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Application of Life Cycle Assessment on Electronic Waste Management: A Review

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Abstract Electronic waste is a rich source of both valuable materials and toxic substances. Management of electronic waste is one of the biggest challenges of current worldwide concern. As an effective and prevailing environmental management tool, life cycle assessment can evaluate the environmental performance of electronic waste management activities. Quite a few scientific literatures reporting life cycle assessment of electronic waste management with significant outcomes have been recently published. This paper reviewed the trends, characteristics, research gaps, and challenges of these studies providing detailed information for practitioners involved in electronic waste management. The results showed that life cycle assessment studies were most carried out in Europe, followed by Asia and North America. The research subject of the studies mainly includes monitors, waste printed circuit boards, mobile phones, computers, printers, batteries, toys, dishwashers, and light-emitting diodes. CML was the most widely used life cycle impact assessment method in life cycle assessment studies on electronic waste management, followed by EI99. Furthermore, 40% of the reviewed studies combined with other environmental tools, including life cycle cost, material flow analysis, multi-criteria decision analysis, emergy analysis, and hazard assessment which came to more comprehensive conclusions from different aspects. The research gaps and challenges including uneven distribution of life cycle assessment studies, life cycle impact assessment methods selection, comparison of the results, and uncertainty of the life cycle assessment studies were examined. Although life cycle assessment of electronic waste management facing challenges, their results will play more and more important role in electronic waste management practices.

Keywords Electronic waste · Waste management · Waste treatment · Life cycle assessment

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Introduction

With the development of industrialization and urbanization, resources have been transforming from ore minerals to urban mines, i.e., anthropogenic stocks of materials (Cossu 2013). Electronic waste is a typical stream of urban mines and its volume is projected to reach about 66.5 million tons in 2017 globally (Xue and Xu 2015). On the one hand, electronic waste represents a rich source of basic metals, precious metals, and rare earth metals for reutilization (Tanskanen 2013). On the other hand, electronic waste contains a variety of toxic substances that are harmful to the environment and human health if inadequately handled (Ogunseitan et al. 2009; Song and Li 2014). Within the context of sustainable development, electronic waste management is one of the biggest challenges of current worldwide concern (Ongondo et al. 2011).

Extensive investigations have been conducted to cope with these challenges (Pérez-Belis et al. 2015). Recycling of electronic waste is a critical part closing the material loops. Currently, various recycling options are available for electronic waste treatment. Pyro-metallurgical process is a traditional approach to recover non-ferrous and precious metals, which has been practiced in Noranda, Boliden, and Umicore (Cui and Zhang 2008). Hydrometallurgical process features in its high recovery efficiency and suitability for small-scale applications (Kolencik et al. 2013; Sun et al. 2015; Tuncuk et al. 2012; Yazici and Deveci 2013). Due to easier operability, mechanical process draws attention for material recovery from electronic waste especially in upgrading stages (Cui and Forssberg 2003; He et al. 2006; Huang et al. 2009). Bioleaching and pyrolysis are also researched (De Marco et al. 2008; Shah et al. 2014) and many other new methods can be expected in the future. In many situations, some of the above processes are combined together forming a whole recycling chain.

Although these technologies promote electronic waste recycling, questions about the quantitative environmental impacts are raised. How much impact on the environment and human health dose each process have? What is the most significant environmental impact category? Which process or method is better for a certain kind of electronic waste? This information is of importance for improving the environmental performance of recycling activities toward a more sustainable electronic waste management.

Life cycle assessment (LCA), an effective and prevailing environmental management tool, can answer the above-mentioned questions by evaluating environmental impacts of a product or service and help to identify improvement potentials (Barton et al. 1996; Rebitzer et al. 2004). LCA was proposed and went through a conception times from 1970s to 1990s, which was mainly used for sustainable market claims with diverging approaches (Chang et al. 2014). In the following decade, Society of Environmental Toxicology and Chemistry and International Organization for Standardization (ISO) promoted a tremendous development of LCA by harmonizing and standardizing the methods (Guinée et al. 2011). According to the ISO, the framework of LCA includes four phases: goal and scope definition, life cycle inventory, life cycle impact assessment, and interpretation (ISO 2006). In the 21st century, the LCA studies are evolving with broader application in more depth (Finnveden et al. 2009; Pennington et al. 2004).

As a matter of fact, quite a few scientific literatures with respect to application of LCA on electronic waste management with significant findings have been recently published. However, there is still a lack of systematic analysis on the trends, characteristics, and challenges of LCA studies on electronic waste management. In this work, the state-of-the-art LCA practices on electronic waste management were reviewed and the challenges were comprehensively analyzed. The main objective of this work is to provide referential information for LCA practitioner focusing on electronic waste management.

