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Life cycle assessment of electronic waste treatment

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ABSTRACT

Life cycle assessment was conducted to estimate the environmental impact of electronic waste (e-waste) treatment. E-waste recycling with an end-life disposal scenario is environmentally beneficial because of the low environmental burden generated from human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, and marine ecotoxicity categories. Landfill and incineration technologies have a lower and higher environmental burden than the e-waste recycling with an end-life disposal scenario, respectively. The key factors in reducing the overall environmental impact of e-waste recycling are optimizing energy consumption efficiency, reducing wastewater and solid waste effluent, increasing proper e-waste treatment amount, avoiding e-waste disposal to landfill and incineration sites, and clearly defining the duties of all stakeholders (e.g., manufacturers, retailers, recycling companies, and consumers).

1. Introduction

Electronic waste (e-waste) refers to waste generated from discarded electrical or electronic devices (e.g., cell phones, computers, TV, printers). Given the vast technological advancement and economic development in many countries in recent years, the volume of e-waste produced has significantly increased (Qu et al., 2013; Robinson, 2009). The current global production of e-waste is around 25 million tons per year (Robinson, 2009), with the greatest amount of e-waste imported in China (Chi et al., 2014). However, compared with e-waste recycling in developed countries, that in China suffers from a high occurrence of environmental pollution and low energy efficiency. One of the most important mineral resources, e-waste is traditionally recovered in China by workers with the use of open flames or hot plates as a convenient way to remove electronic components (Allsopp et al., 2006). The improper handling of e-waste releases heavy metals (e.g., lead, cadmium, mercury, and beryllium) and hazardous chemicals (e.g., dioxins, furans, polychlorinated biphenyl) that seriously deteriorate the atmosphere, water, and soil quality (Li et al., 2014; Xu et al., 2014) and thus affect human health (Liu et al., 2009). The potential environmental impacts generated by e-waste recycling are complex and involve multi-factorial participation (e.g., process, activity, and substances). In this regard, a systematic consideration of emission inventories and the environmental potential impacts caused by e-waste recycling is highly needed.

Life cycle assessment (LCA) is a systematic approach to assess and quantify the environmental performance associated with all stages of a product creation, processes, and activities (ISO 14040, 2006). LCA can simultaneously, systematically, and effectively evaluate and identify environmental inventory, impact, key factors, decisions, optimization, and improvement opportunities associated with all stages of system boundary. Several studies have analyzed the environmental impact of e-waste treatment on the environment via LCA (Song et al., 2012; Niu et al., 2012). Song et al. (2012) investigated e-waste treatment by using emergy analysis combined with the LCA method for a trial project in Macau. Their results showed that recovery of metals, glass, and plastic from e-waste can generate environmental benefits. Niu et al. (2012) compared three cathode ray tube (CRT) display treatment scenarios (i.e., incineration, manually dismantling, and mechanically dismantling) via LCA by using literature review. Their results showed that the incineration of CRT displays has the greatest impact, followed by mechanical dismantling. Despite their scientific contributions, the aforementioned studies are unclear as to whether direct air, water, and soil emissions from the industry site of e-waste recycling are included in the calculation of results. Inventory databases are also variable in terms of regionalization,

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geography, and uncertainties involved. However, in the aforementioned studies, no regionalized database was selected to determine the environmental effects of e-waste in China. Most data were collected from European database (Ecoinvent centre, 2010). Therefore, accurate results for Chinese case studies are difficult to obtain. The quantification and communication of uncertainties related to LCA results are also vital for their correct interpretation and use. However, most LCA experts, including the authors of the aforementioned studies, still conduct LCA without considering uncertainties. The environmental impact generated from informal recycling processes should also be quantified because substantial e-waste in China is recycled by individual workshops (Lin and Liu, 2012). In this regard, the current study aims to address the aforementioned needs, identify the key factors to improve the processes in the Chinese e-waste recycling industry, characterize and compare two e-waste recycling technologies commonly applied in China, and introduce a Chinese e-waste recycling database.

2. Scope definition

2.1. Functional unit

In this study, the management of 1 ton of e-waste (i.e., computer and television) is selected as the functional unit to provide a quantified reference for all other related inputs and outputs. All air, water, and soil emissions, raw materials and energy consumption, and waste disposal are based to this functional unit.

2.2. System boundary

System boundaries were set by application of a gate-to-gate approach. Two scenarios commonly used in China were considered in this study, namely, e-waste treatment with end-life disposal (ET-D) and e-waste treatment without end-life disposal (ET-ND). Fig. 1a presents the system boundary and mass flow for the ET-D scenario. The ET-ND scenario is simpler than the ET-D scenario because the pollutant control system is commonly excluded in the ET-ND scenario in many individual workshops (Fig. 1b). The ET-D scenario involves raw materials and energy production; road transportation of raw materials to the e-waste treatment site; direct air, water, and soil emissions during e-waste treatment processes (i.e., classification, disassembly, crush, electrodialysis, and metal refining); and waste disposal (i.e., on-site wastewater and air pollution treatment, landfill and leachates treatment, incineration). To simplify the LCA analysis of the ET-D and ET-ND scenarios, the common process of e-waste collection to the e-waste treatment site is excluded. The infrastructure (i.e., construction and equipment) process is also excluded because of the lack of information from selected e-waste treatment sites. Moreover, infrastructure provides a minimal overall contribution to the potential environmental impact (Ecoinvent centre, 2010).

