and large-mass wastes are hardly disposed by microwave technology; 3) mercury compounds, volatile organic compounds, and large pathological waste are unsuitable for chemical disinfection technology; 4) waste remains infectious for shredding and compacting technologies; and 5) significant energy requirements are required for steam sterilization. The advantages of the MW disposal technologies vis-à-vis their disadvantages have been strongly debated on during the last decades. Accordingly, a systematic approach is required to quantify the effective technique for MW disposal.

Life cycle assessment (LCA)-coupled life cycle costing (LCC), a systematic and effective approach for quantifying the

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https://doi.org/10.1016/j.jclepro.2017.10.206

Table 1
Characteristics of the medical waste disposal plant and medical waste considered in the study.

		Unit	Value
Composition	Plastics	%	45
	Wastepaper & cotton yarn	%	13
	Glass	%	10
	Others (needles, surgical waste, drugs etc)	%	12
	Water content	%	20
Temperature	Steam sterilization	°C	130–140
	Pyrolysis	°C	900–1100
Residence time of chemical disinfection system		min	130
Life time of plants		Years	40
Capacity		t/d	3–5

environmental and economic impact of targeted process, activity, or product during its whole life cycle, is widely applied in eco-design, product improvement, decision-making, and policy formulation. Limited LCAs on MW have been conducted except for Qing et al. (2006), Zhao et al. (2009), Soares et al. (2013), Chen et al. (2014), and Koo and Jeong (2015). Qing et al. (2006) conducted an LCA analysis in China without observing ISO standards (2006a,b). Zhao et al. (2009) reported an LCA on MW disposal with autoclave, incineration, and landfill technologies based on a dated operation report in 1998 and theory-derived data. Soares et al. (2013) performed a LCA analysis of MW treatment with microwave, autoclave, and lime disinfection technologies based on laboratory data. Moreover, Chen et al. (2014) conducted a LCA-based theoretical framework for MW disposal. No actual LCA of MW management was quantified. Koo and Jeong (2015) conducted further research on MW incineration with and without heat recovery, steam sterilization, and microwave disinfection technologies. However, only four categories (i.e., global warming, photochemical oxidation, acidification, and human toxicity) were discussed. Additionally, no detailed on-site data on direct air and water emissions, which are significant information on the MW disposal, were reported. Moreover, studies on LCA comparisons among various MW disposal technologies were conducted regardless of uncertainty in information. Furthermore, no research was carried out on LCC for MW disposal considering the external cost (e.g., human health cost, eco-remediation cost). In addition, significant differences in LCA results for MW disposal were observed because of a range of factors (e.g., background data, energy type, technology, plant size, and management attention). Therefore, an LCA-coupled LCC on three commonly used MW treatment technologies in China (i.e., pyrolysis, chemical disinfection, and steam sterilization) based on recent and actual company monitoring data were conducted in this study to address the abovementioned requirements. The key factors and improvements contributing to the overall environmental and economic effects from each scenario were identified. Monte-Carlo simulation was used to decide on the environmentally friendly MW disposal technology.

2. Scope definition

2.1. Functional unit and system boundary

The disposal of one tone of MW was selected as the functional unit, which is the base for life-cycle inventory comparison. System boundaries were set by applying a gate-to-gate approach, which is a partial LCA looking at only MW disposal process in the entire MW management chain. Three commonly used MW disposal technologies in China, namely, pyrolysis, chemical disinfection, and steam sterilization were involved. Table 1 represents the main characteristics of the MW disposal scenarios, whereas Fig. 1 shows the system boundary of the scenarios. The MW collection and storage were excluded because they were common to each scenario, which involves raw materials and energy production, transportation, direct emissions, and waste disposal. Specifically, the vertical shaft pyrolysis furnace in the pyrolysis scenario was adopted. The furnace was mainly composed of pyrolysis gasifier, pyrolysis gas combustion chamber, gas heat exchange, rotary grate extrusion, and slag removal. In addition, activated carbon adsorption and bag filter were used for air control. In the chemical disinfection scenario, primary crushing, sterilizing with disinfectant powder, and pulverizing system were used. In the steam sterilization scenario, high-temperature steam sterilization and crush processes were utilized. High-efficiency exhaust filter and activated carbon adsorption were used to remove air pollutants in the two latter scenarios. Additionally, disinfected solid waste was disposed of in sanitary landfill site as general industry solid wastes, whereas the waste activated carbon, waste filter, and the sludge generated from wastewater were disposed of in a hazardous waste incineration site as industrial hazardous waste.