This review starts with a background introduction. Then, the section "Review method" introduces the review method. The section "LCA of electronic waste management—Current practices" presents main findings of current LCA studies on electronic waste management. The section "LCA of electronic waste management—Characteristic analysis" analyzes the characteristics of these studies. The section "LCA of electronic waste management—Research gaps and challenges" provides research gaps and challenges on the basis of sections "LCA of electronic waste management—Current practices" and "LCA of electronic waste management—Characteristic analysis". Finally, the section "Conclusions" comes with important conclusions.

Review Method

This study is based on scientific literature review. We carried out reference retrieval using online databases including Web of Knowledge and Scopus, with search keywords of "life cycle assessment/analysis", "LCA", "electronic waste", "e-waste", "waste electrical and electronic equipment (WEEE)", and so on.

Considering on our objectives for better waste management, only studies of LCA on electronic waste recycling and management were included. Studies with the purpose of identifying environmental information of all stages including manufacturing and use of electrical and electronic equipment were not within the scope of this review. In addition, this work focuses on the practices of LCA rather than the theoretical development. Studies written in English were considered and in other languages were excluded.

After retrieval and screening, 33 papers were finally selected. Then, these studies were classified and analyzed thoroughly according to the research scale, location, electronic waste type, environmental impact category, and so on.

LCA of Electronic Waste Management—Current Practices

Monitors

Several studies conducted LCA of monitors including both cathode ray tube (CRT) and liquid crystal display (LCD). The environment burdens of two recycling scenarios for management of waste CRT were evaluated and then compared with landfill. The results confirmed that the recycling process allowed environmental benefits (Rocchetti and Beolchini 2014). In the United States, five waste CRT funnel glass management options including hazardous waste landfill, municipal waste landfill, pyro-metallurgy, close loop recycling, and hydrometallurgy were assessed, which concluded that pyro-metallurgy and hydrometallurgy were the most feasible methods from the view point of environment and economy. Also, transportation was identified as a key factor affecting the LCA results (Xu et al. 2013). In another study, waste CRT glass was used to produce ceramic glaze without decreasing properties. This process was analyzed by LCA, which indicated an environmental impact reduction compared with the standard one (Andreola et al. 2005). Under the background that LCDs was replacing CRTs, a study analyzed indium and glass recycling from LCD through grinding and electrical disintegration by applying LCA. The electrical disintegration performed better that generated much smaller environmental burdens (Dodbiba et al. 2012). Likewise, the environmental burdens of CRT and LCD management considering four options including reuse, recycling, sanitary landfill, and hazardous waste landfill were compared, which demonstrated that LCD disposal had less impact than CRT disposal except the mercury management (Noon et al. 2011).

Printed Circuit Boards (PCBs)

PCBs were another typical electronic waste components. Two methods consisted of mechanical and electrochemical processes recovering copper from PCBs were compared by LCA. It showed that using aqua regia produced better outcomes than using sulfuric acid from the environmental impact perspective (Soares Rubin et al. 2014). Further, a PCBs process chain recovering not only copper but also heavy metals and precious metals was assessed in a LCA study, which identified refining stage as a critical process posing most of the environmental impact (Xue et al. 2015). The recycling of PCBs from mobile phones was assessed in Malaysia and Australia. It was found that demand of recycled materials, law, and management system influenced the recycling impact significantly (Soo and Doolan 2014).

Other Electronic Wastes

Mobile phones treatment was evaluated by LCA in Brazil, the results of which indicated that recycling interiorly generated less environmental impact than partially exported to Europe (Moraes et al. 2014). Notebook computers treatment in 13 scenarios based on different ratios of recovery, incineration, landfill, and second-hand market was analyzed. It concluded that policy should not stress recovery (Lu et al. 2006). Four scenarios of printer treatment with different recovery ratios in the United Kingdom were assessed. The environmental burdens relied on the material type and waste management process. So the specific environmental objectives and operating standards might be researched to replace the mass-based recovery target in European Union (Mayers et al. 2005). The environmental burdens of energy recovery and mechanical recycling of plastics from waste TV sets were calculated, indicating that the latter option is better (Dodbiba et al. 2008). Different treatment processes of waste fluorescent lamp, i.e., recycling and non-recycling, were assessed in Thailand. The results showed that the higher the recycling rate, the more the reduction in environmental impact (Apisitpuvakul et al. 2008). For disposal of dishwashers, the environmental burdens of whether remove copper or not prior shredding were analyzed by LCA. It was found that pre-step can reduce environmental impact and suggested material hygiene concept to be a sound guiding principle (Johansson and Bjorklund 2010).