2.3. Life cycle impact assessment methodology

Life cycle impact assessment (LCIA) results were calculated at midpoint level by using the ReCiPe method (Goedkoop et al., 2009) because the fate exposure of this model is consistent with multimedia modeling. This method is also the most recent indicator approach available in LCA analysis. It considers a broad set of 18 midpoint impact categories (i.e., human toxicity, photochemical oxidant formation, particulate matter formation, ionising radiation, climate change, ozone depletion, terrestrial acidification, freshwater eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine eutrophication, marine ecotoxicity, urban land occupation, natural land transformation, agricultural land occupation, water depletion, metal depletion, and fossil depletion). Normalization, which is determined by the ratio of the impact per unit of emission divided by the per capita world impact for the year 2000 (Wegener Sleeswijk et al., 2008), was applied in this study to compare midpoint impacts and analyze the respective share of each midpoint impact to the overall impact. The complete characterization factors and detailed methodology for ReCiPe are available on the website of Institute of Environmental Science in Leiden University of Nederland (http://www.cml.leiden.edu/research/industrialecology/researchprojects/finished/recipe.html).

To determine the level of confidence in the assertion that ET-D is more environmentally friendly than ET-ND, uncertainty analysis is performed via Monte-Carlo analysis by using Simapro 8.0. The geometric variation coefficient (GSD^2) defined the 2.5th and 97.5th percentiles, namely, the 95% confidence interval of a probability distribution near the median μ. For each unit process, the GSD^2 for all LCI parameters is defined by Eq. (1) (Ecoinvent centre, 2010).

$$GSD^2 = \exp^{\sqrt{[\ln(U_1)]^2+[\ln(U_2)]^2+[\ln(U_3)]^2+[\ln(U_4)]^2+[\ln(U_5)]^2+[\ln(U_6)]^2+[\ln(U_b)]^2}} \quad (1)$$

where U_b is the basic uncertainty factor, whereas U_1, U_2, U_3, U_4, U_5, and U_6, are the uncertainty factor for reliability, completeness, temporal correlation, geographic correlation, other technological correlation, and sample size, respectively The detailed methodology for Monte-Carlo analysis using Simapro software is available in the Ecoinvent report (Ecoinvent centre, 2010). Additionally, the contribution of individual parameters in the life cycle of both scenarios is identified by Eq. (2) (Hong et al., 2010a).

$$GSD_O^2 = \exp\left[S_{I_1}^2(\ln GSD_{I_1}^2)^2 + S_{I_2}^2(\ln GSD_{I_2}^2)^2 + \cdots S_{I_n}^2(\ln GSD_{I_n}^2)^2\right]^{1/2} \quad (2)$$

where GSD_O^2, S_i, and $GSD_i{}^2$ are the overall coefficient of variation in the final result, the model sensitivity to each input parameter (i), and its coefficient of variation of individual inputs, respectively.

2.4. Data sources

Operation data (i.e., energy, chemicals, raw material, water, wastewater, solid waste, and product) and direct water and air emissions (i.e., before and after pollutant treatment) from an e-waste recycling site in Tianjin, China were collected to generate a life cycle inventory for e-waste treatment (Table 1). The annual capacity for e-waste treatment in this site, which is a professional dismantling enterprise in northern China, is around 24 kt in 2012. For the ET-ND scenario, the company monitoring data of the Tianjin e-waste recycling site related to the direct air and water emissions from e-waste classification, disassembly, crushing, electrodialysis, and metal refining process before pollutant treatment were used to generate water and air emissions. Furthermore, data from five Guiyu e-waste dumpsite samples were aggregated to generate the average direct soil emissions for the ET-ND scenario (Brigden et al., 2005). Guiyu is a town located in Guangdong, China and is one of the largest e-waste sites in the world. This town has been extensively working in the e-waste processing business by using primitive and hazardous methods (Sthiannopkao and Wong, 2013; Brigden et al., 2005). It therefore represents a typical situation for the ET-ND scenario. In addition, 2009 onsite data-based life cycle inventory (LCI) on coal-based electricity generation (Cui et al., 2012), theoretical LCI calculation of road transport data (Chen et al., 2014), and 2007 onsite data-based LCI on solid waste landfill and incineration (Hong et al., 2010b) in China were used in this study. Relevant background data from Europe (Ecoinvent centre, 2010), including those on chemical production, were also collected because of the limited information on sites.