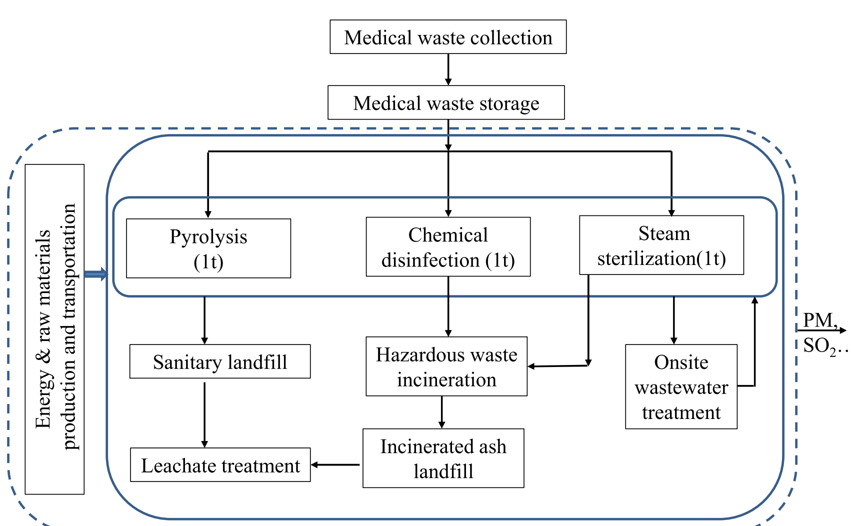

Fig. 1. System boundary.

Table 2
Life cycle inventory of each scenario. Values are presented per functional unit.

	Substance	Unit	Amount		
			Pyrolysis	Chemical disinfection	Steam sterilization
Raw materials	Fresh water	t	2.9	0.48	2.14
	Land occupation	m^2	0.09	0.1	0.08
	Lime	kg	34	0.07	–
	Organic chemicals	g	–	3.75	–
	Sodium hydroxide	t	0.17	–	–
	Sodium hypochlorite	kg	2.78	–	–
	Chlorine dioxide	kg	–	3.76	–
	Chlorine	kg	–	–	0.37
	Activated carbon	kg	13	2.42	0.26
	Diesel	kg	8.8	–	48.09
	Electricity	kWh	238.89	420.61	774.97
Solid Waste	Sanitary landfill	t	0.06	1.08	1.02
	Hazardous waste incineration	kg	–	4.68	0.26
Wastewater		m^3	5.64	1.31	6.74
Direct air emissions	Sulfur dioxide	kg	0.15	–	0.22
	Nitrogen oxides	kg	0.24	–	0.06
	Carbon monoxide	g	0.52	–	–
	Hydrogen fluoride	g	1.97	–	–
	Hydrogen chloride	kg	0.45	–	3.28
	Copper	g	0.93	–	–
	Lead	mg	0.03	–	–
	Nickel	g	6.0	–	–
	Cadmium	mg	0.51	–	–
	Chromium	g	3.74	–	–
	Manganese	g	0.93	–	–
	Tin	mg	0.2	–	–
	Mercury	mg	3.6	–	0.16
	Antimony	mg	4.94	–	–
	Dioxins (TEQ)	μg	0.25	–	–
	Particulates	g	0.11	23.33	5.74
	Carbon dioxide	t	0.03	–	0.15
	Ammonia	g	–	0.43	0.28
	Volatile organic compounds	g	–	5.57	–
Direct soil emissions	Ammonia	g	–	1.78	0.14
	Petroleum oil	mg	–	–	43.48
	Mercury	mg	–	–	0.01
	Biogenic oil	g	–	–	1.67
	Phenol	mg	–	–	20.59
	Chromium	mg	–	–	2.17
	Chloride	g	–	0.10	7.83
	Phosphorus	mg	–	12.79	–

2.2. Methodology

The LCA-coupled LCC was conducted at midpoint level via the SDU (i.e., Shandong University) method in this study, as presented by Hong et al. (2017a). The SDU method is a combined life cycle impact assessment method of three methods (i.e., ReCiPe, IMPACTWorld+, and USEtox) developed in response to the requirement of the LCA analysis in China (Zhang et al., 2016; Li et al., 2016). Fifteen midpoint categories were considered, including carcinogens, non-carcinogens, freshwater ecotoxicity, respiratory inorganics, respiratory organics, global warming, ionizing radiation, ozone layer depletion, land occupation, terrestrial acidification, aquatic eutrophication, marine eutrophication, metal depletion, water depletion, and fossil depletion. The characterization factors of former three categories updated by Zhang et al. (2016), Chen et al. (2014), and Li et al. (2016) were used in this study to obtain regionalized results and to reduce the regional effect of European models on the LCIA analysis in China. More details were shown in Supplementary note 1. The LCC method was then used in this study to assess the economic impact caused by LCA. Internal (i.e., company actual cost) and external cost (i.e., external market price on environmental emissions, human health protection, and land eco-remediation cost) were assessed. Current market charges on pollutants and land eco-remediation willingness-to-pay cost in China, as shown in Hong et al. (2017a) investigations, were used to calculate the external cost. For the economic impact of human health burden, the human capital method was used to assess the indirect human health cost, whereas the actual cost, including social health expenditure, government expenditure on health, and personal health expenditure was used to assess the direct human health cost. Market price of diesel ($866.89/t), carbon trade cost ($1.47/t), investment of pyrolysis system ($53.76/t), investment of chemical disinfection system ($31.74/t), investment of steam sterilization system ($46.26/t), sodium hydroxide ($426.99/t), sodium hypochlorite ($2900.37/t), chlorine ($104.73/t), freshwater ($0.08/t), arsenic ($216.05/t), COD ($216.05/t), organic chemicals (i.e., ethylene oxide, $1160.15/t) lead ($216.05/t), mercury ($216.05/t), activated carbon ($1812.73/t), nitrogen oxides ($185.18/t), particulates ($92.59/t), electricity ($0.13/kWh), chlorine dioxide ($1369.62/t), and sulfur dioxide ($185.18/t) in 2015 were also used for LCC analysis. The difference between the LCC and the price that is paid for MW disposal is used to calculate the net profit of each scenario.