Mixed Plastics and Metals

Generally, mixed plastics and metals would be produced after pre-treatment of electronic waste. With respect to the plastic parts, two thermal methods were assessed coming to a conclusion that staged-gasification performed better than co-combustion (Bientinesi and Petarca 2009). Similarly, another study evaluated the pyrolysis treatment of plastic reminders and then compared with incineration and landfill in Europe. Pyrolysis was considered as a strong compromise way (Alston and Arnold 2011). With respect to the mixed metal parts, a portable prototype plant employing hydrometallurgical processes was analyzed by LCA, which found that metal extraction steps generated highest environmental impact (Rocchetti et al. 2013). Another study looked into the process from manual sorting, through physical separation, to metallurgical treatment for metal recovery from high grade electronic waste. The results indicated that metal recovery created a lot of environmental saving through avoiding resource consumption (Bigum et al. 2012). Hence, metal treatment during electronic waste management is critical for the total environmental performance.

Electronic Waste Management System

Except for aiming at one kind of electronic waste, there were many studies assessing whole electronic waste treatment system or an enterprise project. Two Swiss take-back and recycling systems of electronic waste were examined, indicating environmental advantages over the baseline scenario of incineration (Hischier et al. 2005). Five years later, a follow-up study calculated the existing Swiss take-back and recycling systems based on new data. The environmental impact of electronic waste management in 2009 is lower than in 2004 as a result of the plastic treatment improvement (Wager et al. 2011).

Also, the electronic waste management in Italy was assessed. Due to the recovery of metals, the benefits of recycling processes balanced their burdens for most of the impact category (Biganzoli et al. 2015). Considering to the situation in China, a study evaluated the electronic waste treatment with and without end-of-life disposal. The overall environmental impact could be significantly reduced by implementing end-of-life disposal (Hong et al. 2015). To provide referential information, a typical electronic waste treatment enterprise in China was evaluated by LCA. The formal methods applied in this enterprise could achieve lots of environmental benefits (Song et al. 2013b). What is more, a combination of emergy analysis and LCA was undertaken to assess a trial project in an electronic waste treatment enterprise. It indicated that the project was not sustainable because of the low profit at a long-term basis (Song et al. 2013a). In Japan, electronic waste recycling was assessed focusing on climate change problem, which showed that appropriate recycling could significantly avoid greenhouse gas production (Menikpura et al. 2014).

Collection System

Collection systems as the pre-stage of electronic waste treatment also attracted some attention. The transportation network in Italy was assessed and found that fossil fuels were the impact category with highest influence (Gamberini et al. 2010). In response to the low collection rate for the small electronic waste, a LCA study designed and evaluated a new collection model that was proved to be environmentally beneficial (Sole et al. 2012). However, one study analyzed the electronic waste collection system, which showed that collection was harmful in terms of environment (Barba-Gutierrez et al. 2008). One program providing refurbished or new low-cost computers to schools in Colombia was examined by integrated methods, which showed that local refurbishment of computers was more sustainable (Streicher-Porte et al. 2009).

Partial LCA of Electronic Waste

Some studies carried out complete LCA, while others conducted partial LCA. For example, there are some studies using life cycle impact-based method combined with hazard-based method to assess the potential environmental impact of typical electronic waste. The potential environmental impact of light-emitting diodes (LEDs) was examined, indicating that resource depletion mainly resulted from gold and silver while toxicity potentials mainly resulted from arsenic, copper, nickel, lead, iron, and silver (Lim et al. 2011). Moreover, the resource depletion and toxicity potentials from metals in incandescent, compact fluorescent lamp (CFL), and LED bulbs were evaluated and compared, which showed that CFLs and LEDs had higher impact than the incandescent bulb (Lim et al. 2013). The ash residue chemicals from artisanal mining of mobile phones was assessed, which revealed that metals such as copper, beryllium, and nickel, and organic chemicals such as dioxins and furans had high impact to the environment and human health (Hibbert and Ogunseitan 2014). Lithium batteries from mobile phone were also evaluated. It was found that the resource depletion and human toxicity were primarily related to cobalt, copper, nickel, thallium, and silver, while the toxicity potential was related to cobalt, copper, nickel, thallium, and silver (Kang et al. 2013).

LCA of Electronic Waste Management—Characteristic Analysis

Development Process and Research Region of the Studies

The papers reviewed in this study were described in Table 1, among which the first three LCA papers focusing on electronic waste management were published in 2005 (Andreola et al. 2005; Hischier et al. 2005; Mayers et al. 2005). In the following 5 years from 2005 to 2009, there were 10 published papers, implying that researchers began to carry out LCA on electronic waste management gradually along with the expansion of LCA application. Not surprisingly, in the latest 5 years from 2010 to 2014 the amount of studies increased evidently, which is two times higher than the former 5 years. There are all kinds of electronic wastes that need to be disposed of and there exist a variety of disposal methods. The results of LCA studies provide important information in the decision-making process. Hence, it is expected that more and more LCA on electronic waste management would be conducted in the near future.