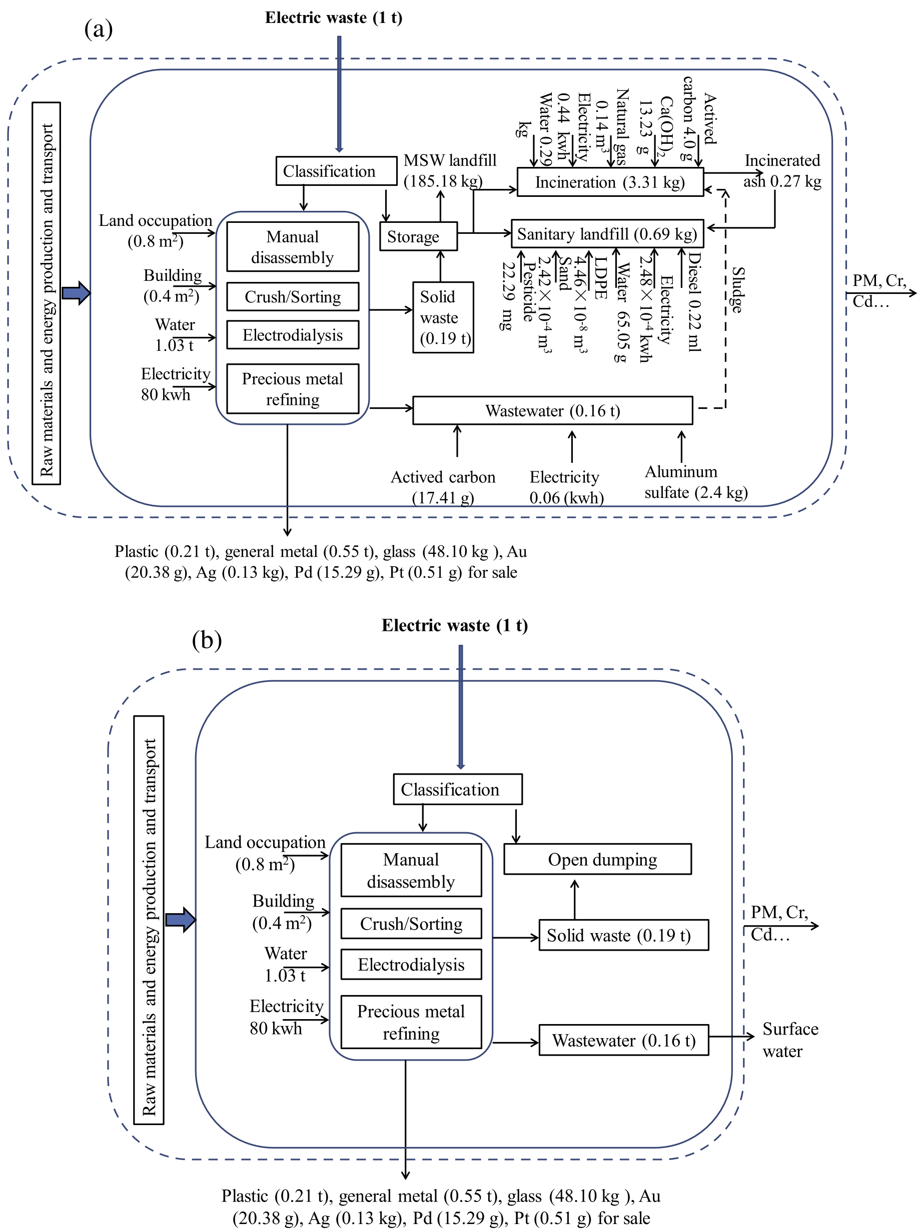

Fig. 1. System boundary and mass flow (a) ET-D scenario; (b) ET-ND scenario.

3. Results

3.1. LCIA results

Table 2 presents the LCIA midpoint assessment results with the use of the ReCiPe method. The ET-ND scenario has a high potential impact on human health, photochemical oxidant formation, terrestrial ecotoxicity, freshwater ecotoxicity, marine eutrophication, and marine ecotoxicity. Coal-based electricity generation significantly contributed to the overall environmental burden for both scenarios. Landfill and wastewater disposal showed an additional dominant contribution to the overall environmental burden for the ET-D scenario, whereas the additional dominant process for the ET-ND scenario showed direct pollutant emissions as a result of e-waste on-site disposal.

3.2. Normalized LCIA results

Fig. 2 shows the normalized midpoint results in each scenario. For the ET-D scenario, the impact of climate change, human toxicity, photochemical oxidant formation, particulate matter formation, terrestrial acidification, freshwater eutrophication, marine eutrophication, freshwater ecotoxicity, marine ecotoxicity, and fossil depletion has a dominant contribution to the overall environmental impact. For the ET-ND scenario, the overall environmental impact is mainly attributed to human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, and marine ecotoxicity. For both scenarios, the impact from the other categories has a relatively small role. The overall environmental impact of the ET-D scenario is relatively smaller than that of the ET-ND because of the significant high soil emissions of the latter.

Table 1
Life cycle inventory of electric waste disassembling processes. Values are presented per functional unit.

		Unit	ET-D	ET-ND
			Amount	Amount
Operation stage	Electricity	kW h	80	80
	Land occupation	m^2	0.8	0.8
	Building	m^2	0.4	0.4
	Water	g	1.03×10^6	1.03×10^6
	Wastewater	g	1.59×10^5	1.59×10^5
	Solid waste	g	1.85×10^5	1.85×10^5
Direct air emissions	Particulates	g	2.38	5.29×10^4
	Nitrogen oxides	g	3.48	96.99
	Ammonia	g	8.66×10^{-2}	2.04
	Hydrogen chloride	g	1.53	39.24
	Sulfuric acid mist	g	9.75×10^{-2}	2.04
Direct emissions from wastewater	Nickel	g	7.98×10^{-3}	1.11×10^{-2}
	Petroleum	g	1.06×10^{-2}	3.31×10^{-2}
	Zinc	g	3.19×10^{-3}	2.26×10^{-2}
	Cyanogen	g	6.4×10^{-4}	6.4×10^{-4}
	Suspended solids	g	6.39×10^{-2}	3.19
	Chemical oxygen demand (COD)	g	1.72	5.43
	Chromium	g	4.79×10^{-3}	4.79×10^{-3}
	Copper	g	7.98×10^{-3}	19.2
	Cadmium	g	7.98×10^{-3}	7.98×10^{-3}
	Lead	g	3.19×10^{-2}	3.19×10^{-2}
	Ammonia–nitrogen	g	2.63×10^{-2}	5.28×10^{-2}
Solid waste	Antimony	g		85.17
	Arsenic	g		4.26
	Barium	g		207.14
	Beryllium	g		2.0×10^{-4}
	Bismuth	g		0.02
	Cadmium	g		7.59×10^{-3}
	Chromium	g		29.83
	Cobalt	g		3.08
	Copper	g		1.34×10^3
	Gold	g		2.43
	Lead	g		318.21
	Manganese	g		117.23
	Mercury	g		0.17
	Molybdenum	g		3.23
	Nickel	g		64.98
	Silver	g		10.53
	Tin	g		67.26
	Vanadium	g		2.62
	Yttrium	g		1.25
	Zinc	g		512.87
	Chlorinated benzenes	g		1.10
	Polychlorinated biphenyl	g		76
	Polybrominated Biphenyl Ethers	g		0.42
	Phthalate esters	g		0.27
	Aliphatic hydrocarbons	g		2.85
	Aromatic hydrocarbons	g		2.93
	Organosilicon compounds	g		0.04
	Organophosphate compounds	g		0.04