2.3. Inventory and data sources

The inventory data for the operation processes conducted in three MW pyrolysis, chemical disinfection, and steam sterilization sites located in the southeastern region of China for the reference year 2015–2016 were used in this study. Table 2 displays the

Table 3
Life cycle impact assessment results of each scenario. Values are presented per functional unit.

Category	Pyrolysis		Chemical disinfection		Steam sterilization	
	Impact	Process contribution	Impact	Process contribution	Impact	Process contribution
Global warming (kg CO_2 eq)	1.26×10^3	Electricity (23.8%) + diesel (36.1%) + sodium hydroxide (29.9%)	800.69	Lime (11%) + electricity (66%)	3.73×10^3	Diesel (66.7%) + electricity (26.1%)
Land occupation (ha.yr arable)	1.09×10^{-3}	Electricity (14.3%) + diesel (43.9%) + sodium hydroxide (20.9%)	6.31×10^{-4}	Landfill (22.3%) + electricity (43.6%) + transport (17.4%)	3.42×10^{-3}	Diesel (76.5%) + electricity (14.8%)
Terrestrial acidification (kg SO_2 eq)	2.60	Electricity (11.0%) + diesel (25.9%) + sodium hydroxide (44.3%)	0.95	Electricity (53%) + transport (17.2%)	5.22	Diesel (70.5%) + electricity (17.8%)
Aquatic eutrophication (kg PO_4^- eq)	0.02	Diesel (22.7%) + sodium hydroxide (62.6%)	9.62×10^{-3}	Organic chemicals (21.5%) + electricity (22.9%) + landfill (33.2%)	0.04	Diesel (74.9%) + electricity (10.6%)
Respiratory inorganics (kg $PM_{2.5}$ eq)	0.36	Electricity (11.2%) + Diesel (23.4%) + sodium hydroxide (33.5%)	0.16	Lime (13.3%) + electricity (44.2%) + landfill (11.2%)	0.66	Diesel (69.3%) + electricity (19.7%)
Respiratory organics (kg NMVOC eq)	3.07	Electricity (10.8%) + Diesel (33.8%) + sodium hydroxide (33.7%)	1.17	Electricity (45.9%) + transport (12.2%) + landfill (16.9%)	7.26	Diesel (78.0%) + electricity (14.7%)
Ionizing radiation (Bq C-14 eq)	469.68	Activated carbon (10.3%) + Diesel (12.4%) + sodium hydroxide (52%) + infrastructure (10.4%)	220	Organic chemicals (15.8%) + Chlorine dioxide (12.4%) + infrastructure (14.7%) + electricity (26%) + landfill + (15.9%)	589.33	Diesel (53.9%) + electricity (17.9%) + Infrastructure (18.6%)
Ozone Layer Depletion (kg CFC-11 eq)	5.05×10^{-6}	Diesel (14.6%) + sodium hydroxide (50.4%) + infrastructure (15.5%)	2.21×10^{-6}	Organic chemicals (12.0%) + infrastructure (10.8%) + electricity (33%) + landfill + (17%) + transport (12.2%)	6.87×10^{-6}	Diesel (58.9%) + electricity (11.7%) + Infrastructure (19.6%)
Water depletion (m^3)	71.87	Diesel (15.1%) + sodium hydroxide (47.1%) + infrastructure (11.6%)	33.31	Organic chemicals (12.3%) + infrastructure (18.7%) + electricity (28.4%) + landfill + (18.4%)	109.3	Diesel (54.1%) + electricity (19.4%) + Infrastructure (15.9%)
Metal depletion (kg Fe eq)	5.76	Diesel (16.3%) + sodium hydroxide (36.1%) + infrastructure (17.9%)	3.97	Infrastructure (32.7%) + electricity (33.2%)	12.76	Diesel (40.3%) + electricity (19.0%) + infrastructure (34.6%)
Fossil depletion (kg oil eq)	182.37	Electricity (30.8%) + Diesel (21.7%) + sodium hydroxide (38.1%)	151.3	Electricity (65.4%) + landfill (14.8%)	429.75	Diesel (50.2%) + electricity (42.4%)
Carcinogens (CTUh)	2.07×10^{-5}	Diesel (12.4%) + sodium hydroxide (65.2%)	5.14×10^{-6}	Organic chemicals (11%) + chlorine dioxide (11%) + electricity (38%) + landfill + (15.2%)	2.06×10^{-5}	Diesel (68.2%) + electricity (17.5%)
Non-carcinogens (CTUh)	2.14×10^{-4}	Electricity (23.9%) + diesel (32.1%) + sodium hydroxide (34.8%)	1.24×10^{-4}	Electricity (72.7%)	5.61×10^{-4}	Diesel (66.8%) + electricity (29.6%)
Freshwater ecotoxicity (CTUe)	2.38×10^4	Direct emission (59.1%) + sodium hydroxide (30.7%)	1.88×10^4	Chlorine dioxide (90%)	8.70×10^3	Diesel (72.0%) + electricity (15.6%)
Marine eutrophication (kg N eq)	0.09	Diesel (35.3%) + sodium hydroxide (41.8%)	0.05	Electricity (28.7%) + landfill (49.5%)	0.23	Diesel (73.2%) + electricity (11.3%) + landfill (10%)