With respect to the geographical distribution, most of the studies were undertaken in Europe, followed by Asia and North America, as shown in Fig. 1. The Europe began to pay attention to the electronic waste disposal problems very early, which can be dated back to about 20 years ago. After a period of development, the technologies for electronic waste disposal were becoming relatively mature. Moreover, the European Parliament enacted regulations such as the WEEE Directive (European Union 2003a) encouraging recycling and reuse of materials and the Restriction of Hazardous Substances Directive (European Union 2003b) restricting the use of hazardous substances. Hence, in this context the Europe has been very active in carrying out LCA to support electronic waste management. On the other hand, the Europe is also a pioneer of exploration of LCA methodology. The complete inventory database and available life cycle impact assessment tools are other important stimulating factors for carrying out LCA on electronic waste management.

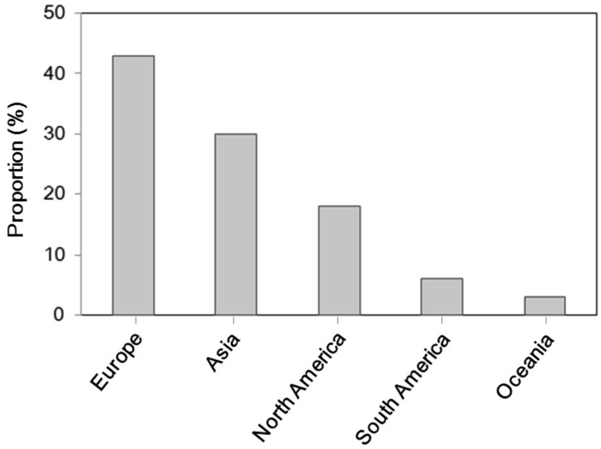

Fig. 1 Geographical distribution of the reviewed studies

Recently, there is an evident increase of LCA on electronic waste management in Asia, especially in China. Due to the difference in development stage, China is the dumping site that processes a large quantity of electronic waste adopting both informal and formal methods. There has been growing recognition of adverse impact on human health and the ecosystems. This resulted in more efforts on LCA of electronic waste management with an expectation of identifying resource depletion and environment impact hotspots during the end-of-pipe treatment. In contrast to the Europe, Asia, and North America, very little studies were conducted in the South America and Oceania. Remarkably, no study was conducted in the Africa among the papers reviewed. Considering the regional characteristics of the background data, there would be a demand in this respect for developing countries in the near future.

Research Subject and Objective of the Studies

The research subjects of the studies mainly include monitors, waste PCBs, mobile phones, computers, printers, batteries, toys, dishwashers, LEDs, and so on. Among them, monitors, PCBs, and mobile phones received more attention. This is mainly because those components have complex composition and there exist several disposal methods. In the reviewed studies, four types of the functional units are identified, i.e., quantity-based, quality-based, collection and treatment-based, and production-based. As shown in Fig. 2, the quality-based functional unit was used most frequently, such as 1 kg (Bientinesi and Petarca 2009), 1 t (Hong et al. 2015), and 100 t (Rocchetti et al. 2013) of the considered electronic waste or its components. In addition, more than 30% of the studies applied quantity-based functional unit. For example, the functional unit was defined as one 14″ CRT (Rocchetti and Beolchini 2014) or one unit of

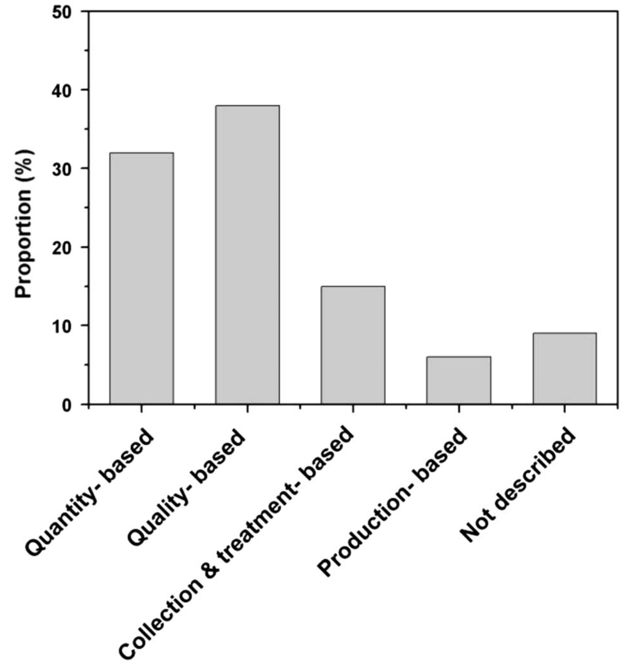

Fig. 2 Proportions of the functional unit used in the reviewed studies (one study was classified into two categories)

the house appliance that was treated (Barba-Gutierrez et al. 2008). It is also found that some studies use the collection and treatment-based and the production-based functional unit, which account for 15 and 6%, respectively. They are related to the amount of collected and treated electronic waste or the amount of product obtained from the recycling process, such as the received printers for treatment and recycling at retail points (Mayers et al. 2005) and recovery of 102 g of copper (Soares Rubin et al. 2014). One study used two types of functional units: the quantity-based functional unit to compare CRT and LCD disposal; and the quality-based unit to compare the expected regional change in monitor disposal from 2008 to 2010 (Noon et al. 2011). The functional unit has an important effect on the inventory analysis and the results interpretation. According to their objectives, the LCA practitioners can select a specific functional unit.