3.3. Main contributors

The most significant contributions to LCA are shown in Fig. 3 to further elucidate the dominant substances in the e-waste treatment scenarios. For the ET-D scenario, the most dominant substances that contribute to climate change are carbon dioxide and methane. The emissions of arsenic and selenium to water and mercury to air play important roles in human toxicity. The dominant substance in photochemical oxidant formation and marine eutrophication is nitrogen oxide. The emissions of non-methane volatile organic compounds to air and nitrate and ammonium to water are additional dominant substances in photochemical oxidant formation and marine eutrophication, respectively. In particulate matter formation and terrestrial acidification, nitrogen oxides and sulfur dioxide emitted to the air are the most significant substances. The emission of particulates to the air also plays an important role in particulate matter formation. Phosphate in water has a dominant contribution to freshwater eutrophication. Vanadium, nickel, beryllium, and selenium are the most significant substances in freshwater and marine ecotoxicity. The emission of bromine to water has an additional dominant contribution to freshwater ecotoxicity. The use of coal, natural gas, and oil also significantly contributes to fossil depletion. For the ET-ND scenario, the substances that contributed the most to each dominant category are direct silver and zinc to soil from the solid waste open dumping stage. Direct copper from the waste open dumping process plays an important role in most categories, except for human toxicity. Direct barium and antimony emissions from the same process are additional dominant substances in most categories, except for terrestrial ecotoxicity.

Table 2
LCIA midpoint assessment results by using the ReCiPe method.

Category	Unit	ET-D		ET-ND	
		Amount	Process	Amount	Process
Climate change	kg CO_2 eq	125.15	Electricity (54.8%) + landfill (37.3%)	68.53	Electricity (100%)
Ozone depletion	kg CFC-11 eq	8.29×10^{-7}	Electricity (10.4%) + wastewater (80.3%)	8.65×10^{-8}	Electricity (100%)
Human toxicity	kg 1,4-DB eq	4.15	Electricity (80.3%) + wastewater (13.7%)	84.37	Direct emission (96.05%)
Photochemical oxidant formation	kg NMVOC	0.54	Electricity (89.8%)	0.58	Electricity (83.2%)
Particulate matter formation	kg PM10 eq	0.14	Electricity (79.2%) + landfill (12.4%)	0.13	Electricity (83.0%)
Ionising radiation	kg U235 eq	1.76	Wastewater (69.1%) + electricity (14.5%) + landfill (15.3%)	0.26	Electricity (100%)
Terrestrial acidification	kg SO_2 eq	0.35	Electricity (81.2%)	0.34	Electricity (82.7%)
Freshwater eutrophication	kg P eq	5.49×10^{-3}	Wastewater (43.4%) + electricity (46.8%)	2.57×10^{-3}	Electricity (100%)
Marine eutrophication	kg N eq	7.68×10^{-2}	Electricity (77.6%) + landfill (12.4%)	7.22×10^{-2}	Electricity (82.5%)
Terrestrial ecotoxicity	kg 1,4-DB eq	1.08×10^{-3}	Wastewater (49.1%) + electricity (35.0%)	37.83	Direct emission (100%)
Freshwater ecotoxicity	kg 1,4-DB eq	8.67×10^{-2}	Electricity (82.1%)	4.39	Direct emission (98.4%)
Marine ecotoxicity	kg 1,4-DB eq	8.90×10^{-2}	Electricity (77.8%) + wastewater (18.0%)	2.25	Direct emission (96.9%)
Agricultural land occupation	m^2 a	0.46	Landfill (58.7%) + Wastewater (35.2%)	8.74×10^{-3}	Electricity (100%)
Urban land occupation	m^2 a	1.04	Electric waste (77.3%)	0.89	Electric waste (89.6%)
Natural land transformation	m^2	1.70×10^{-3}	Electricity (13.4%) + landfill (34.1%) + wastewater (51.5%)	2.27×10^{-4}	Electricity (100%)
Water depletion	m^3	0.16	Wastewater (70%) + landfill (24.9%)	7.17×10^{-3}	Electricity (100%)
Metal depletion	kg Fe eq	0.56	Wastewater (68.3%) + electricity (17.9%) + landfill (10.7%)	0.10	Electricity (100%)
Fossil depletion	kg oil eq	21.93	Electricity (79.2%) + landfill (13.9%)	17.35	Electricity (100%)