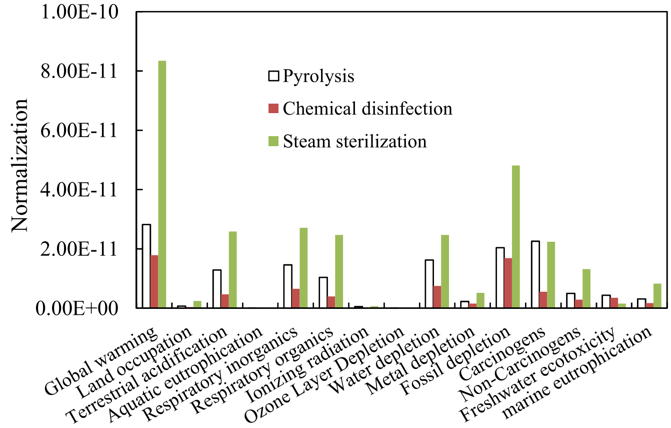

Fig. 2. Normalized mid-point scores for the full life cycle.

primary inventory of each scenario. The background data of electricity, steam, diesel, transportation, chlorine, lime, chlorine dioxide, sodium hydroxide, wastewater disposal, activated carbon, sanitary landfill, and hazardous waste incineration processes in China were obtained from the reviewed Chinese process-based life cycle inventory database (CPLCID, Supplementary note 2). The organic chemicals for disinfectant power production, infrastructure, and sodium hypochlorite were collected from the ecoinvent database (Ecoinvent centre, 2014) to compensate for the lack of data in China. The Chinese data contained in the CPLCID database, such as electricity generation, transportation, and waste disposal, were used to reduce the regionalized effect and adapt the foreign data to the Chinese context.

3. Results

3.1. LCA analysis results

Table 3 presents the life cycle impact assessment results and dominant processes in each scenario. The steam sterilization scenario exhibited the highest impact in most categories, except for carcinogens and freshwater ecotoxicity. The pyrolysis scenario demonstrated a similar and the highest impact in the carcinogens and freshwater ecotoxicity categories, respectively. By contrast, the chemical disinfection scenario indicated the lowest impact in most categories, except for freshwater ecotoxicity, in which the lowest potential impact was observed in the steam sterilization scenario. For the pyrolysis scenario, energy (e.g., electricity and diesel) and sodium hydroxide production provided the dominant contribution to the overall environmental burden. The process of infrastructure played an additional important role in ionizing radiation, ozone layer depletion, water depletion, and metal depletion, whereas active carbon production and direct emissions exhibited the dominant contributions to ionizing radiation and freshwater ecotoxicity, respectively. For the chemical disinfection scenario,