When carrying out LCA studies on electronic waste management, the starting points could be classified into three categories. The first category is to investigate the environmental impact of processing one specific electronic waste, which aims at identifying hotspots of one treatment technology or comparing different treatment technologies. The second one is taking electronic waste as a whole to optimize a trial project or reduce environmental impact of activities of an electronic waste treatment factory. The third one is focusing on the collection systems for electronic waste, which explores effective feedstock gathering.

Impact Assessment Method of the Studies

Life cycle impact assessment is the third phase of LCA following the inventory analysis. There are various kinds of life cycle impact assessment methods, as show in Fig. 3. It was observed that CML was most widely used in LCA studies on electronic waste management, followed by EI99. Other methods such as EPS 2000, EDIP, IMPACT 2002+, TRACI, USEtox, ReCiPe, and ES06 were also used in some studies. Nevertheless, it is not clear in some studies which life cycle impact assessment method was used. Interestingly, sometimes two or more methods were applied in one LCA study. The authors tried to compare the results obtained from different methods to testify whether they were consistent and to provide information in multiply dimensions.

In addition, many of these life cycle impact assessment methods are embedded in commercial LCA software. SimaPro and GaBi were most commonly used softwares, accounting for 39 and 15%, respectively. There are also many studies that were calculated by establishing models rather than using commercial software. In this case, the inventory analysis and characterization factors used for calculation were easier to be learned by the readers.

With respect to the impact categories, the studies vary differently. In some cases, only one impact category such as greenhouse effect was covered (Menikpura et al. 2014). In other cases, up to 18 different types of impact categories were covered (Hong et al. 2015). Normalization and weighting, as optional procedures of life cycle impact assessment, could be conducted to make different types of

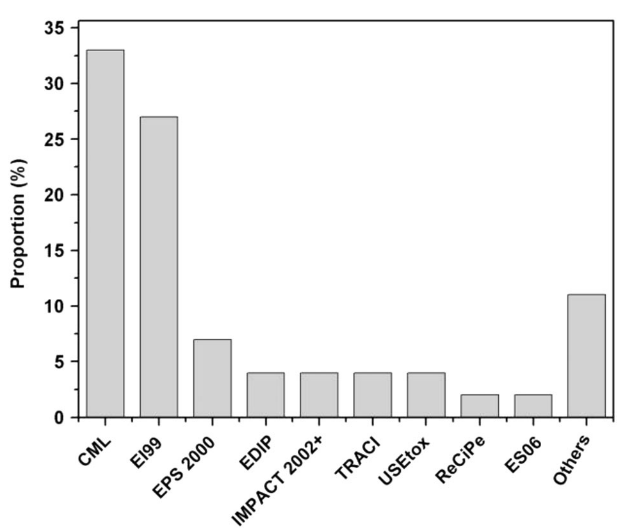

Fig. 3 Proportions of the life cycle impact assessment method used in the reviewed studies (some studies contain more than one life cycle impact assessment method and some others using new models or not described)

impact categories comparable when more than two impact categories were selected. Of all, 63% of the studies conducted the normalization and weighting, although these parts are relatively controversial due to their uncertainty and subjectivity at present.

Combination with Other Environmental Tools

For the reviewed studies, 60% of them were conducted to evaluate the environmental performance of electronic waste management activities by LCA only, while other 40% were conducted with a combination of other environmental management tools. Except the environmental performance, the economic feasibility is always considered when assessing the related activities. Hence, the economic evaluation, cost-benefit analysis, or life cycle cost (LCC) combined with LCA could give a comprehensive conclusion (Xu et al. 2013; Mayers et al. 2005; Lu et al. 2006). Material flow analysis (MFA) can identify the material flows associated with the processes or systems. Several studies performed MFA providing input and output data, on the basis of which LCA was conducted to calculate the environmental impacts (Hischier et al. 2005; Soo and Doolan 2014; Wager et al. 2011). Multi-criteria decision analysis (MCDA) was also used to pick out the best option considering LCA and technical results (Gamberini et al. 2010). In another study, emergy analysis was combined with LCA investigating the effectiveness of an electronic waste treatment project from the perspective of energy and environment (Song et al. 2013a). There were also some studies using life cycle-based and hazard assessment-based methods to evaluate the potential environmental and human health impacts, supporting the decision making in government policy (Kang et al. 2013; Lim et al. 2011; Lim et al. 2013).