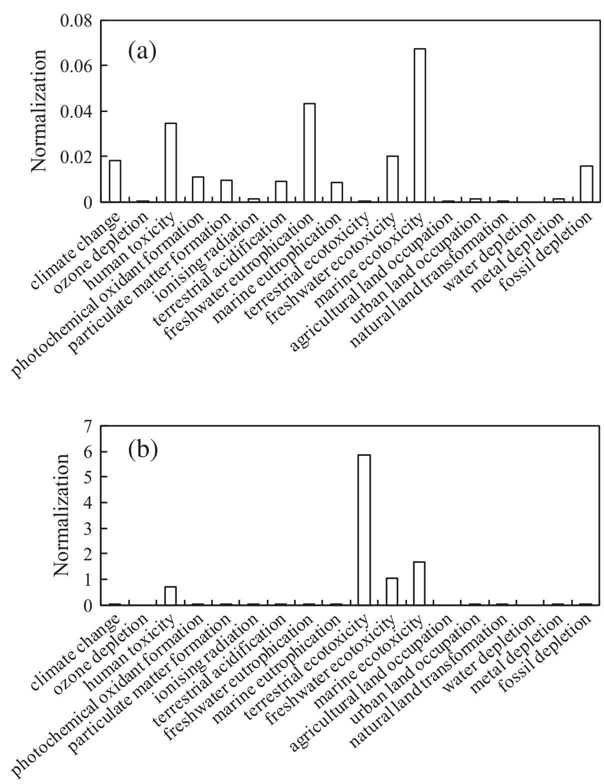

Fig. 2. Normalized LCIA mid-point results (a) ET-D; (b) ET-ND.

3.4. Mass balance

The mass balance of both scenarios was studied to further understand the reliability of the life cycle inventory (Fig. 4). For both scenarios, the initial e-waste treatment mass was 1 t. The masses of products (e.g., metal, plastic, glass) from disassembly, CRT treatment, crush, and electrodialysis plus the precious metal refining processes were 0.75 t, 9.38×10^{-3} t, 3.79×10^{-2} t, and 1.66×10^{-4} t, respectively. For the ET-D scenario, the masses of direct air emission, water emission, and solid waste disposal were 7.57×10^{-6} t, 1.88×10^{-6} t, and 0.184 t, respectively. For the ET-ND scenario, these were 5.30×10^{-2} t, 2.80×10^{-5} t, and 0.186 t, respectively. Accordingly, approximately 1.72×10^{-2} t of loss for

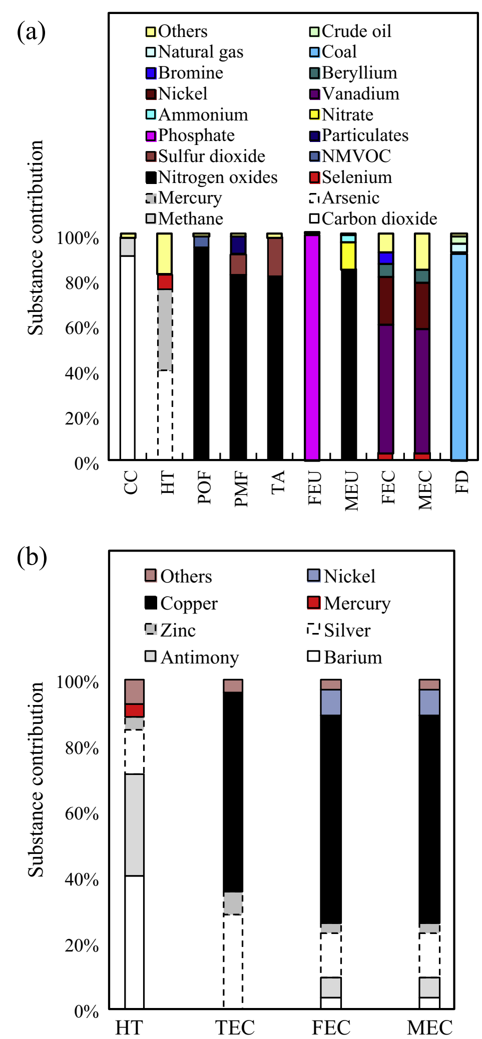

Fig. 3. Contribution of substances to the key categories (a) ET-D; (b) ET-ND. CC: climate change; HT: human toxicity; POF: photochemical oxidant formation; PMF: particulate matter formation; TA: terrestrial acidification; FEU: freshwater eutrophication; MEU: marine eutrophication; FEC: freshwater ecotoxicity; MEC: marine ecotoxicity; TEC: terrestrial ecotoxicity; FD: fossil depletion.

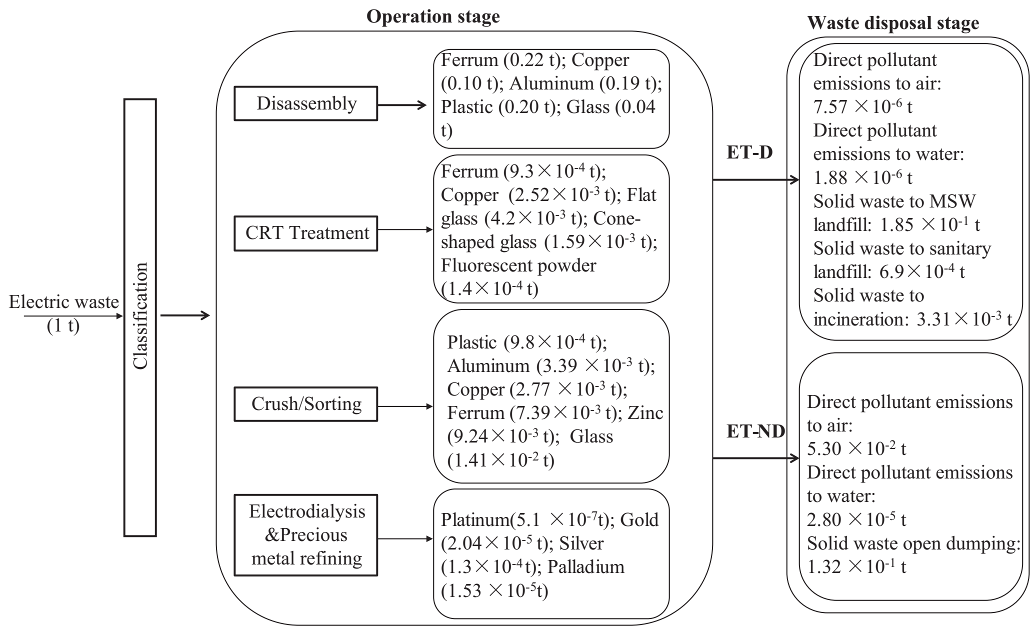

Fig. 4. Mass balance.

the ET-D scenario and 1.76×10^{-2} t of loss for the ET-ND scenario can be observed, which may have resulted from missing inventory data and measurement error problems.