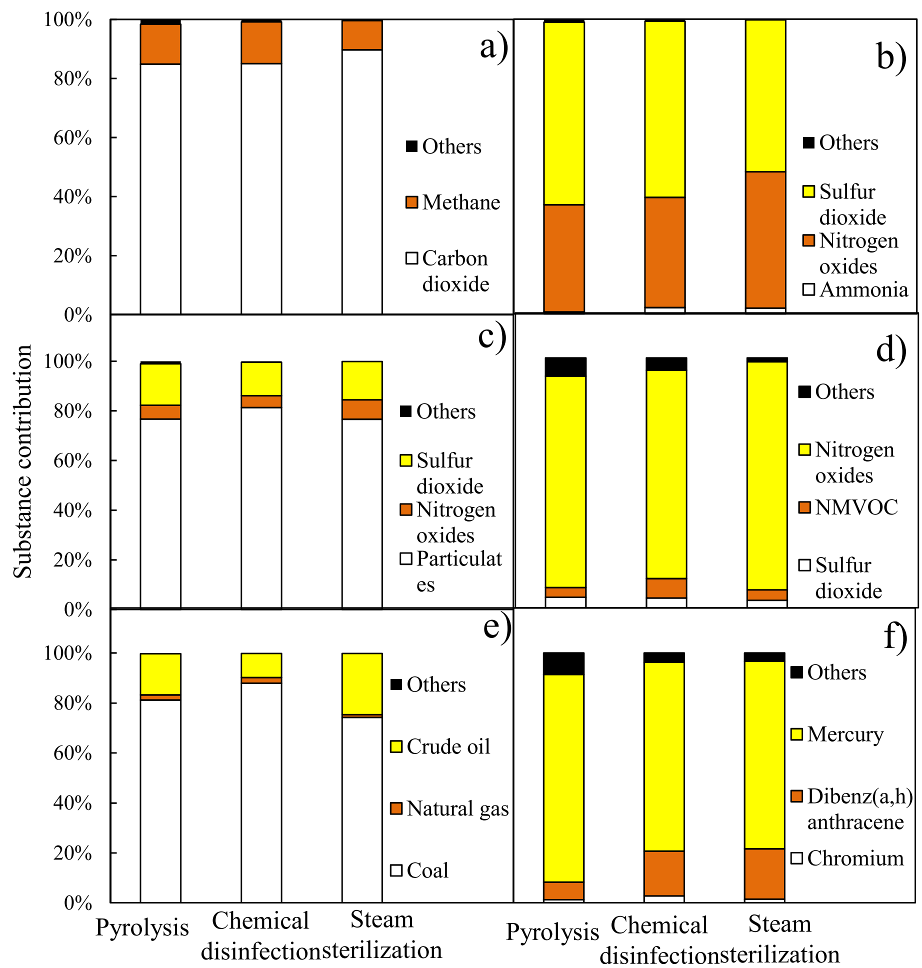

Fig. 3. Substance contribution a) global warming; b) terrestrial acidification; c) respiratory inorganics; d) respiratory organics; e) fossil depletion; f) carcinogens.

electricity consumption revealed the dominant contribution in most categories, except for freshwater ecotoxicity, which is dominated by chlorine dioxide process. Lime production mostly contributed to global warming and respiratory inorganics, whereas landfill process played an important role in most categories, except in global warming, terrestrial acidification, metal depletion, non-carcinogens, and freshwater ecotoxicity. Additionally, raw materials transportation, infrastructure, and consumption of organic chemicals for producing disinfectants played an additional important role in the overall environmental burden. For the steam sterilization scenario, energy (e.g., electricity and diesel) production provided the dominant contribution to each category, whereas infrastructure and landfill processes demonstrated additional dominant contributions to the overall environmental burden. The normalized results shows that the impact seen from global warming, terrestrial acidification, respiratory inorganics, respiratory organics, water depletion, fossil depletion, and carcinogens categories had an important contribution for the pyrolysis and steam sterilization scenarios; the impact seen from land occupation, metal depletion, non-carcinogens, freshwater ecotocixity, and marine eutrophication played relatively small roles (Fig. 2). For the chemical disinfection scenario, the impact seen from global warming and fossil depletion categories had an important contribution to the overall environmental; the impact seen from rest categories played relatively small roles. Accordingly, the effect of the LCA analysis results caused by organic chemicals for disinfectant power production, infrastructure, and sodium hypochlorite processes presented in this study was minimal, although these inventory data of were collected from the ecoinvent database.

Carbon dioxide, nitrogen oxides, particulates, nitrogen oxides, coal, and chromium emitted from each scenario provided major contributions to the overall global warming, terrestrial acidification, respiratory inorganics, respiratory organics, fossil depletion, and carcinogens effect, respectively (Fig. 3). The additional dominant substances contributing the most to global warming, respiratory organics, fossil depletion, carcinogens were methane, NMVOC, crude oil, and dibenz (a,h)anthracene, respectively. Sulfur dioxide emission was the secondary main contributor to the terrestrial acidification and respiratory inorganics.

3.2. Life cycle costing

Fig. 4 shows the LCC analysis results. The total economic impact is \$293.43/t, \$263.27/t, and \$454.74/t with a net profit of \$189.96/t, \$220.13/t, and \$28.66/t in the pyrolysis, chemical disinfection, and steam sterilization scenarios, respectively. The overall economic burden was mainly attributed to the cost of investment, labor, electricity, and human health protection for all scenarios (Fig. 4a). The cost of sodium hydroxide and diesel consumption played an additional important role, respectively, to the pyrolysis and steam sterilization scenarios. The economic impact generated from rest processes such as lime, sodium hypochlorite, chlorine, chlorine dioxide, activated carbon, maintenance, transport, landfill, environmental emissions, and eco-remediation was small. The cost combined LCA analysis results showed that the sodium hydroxide, electricity, and active carbon production stages exhibited 24.8%, 10.4%, 8.1% in the overall economic impact and 44.5%, 16.5%, and 4.5% in the overall environmental burdens of pyrolysis scenario, respectively (Fig. 4b). By contrast, the diesel stage resulted in low economic (~2%) and high environmental (25.8%) burdens, whereas the labor, human health protection, and investment cost resulted in high economic (~18.4%) and low environmental (~3.4%) burdens. For the chemicals disinfection scenario, the electricity, chlorine, and landfill stages exhibited high environmental (75%) and economic (27.5%) burdens, whereas the environmental burden of