LCA of Electronic Waste Management—Research Gaps and Challenges

Through reviewing the LCA practices on electronic waste management, several research gaps and challenges were identified as discussed below.

Uneven Distribution of LCA Studies in the Word

As analyzed in the section “Development process and research region of the studies”, most of the LCA studies on electronic waste management were carried out in developed regions such as Europe. It is worth noting that no study was conducted in Africa. This may be attributed to the different economic development stages, environmental awareness, and LCA data availability. In fact, electronic waste is seen as valuable resource rather than waste in developing countries. Many electronic wastes are transferred from developed countries to developing countries, causing potential adverse impact to human health and the ecosystems. This calls for assessment studies to evaluate the impact of electronic waste treatment activities. However, the LCA studies on electronic waste management in developing countries are very limited. On the other hand, most of the environmental impacts are regional specific. So the regional-specific fate models and characterization factors in developing countries need to be developed.

Life Cycle Impact Assessment Method Selection

The identified life cycle impact assessment methods can be classified into damage-oriented (EI 99; EPS 2000; IMPACT 2002+; USEtox; ReCiPe 2008) and problem-oriented (CML; EDIP 2003; TRACI) methods. The damage-oriented methods model the cause effect chain to endpoint level, while the problem-oriented methods model to midpoint level. The frameworks of life cycle impact assessment methods were shown in Figs. 4–10. In these methods, the assessment level in the cause effect chain, spatial scale, time scope, impact category, indicator, and covered substances are different. So it would be very challenging to choose a proper life cycle impact assessment method when conducting LCA study on electronic waste management. When the assessment area was inconsistent with that in the existing method, it is encouraged to calculate the result using indigenous parameters. Further, it is not necessary to use all the impact categories embodied in these life cycle impact assessment methods. For example, only two impact categories (abiotic depletion and global warming potential) were used to explore the potential for improving the effectiveness of material recovery (Johansson and Bjorklund 2010).

Comparison of the Results

Generally speaking, the results of LCA studies cannot be compared, since different methods have different background with their featured parameters. However, for the same impact category the results from different methods can be used to analyze how the model and parameter selection affect the outcomes. Furthermore, different methods can be used in one study to investigate the sensitivity of LCA of electronic waste management (Song et al. 2013b; Wager et al. 2011; Xu et al. 2013).

Uncertainty of the LCA Studies

Apart from the method itself, data quality is another important source of uncertainty. Unfortunately, LCA data deficiency was mentioned in many studies resulting in many assumptions during inventory analysis and life cycle impact assessment. Most of the commonly used life cycle impact assessment methods were integrated into popular commercial LCA softwares. Even the LCA model was established by the practitioners using the commercial LCA software, the parameters such as characterization factors were mostly based on Europe or the United States. For example, the PCBs processing chain in China was assessed using CML method integrated into GaBi software (Xue et al. 2015). The recycling activities and emissions took place in China where data for converting inventory result to environmental impact was limited. Nevertheless, some of the impact categories are based on Europe. This type of uncertainty must be kept in mind when doing results interpretation. In addition, in some cases the LCA contents such as the boundary condition, functional unit, inventory analysis data sources, LCA method, and impact categories were not transparent. It would be easier to understand the LCA results with these information available in the studies in future.

Conclusions

There is an increase trend in LCA studies on electronic waste management in recent years. It is expected that more LCA studies would be undertaken in the future since LCA results could provide important information in decision-making. LCA studies were mostly conducted in Europe, followed by Asia and North America. Europe, where development of LCA theory, database, and application are the most mature, pays attention to electronic waste problems at the earliest time. The research subjects of the studies mainly include monitors, waste PCBs, mobile phones, computers, printers, batteries, toys, dishwashers, and LEDs. The studies investigated the environmental impact of electronic management to identify the hotspots of one treatment technology or compare different treatment technologies. CML was most widely used in LCA studies on electronic waste management, followed by EI99. In addition, 40% of the reviewed studies combined with other environmental tools including LCC, MFA, MCDA, emergy analysis, and hazard assessment method brought about more comprehensive conclusions from different aspects. Through analyzing LCA studies on electronic waste management, research gaps and challenges associated with uneven distribution geographically, life cycle impact assessment method selection, results comparison, and uncertainty of the LCA studies are identified.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

Appendix

See Figures 4–10 and Tables 1 and 2.