3.5. Sensitivity analysis

Table 3 shows the sensitivity analysis results obtained from the study. A 5% decrease in electricity consumption obtains approximately 3.43 kg CO_2 eq, 0.17 kg 1,4-DB eq, and 2.41×10^{-2} kg NMVOC environmental benefit in the climate change, human toxicity, and photochemical oxidant formation categories, respectively. For the rest categories and processes, a similar analogy can be made with the sensitivity results shown in Table 3. Electricity consumption efficiency has the highest environmental benefit in all dominant categories, except human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, and marine ecotoxicity. Direct soil emissions in the ET-ND scenario produce the highest variability. By contrast, for the ET-D scenario, solid waste disposal to incineration has the lowest variability in all dominant categories, except climate change and marine eutrophication, in which wastewater treatment has the lowest variability in this scenario. For the ET-ND scenario, wastewater disposal process has the lowest variability.

3.6. Uncertainty analysis

Uncertainty analysis was conducted to estimate the degree of confidence when the effect of the ET-D scenario is predicted to be lower than that of the ET-ND scenario. The GSD^2 and probability results obtain with the Monte Carlo method are shown in Table 4. For LCIA, we focus on the key categories identified in Fig. 2. The Monte Carlo method yields a GSD^2 on the climate change score of 1.2 for ET-D and 1.4 for ET-ND. These findings indicate that the 95% upper and lower confidence limits are the median (shown in Table 2) multiplied and divided by GSD^2, respectively. The probability that the ET-D scenario has a higher climate change score than ET-ND is 100%. This result implies that the climate change score of the ET-D scenario is significantly higher than that of ET-ND scenario. For the other categories, a similar analogy can be applied with the probability results (Table 4). In summary, the climate change, freshwater eutrophication, and fossil depletion scores obtained from the ET-D scenario are significantly higher than those obtained from the ET-ND. By contrast, the human

Table 3
Sensitivity of main contributors. Values are presented per functional unit.

	Electricity	Wastewater		Solid waste		
		ET-D	ET-ND	ET-D		ET-ND
				Landfill	Incineration	
Variation	5%	5%	5%	5%	5%	5%
Climate change (kg CO_2 eq)	3.43	0.23	0	2.34	0.26	0
Human toxicity (kg 1,4-DB eq)	0.17	2.89×10^{-2}	3.52×10^{-4}	4.76×10^{-3}	7.19×10^{-3}	4.05
Photochemical oxidant formation (kg NMVOC)	2.41×10^{-2}	6.39×10^{-4}	0	1.76×10^{-3}	1.74×10^{-4}	0
Particulate matter formation (kg PM10 eq)	5.37×10^{-3}	4.85×10^{-4}	0	8.42×10^{-4}	4.49×10^{-5}	0
Terrestrial acidification (kg SO_2 eq)	1.41×10^{-2}	1.66×10^{-3}	0	1.39×10^{-3}	1.2×10^{-4}	0
Freshwater eutrophication (kg P eq)	1.28×10^{-4}	1.19×10^{-4}	0	1.43×10^{-5}	1.25×10^{-5}	0
Marine eutrophication (kg N eq)	2.98×10^{-3}	9.35×10^{-5}	3.2×10^{-8}	4.78×10^{-4}	2.67×10^{-4}	0
Terrestrial ecotoxicity (kg 1,4-DB eq)	1.9×10^{-5}	2.66×10^{-5}	0	4.51×10^{-6}	4.08×10^{-6}	1.89
Freshwater ecotoxicity (kg 1,4-DB eq)	3.56×10^{-3}	6.44×10^{-4}	9.0×10^{-7}	8.05×10^{-5}	4.97×10^{-5}	0.22
Marine ecotoxicity (kg 1,4-DB eq)	3.46×10^{-3}	8.0×10^{-4}	5.0×10^{-7}	1.2×10^{-4}	6.84×10^{-5}	0.11
Fossil depletion (kg oil eq)	0.87	6.16×10^{-2}	0	0.15	1.40×10^{-2}	0

Table 4
Squared geometric standard deviation (GSD^2) and probability of main categories using Monte-Carlo technology.

Category	GSD^2		Probability of EWT-D > EWT-ND
	EWT with waste disposal	EWT without waste disposal	
Climate change	1.2	1.4	100%
Human toxicity	2.0	2.4	0%
Photochemical oxidant formation	1.5	1.5	33.3%
Particulate matter formation	1.4	1.5	65.4%
Terrestrial acidification	1.4	1.5	58.1%
Freshwater eutrophication	2.6	7.4	99.8%
Marine eutrophication	1.5	1.5	67.5%
Terrestrial ecotoxicity	1.5	3.0	0%
Freshwater ecotoxicity	2.7	2.8	0%
Marine ecotoxicity	2.6	2.7	0%
Fossil depletion	1.3	1.3	90.2%

D: disposal; ND: without disposal.

toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, and marine ecotoxicity scores obtained from the ET-D scenario are significantly lower than those obtained from ET-ND. Similar LCIA scores are observed in both scenarios for photochemical oxidant formation, particulate matter formation, terrestrial acidification, and marine eutrophication.