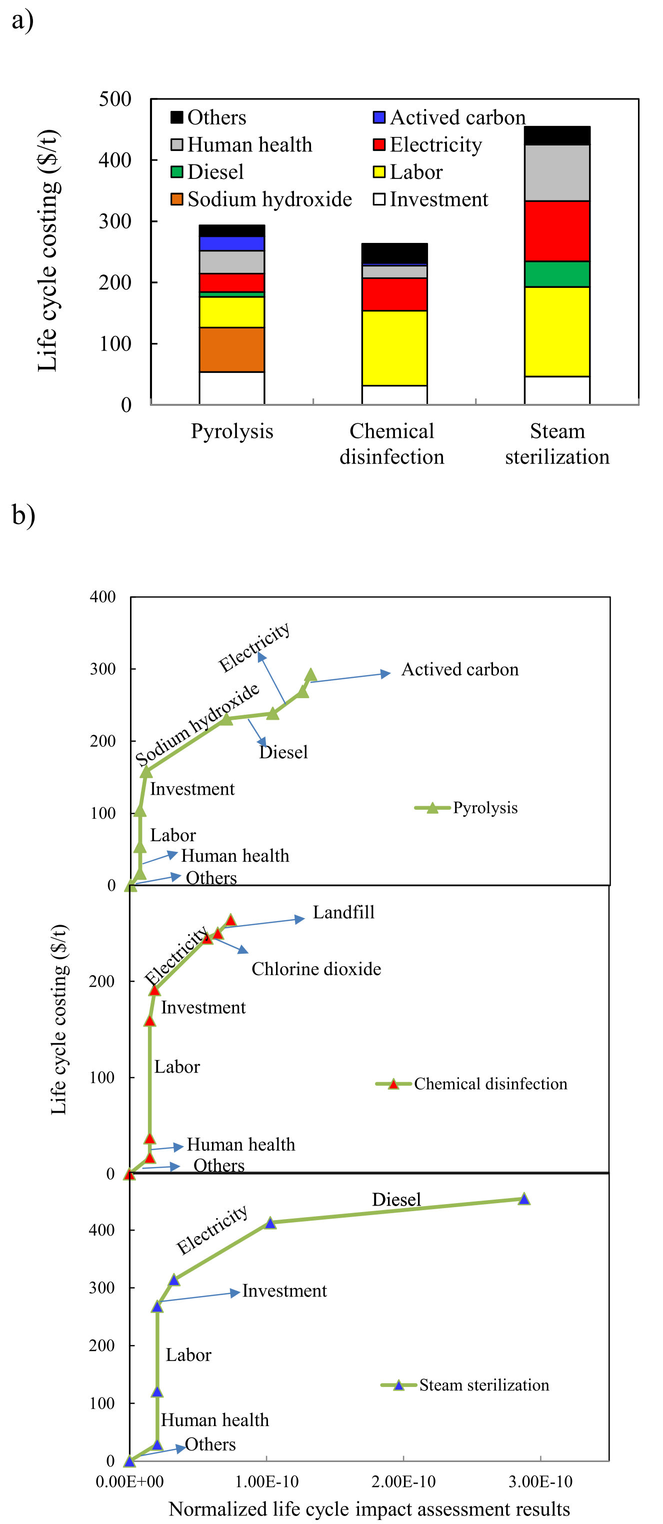

Fig. 4. LCC results a) process contribution; b) economic impact versus environmental impact.

investment, labor, and human health protection resulted in low environmental (4.9%) and high economic (66%) burdens. Similarly, for the steam sterilization scenario, the electricity and diesel stages exhibited high environmental (88.7%) and economic (30.9%) burdens, whereas the environmental burden of rest stages resulted in low environmental (11.3%) and high economic (69.1%) burdens.

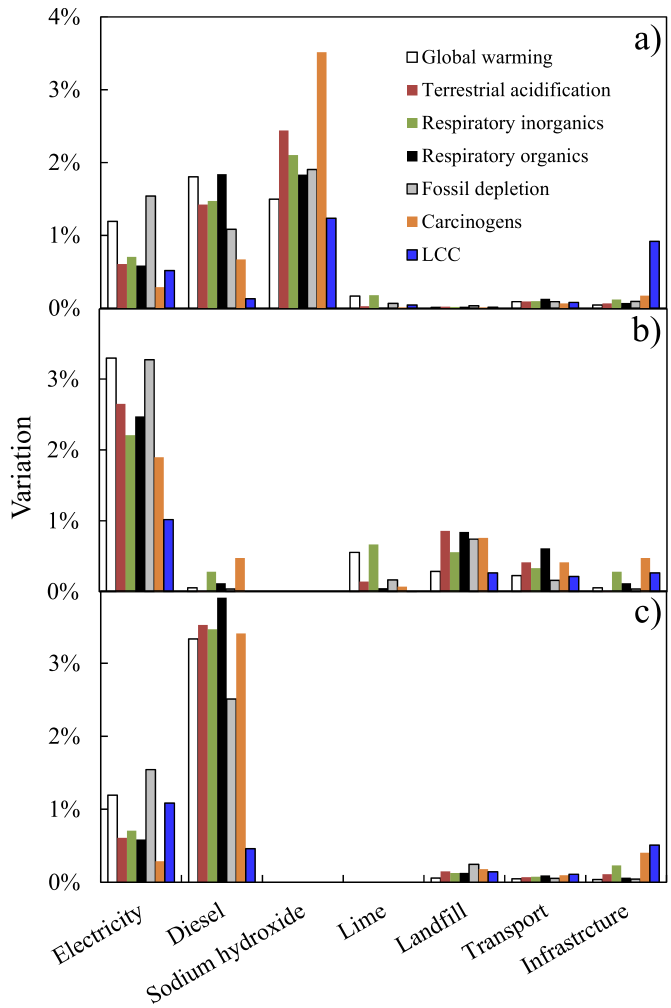

Fig. 5. Sensitivity analysis a) pyrolysis; b) chemical disinfection; c) steam sterilization.