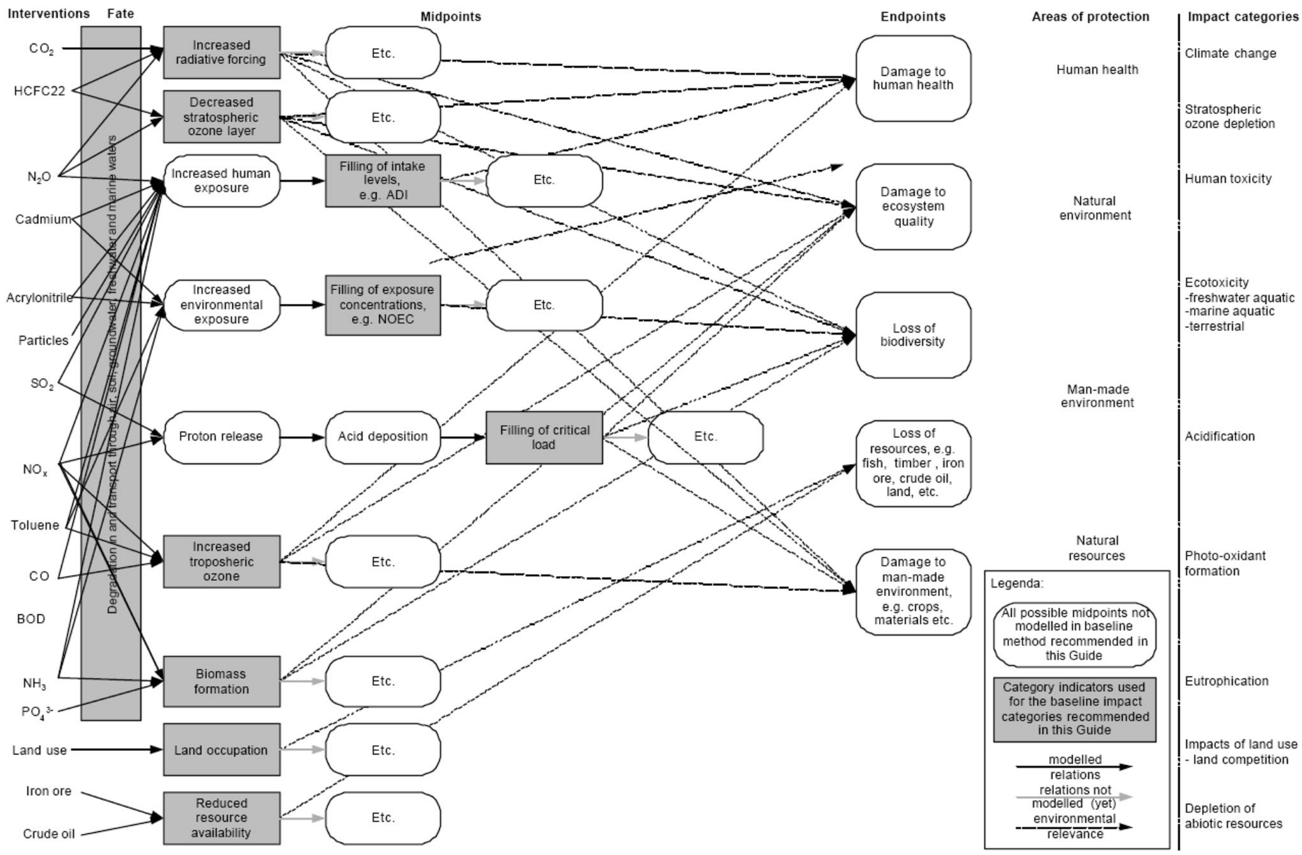


Fig. 4 The framework of CML method for the baseline impact categories (Guinée et al. 2002)

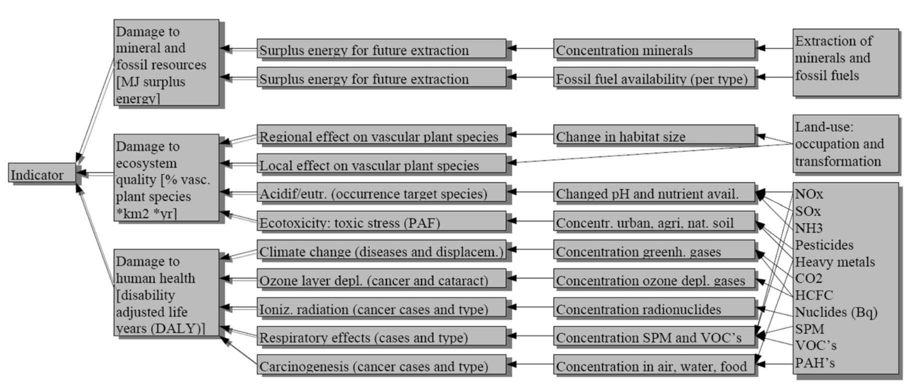


Fig. 5 The framework of Eco-indicator 99 method (Goedkoop and Spriensma 2000)