4. Discussion

Currently, governments are increasingly turning their attention to e-waste disposal because the increasing amount of e-waste worldwide is a critical environmental problem. Although the LCA of e-waste has been extensively studied (Song et al., 2012; Niu et al., 2012), the potential environmental impact of e-waste treatment widely varies (Kiddee et al., 2013). The key process that contributes to the overall environmental burden for both scenarios is electricity generation (Table 2). In this study, the electricity consumption for e-waste recycling is 145.45 kW h/t-metal, which is higher than that in the European database (125.69 kW h/t-metal, process ID: 14601303340, Ecoinvent centre, 2010). If Europe-available technology is used in the present research, approximately 9.48% and 8.04% of the overall potential impact of electricity generation will be reduced in the ET-D and ET-ND scenarios, respectively. Accordingly, improving electricity consumption efficiency is the key to reducing the overall environmental burden for both scenarios.

Notably, data on chemical production in Europe (Ecoinvent centre, 2010) were used in this research because of the lack of information on China. For both scenarios, the uncertainties of overall environmental burden were mainly generated from the emissions of heavy metal and the consumption of electricity. Table 2 shows that the overall environmental impact is mainly generated from coal-based electricity generation, landfill, and wastewater disposal processes for the ET-D scenario. That of the ET-ND scenario is electricity generation and direct pollutant emissions from e-waste on-site disposal. Therefore, although European data on chemical production were used in this study, the overall environmental impact from both e-waste recycling scenarios was not affected.

Table 4 shows that the overall environmental burden obtained from the ET-ND scenario is significantly higher than that obtained from the ET-D because of the relatively high environmental impact of human toxicity, terrestrial ecotoxicity, freshwater ecotoxicity, and marine ecotoxicity obtained from the former scenario (Table 4). Tsydenova and Bengtsson (2011) reported that the improper handling and management of e-waste may pose significant human and environmental health risks because hazards arise from heavy metals and halogenated compounds in e-waste. Previous studies reported that large amounts of e-waste in China are improperly collected and disposed (Chi et al., 2014; Xu et al., 2014), so these from many high-level toxic organic compounds in various environmental mediums and biological samples around e-waste disposal sites (Chi et al., 2014). Accordingly, the proper handling and management of e-waste are the key in decreasing its risk to both human health and environment. Compared with industrialized nations, developing countries lack the conventions, directives, and laws that govern producer responsibility (Sthiannopkao and Wong, 2013), which can efficiently reduce the amount of e-waste that is improper disposal. For instance, although an e-waste disposal law was enacted in China in 2009 (State council, 2009), the obligations and penalties in the law are loosely implemented (Sthiannopkao and Wong, 2013). Clearly defining the duties of manufacturers, retailers, recycling companies, and consumers is important to reducing the amount of improper e-waste disposal.

In addition, although some e-waste resources (e.g., plastic, metals, and glass) have significant environmental benefits compared with their primary manufacturing processes (Song et al., 2012), considerable environmental burden is generated during the e-waste recycling stage (Table 2). Kiddee et al. (2013) reported that importing e-waste and electronic goods from developed countries causes a major e-waste problem in developing countries. Wang et al. (2013) reported that China is now facing serious e-waste problems as a result of foreign imports. Approximately 80% and 18% of e-waste worldwide are produced by developed countries (e.g., Europe, U.S.A.) and China, respectively, accounting for 14% of the national municipal solid waste (MSW) generation in China in 2009 (China Statistics Yearbook, 2010). Therefore, if all e-waste is recycled, the annual e-waste importation and generation in China will cause a significant environmental burden (Table 5).

Zoeteman et al. (2010) and Ongondo et al. (2011) reported that the use of landfills is also a commonly used e-waste disposal method worldwide. Approximately 40% of e-waste comes from disposal to landfill in China (Zoeteman et al., 2010; Hong et al., 2010b), whereas approximately 70% of heavy metals in US landfills come from e-waste (Widmer et al., 2005). An LCA analysis of MSW disposal to landfill and incineration in China was reported by Hong et al. (2010b). Fig. 5 compares the LCIA results of e-waste disposal to landfill and incineration (without energy recovery), and the ET-D and ET-ND scenarios. E-waste with end-life disposal to incineration has the highest environmental impact among the categories, except for climate change, ozone depletion, ecotoxicity (i.e., marine, terrestrial, and freshwater), urban land occupation, natural and agricultural land transformation, and water depletion (Fig. 5a). In ozone depletion and urban land occupation, the highest environmental burden is attributed to the ET-D scenario, whereas that in ecotoxicity (i.e., marine, terrestrial, and freshwater) is

Table 5
Annual estimated environmental burden generated by e-waste import and generation in China.