3.3. Sensitivity analysis

Fig. 5 presents the sensitivity analysis results of main contributors for all scenarios. A 5% decrease in the main processes affecting on aforementioned key categories and economic impact were conducted. For the pyrolysis scenario, the electricity and sodium hydroxide consumption efficiency had a relatively high environmental and economic benefit. Diesel consumption and infrastructure efficiency, respectively, had an additional high environmental and economic benefit. For the chemical disinfection and steam sterilization scenarios, the decrease in electricity and diesel consumption had the highest environmental and economic sensitivity, respectively. Accordingly, electricity, diesel, sodium hydroxide consumption efficiency are crucial to reduce the overall environmental and economic burden. Meanwhile, improving infrastructure efficiency is important to reduce the overall economic burden.

3.4. Uncertainty analysis

Table 4 presents the uncertainty analysis results by using Monte Carlo simulation (Hertwich et al., 1999, 2000; Huijbregts et al., 2003). For global warming, the Monte Carlo method yields a GSD ^{2} of 1.47 for pyrolysis, 1.35 for chemical disinfection, and 1.4 for steam sterilization. These findings indicate that the 95% upper and lower confidence limits were 0.86–1.85 t CO_2 eq. for pyrolysis, 0.59–1.08 t CO_2 eq. for chemical disinfection, and 2.06–6.75 t CO_2 eq. for steam sterilization (Tables 3 and 4). The probability level of pyrolysis $\geq$ steam sterilization is 0%, pyrolysis $\geq$ chemical disinfection is 100%, and chemical disinfection $\geq$ steam sterilization is 0%. This result implies that the global warming score of the steam sterilization is the highest one, followed by the pyrolysis. The lowest global warming potential impact was observed in the chemical disinfection. The same tendencies were observed in most categories, except for carcinogens, freshwater ecotoxicity, ionizing radiation, and metal depletion categories. The carcinogens obtained from the pyrolysis scenario were similar to the carcinogens obtained from the steam sterilization, whereas the metal depletion obtained from chemical disinfection scenario was similar to the metal depletion obtained from steam sterilization. For freshwater ecotoxicity and ionizing radiation categories, similar results were observed across all scenarios. In summary, the steam sterilization and chemical disinfection scenarios demonstrated the highest and lowest overall environmental burden, correspondingly.

4. Discussion

Recently, the volume of MW produced in China has significantly increased due to the level of living and economic development (MEPC, 2014; 2016). For example, the MW generation capacity per hospital bed increased from 0.75 kg/day in 2013 to 0.95 kg/day in 2015 in Shanghai City (MEPC, 2014; 2016), corresponding to an increase of 26.67% within three years. However, only one-third of

Table 4
Uncertainty analysis results.

Category	$GSD^2_{Pyrolysis}$	$GSD^2_{Chemical\ disinfection}$	$GSD^2_{Steam\ sterilization}$	$P_{Pyrolysis} \geq P_{Steam\ sterilization}$	$P_{Pyrolysis} \geq P_{Chemical\ disinfection}$	$P_{Chemical\ disinfection} \geq P_{Steam\ sterilization}$
Global warming	1.47	1.35	1.81	0	100%	0
Aquatic eutrophication	2.83	1.75	2.72	7.6%	98.6%	0
Carcinogens	3.04	1.82	2.73	35%	100%	0
Fossil depletion	1.33	1.31	1.59	0	92.6%	0
Freshwater ecotoxicity	3.30	2.79	2.65	61.6%	18.4%	29.6%
Ionizing radiation	3.16	2.96	3.62	14%	100%	18.2%
Land occupation	2.35	1.29	2.95	0	99.8%	0
marine eutrophication	1.53	1.66	2.03	0	97.2%	0
Metal depletion	1.37	1.63	1.74	0	95.8%	16.8%
Non-Carcinogens	2.20	2.75	2.53	0	99.4%	0
Ozone Layer Depletion	1.67	1.76	2.32	9.2	100%	0.2
Respiratory inorganics	1.48	1.27	1.91	0	100%	0
Respiratory organics	1.53	1.27	2.03	0	100%	0
Terrestrial acidification	1.39	1.23	1.87	0	100%	0
Water depletion	1.29	1.45	2.01	2	100%	0

GSD^2: geometric variation coefficient.