	Average annual LCIA value from e-waste import		Average annual LCIA value from e-waste generation	
	ET-D	ET-ND	ET-D	ET-ND
Climate change (kg CO_2 eq)	1.26×10^9	6.91×10^8	5.04×10^8	2.76×10^8
Human toxicity (kg 1,4-DB eq)	4.18×10^7	8.5×10^8	1.67×10^7	3.4×10^8
Photochemical oxidant formation (kg NMVOC)	5.42×10^6	5.84×10^6	2.16×10^6	2.33×10^6
Particulate matter formation (kg PM10 eq)	1.37×10^6	1.3×10^6	5.46×10^5	5.21×10^5
Terrestrial acidification (kg SO_2 eq)	3.51×10^6	3.45×10^6	1.4×10^6	1.38×10^6
Freshwater eutrophication (kg P eq)	5.53×10^4	2.59×10^4	2.21×10^4	1.03×10^4
Marine eutrophication (kg N eq)	7.75×10^5	7.28×10^5	3.1×10^5	2.91×10^5
Terrestrial ecotoxicity (kg 1,4-DB eq)	1.09×10^4	3.81×10^8	4.36×10^3	1.52×10^8
Freshwater ecotoxicity (kg 1,4-DB eq)	8.98×10^5	4.43×10^7	3.49×10^5	1.77×10^7
Marine ecotoxicity (kg 1,4-DB eq)	8.98×10^5	2.27×10^7	3.59×10^5	9.06×10^6
Fossil depletion (kg oil eq)	2.21×10^8	1.75×10^8	8.83×10^7	6.99×10^7

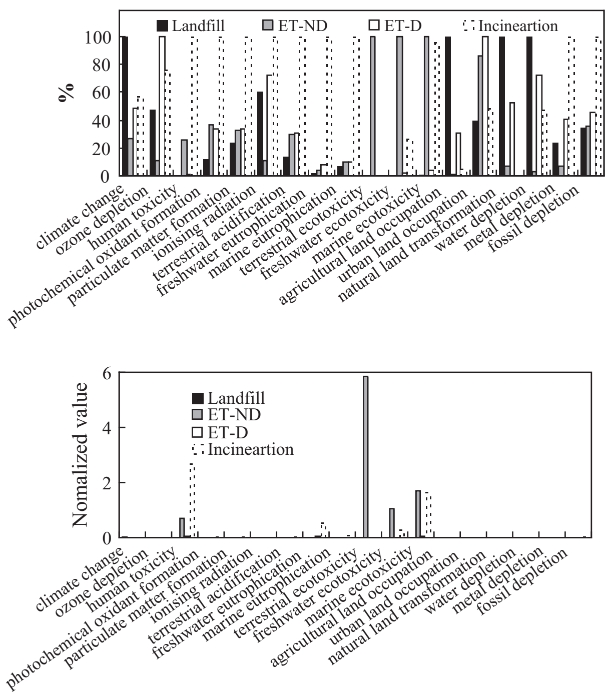

Fig. 5. Life cycle impact assessment results comparison. (a) Midpoint results and (b) normalized value.

attributed to the ET-ND scenario. For the other categories, landfill technology was the highest contributor. The normalized overall environmental impact of landfill, incineration, ET-D, and ET-ND scenarios is 0.10, 5.41, 0.24, and 9.38, respectively. The overall environmental impact of the incineration scenario is approximately 54 times higher than that of landfill because of the direct air emission of heavy metals. Song et al. (2012) compared e-waste disposal to landfill and incineration technologies by using "Eco-indicator 99" method on the basis of the Ecoinvent database. The results showed that the overall environmental impact from the incineration scenario is approximately 37 times higher than that from landfill. The difference in overall environmental burden between incineration and landfill obtained from this study is larger than that reported by Song et al. (2012) because of regionalization, uncertainties, and geographical variability in the applied inventories and LCIA models. The energy type and system boundaries considered in each research played additional and important roles in the variation. Niu et al. (2012) also proved that e-waste incineration can generate a significant environmental burden compared with MSW incineration because of direct toxic material emissions. Hong et al. (2009) compared incineration and melting technologies, which are methods of waste disposal by burning at 800–900 °C and 1300–1800 °C, respectively. Their results showed that waste melting technology can significantly reduce toxic pollutants because of their crystallizability at high temperature. Therefore, e-waste melting technology might be a better choice than e-waste incineration from an environmental perspective. The overall environmental impact of the ET-ND and incineration scenarios is mainly attributed to human toxicity, freshwater ecotoxicity, and marine ecotoxicity (Fig. 5b). The impact of freshwater eutrophication and terrestrial ecotoxicity also plays an important role in the incineration and ET-ND scenarios, respectively. LCA was conducted with the gate-to-gate approach in the current study. The environmental benefit of recovering metals, glass, and plastic from e-waste was excluded in this study. Song et al. (2012) reported that the recovery of copper and plastic from e-waste can generate significant environmental benefits. Therefore, the lowest overall environmental impact could be found in the ET-D scenario in consideration of the environmental benefit of the recovery of metals, glass, and plastic from e-waste.

5. Conclusion

This study compared the LCIA of e-waste with and without end-life disposal. To add credibility to the study, sensitivity and uncertainty analyses were also conducted. The life cycle inventory, the key factors identified, and the LCIA analysis results will be helpful to e-waste management decision makers. The main findings showed that although the impact of the ET-D scenario for climate change, freshwater eutrophication, and fossil depletion are significantly higher than those obtained from the ET-ND scenario, the overall environmental impact of the ET-ND scenario is significantly higher than that of the ET-D scenario. This disadvantage compared with that of the ET-D scenario is mainly ascribed to the increase in direct soil emissions during the waste open dumping stage. Therefore, the scientific improvement of the end-life disposal process of e-waste treatment and the reduction of improper e-waste treatment amounts are efficient ways to reduce the overall environmental burden. Compared with the ET-D scenario, incineration and landfill technologies are also not preferred for e-waste disposal because e-waste can produce many important mineral resources. However, the environmental benefits from the recovery of those mineral resources are unclear. Further research on this subject is therefore needed.

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