the MW is safely treated, indicating that a large amount of MW may be mixed with the municipal solid waste and disposed in a landfill or incineration site. In 2015, approximately 34% of municipal solid waste was disposed by incineration technology (China Statistical Yearbook, 2016). Hong et al. (2017b) reported that dioxin, hydrogen chloride, and mercury emitted from municipal solid waste incineration sites range from 0.32 to 0.43 μg-TEQ/t, 10.59–48.49 g/t, and 71.77–313.68 mg/t, respectively. The concentration of dioxin emission was close to the value presented in this study (0.25 μg-TEQ/t, Table 2), whereas the concentration was significantly lower and higher in hydrogen chloride (0.45 kg/t, Table 2) and mercury (3.6 mg/t, Table 2) emission, respectively, than in MW pyrolysis emissions. Notably, Fig. 2 and Table 3 emphasize that the hydrogen chloride air emissions cause a negligible effect on the overall environmental burden. Furthermore, the energy consumption was much lower in municipal solid waste incineration, which is the main contributor to the overall environmental burden, than the energy consumption shown in Table 2 because of the relatively high incinerated temperature of MW pyrolysis technology. Moreover, Hong et al. (2009) reported that the overall environmental impact is slightly lower in solid waste incineration technology than in pyrolysis technology. These results indicated that the incineration technology may be an environmentally friendly method for MW treatment. However, more than 63% of the municipal solid waste is disposed of in landfill sites (China Statistical Yearbook, 2016) and may generate serious health risks (Hossain et al., 2011). Therefore, an experienced, separated, and specialized MW collection and mixing with municipal solid waste for incineration is required. Furthermore, the dioxin, mercury, and hydrogen chloride emitted from industrial hazardous waste pyrolysis technology, another common approach for MW disposal in China at present, amounted to 2.7 μg-TEQ/t, 42.89 g/t, and 0.15 g/t, respectively (Hong et al., 2017c). The concentration was significantly higher in the two former substances than the concentration presented in this study, whereas the opposite result was observed for the concentration of hydrogen chloride, as shown in Table 2. Similar to municipal solid waste incineration, hydrogen chloride air emissions did not play an important role in the overall environmental burden of industrial hazardous waste pyrolysis, whereas mercury emission was the main contributor (Hong et al., 2017c). However, the life cycle energy, global warming, and carcinogen impact was much lower in industrial hazardous waste pyrolysis, which is the main contributor to the overall environmental burden, than the impact shown in Table 2 because of significantly high sodium hydroxide consumption in the MW pyrolysis (Hong et al., 2017c). MW contributes to the overall industrial hazardous waste stream minimally (<5%, China Statistical Yearbook, 2016; MEPC, 2016). Consequently, energy recovery, a commonly applied technology for solid waste incineration system, is currently disregarded for MW pyrolysis in China due to insufficient MW supply. Extensive studies (Hong et al., 2017b; Defra, 2013) showed that energy recovery is the key factor for reducing the overall environmental burden for solid waste incineration. If the average electricity recovery capacity of grate incinerator (355.35 kWh/t, Hong et al., 2017c) is considered in this study, then the environmental and economic impacts of pyrolysis scenario will be approximate to the environmental and economic impacts of chemical disinfection scenario. These results indicate that MW mixed with industrial hazardous or municipal solid wastes and further incinerating the mixture in a system with energy recovery is a good choice for MW disposal.

Soares et al. (2013) reported that the LCC is \$1.10/kg for steam sterilization and \$1.53/kg for lime-based chemical disinfection, which is approximately 3–4 times higher than the results obtained by this study because of the different market prices of each input between China and Brazil. Moreover, Soares et al. (2013) revealed an opposite conclusion, indicating that the environmental and economic impact (Fig. 2, Table 3, Fig. 4) is higher in the chemical disinfection scenario than in the steam sterilization scenario because of the different energy structure between China and Brazil. In China, more than 70% of electricity is generated from coal (China Statistical Yearbook, 2016), whereas the electricity used in Brazil comes from hydropower (Soares et al., 2013). Moreover, the research conducted by Soares et al. (2013) revealed no diesel consumption and environmental emissions. However, Soares et al. (2013) observed a relatively low environmental effect of the steam sterilization scenario. This result indicates that the use of clean energy is a key to reducing the overall environmental burden because energy (i.e., electricity and diesel) consumption is the most dominant contributor to the overall economic and environmental burden (Table 3 and Fig. 4).

5. Conclusions

Key factors and improvements to the cost-coupled life cycle environmental performance of three MW disposal scenarios were quantified in this study. The results show that the overall environmental impact is mainly generated from global warming and fossil depletion categories because of the carbon dioxide emission and coal utilization during the energy consumption stage. The impact obtained from terrestrial acidification, respiratory inorganics, respiratory organics, water depletion, and carcinogen categories provide additional important contributions in the pyrolysis and steam sterilization scenarios because of the sulfur dioxide, nitrogen oxides, particulates, mercury, and dibenz (a,h) anthracene emitted from the energy and sodium hydroxide production stages. The environmental and economic "win–win" situation is observed in the electricity and sodium hydroxide production processes for the pyrolysis scenario; electricity, chlorine dioxide, and landfill processes for the chemical disinfection scenario; and electricity and infrastructure processes for the steam sterilization scenario. Significant environmental and economic improvements can be achieved by improving energy consumption efficiency, reducing the use of chlorine dioxide and sodium hydroxide, and starting energy recovery from MW by building a specialized MW-mixed municipal solid waste incineration system. The research results obtained in this study will help expand the life cycle inventory database of MW in China, provide scientific information for deciding the best practices for MW pyrolysis, steam sterilization, and chemical disinfection, and rectify problems in MW treatment globally. However, limitations on unifying government policies, management tools, social life cycle assessment, and laws should be applied for more systematic and sustainable MW disposal. Additionally, LCC coupled LCA analysis on additional MW disposal technologies (e.g., landfill, microwave, shredding, and compacting) is advisable. Further research on these areas will be conducted in our research group.

Acknowledgments

Thirteen-Five national key research and development program (Grant nos. 2017YFF0206702), National Natural Science Foundation of China (Grant nos. 71671105), and the Institute of the Fundamental Research Funds of Shandong University (2015JC016).

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2017.10.206.

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