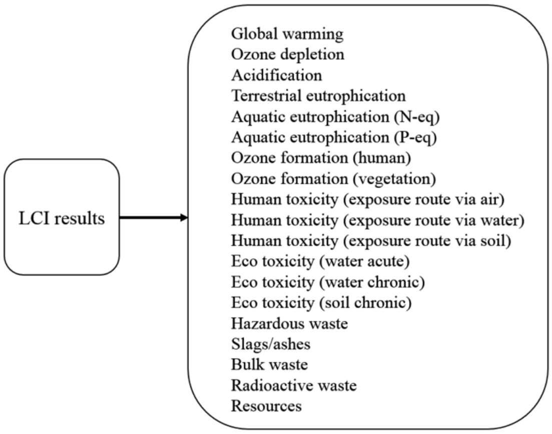


Fig. 6 The framework of EDIP 2003 method

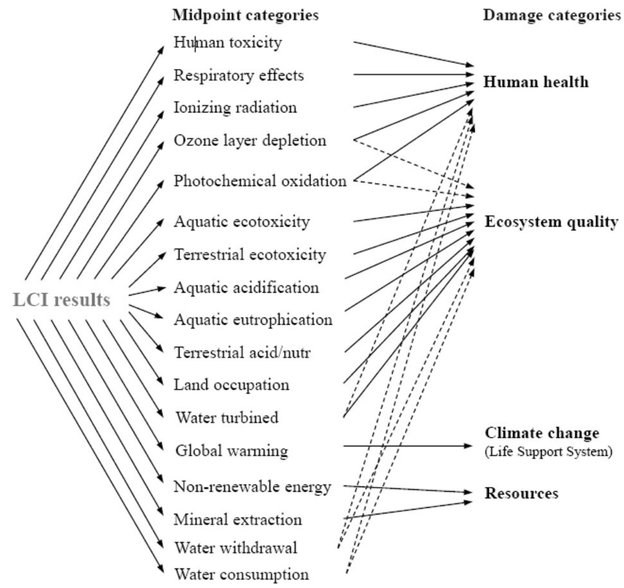


Fig. 7 The framework of IMPACT 2002+ method (Jolliet et al. 2003)

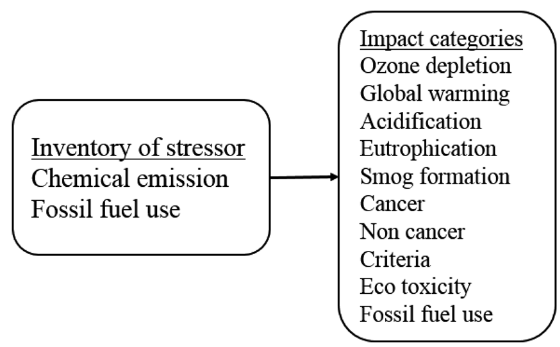
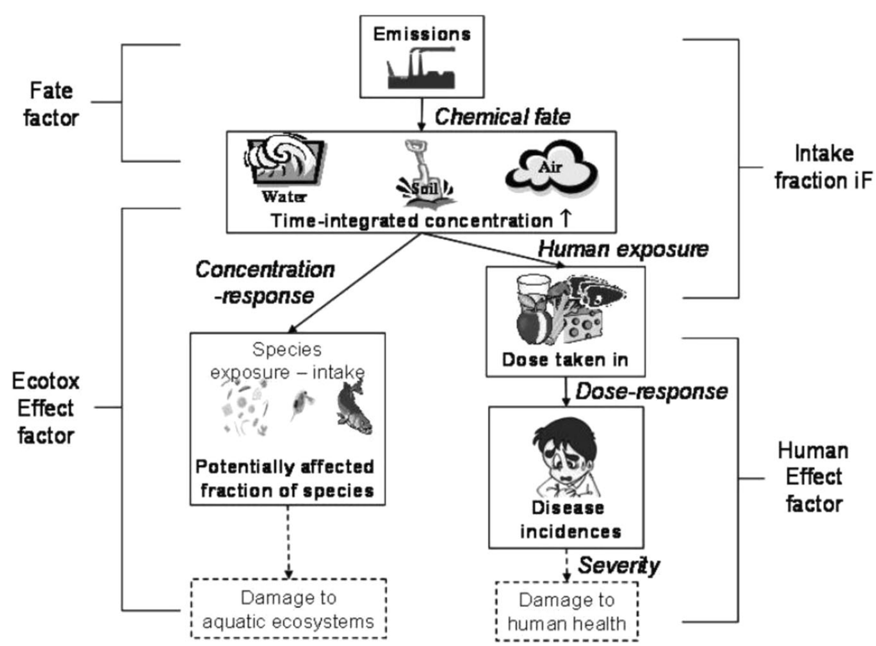


Fig. 8 The framework of TRACI method (Bare 2011)

Fig. 9 The framework of USEtox method (Huijbregts et al. 2010)



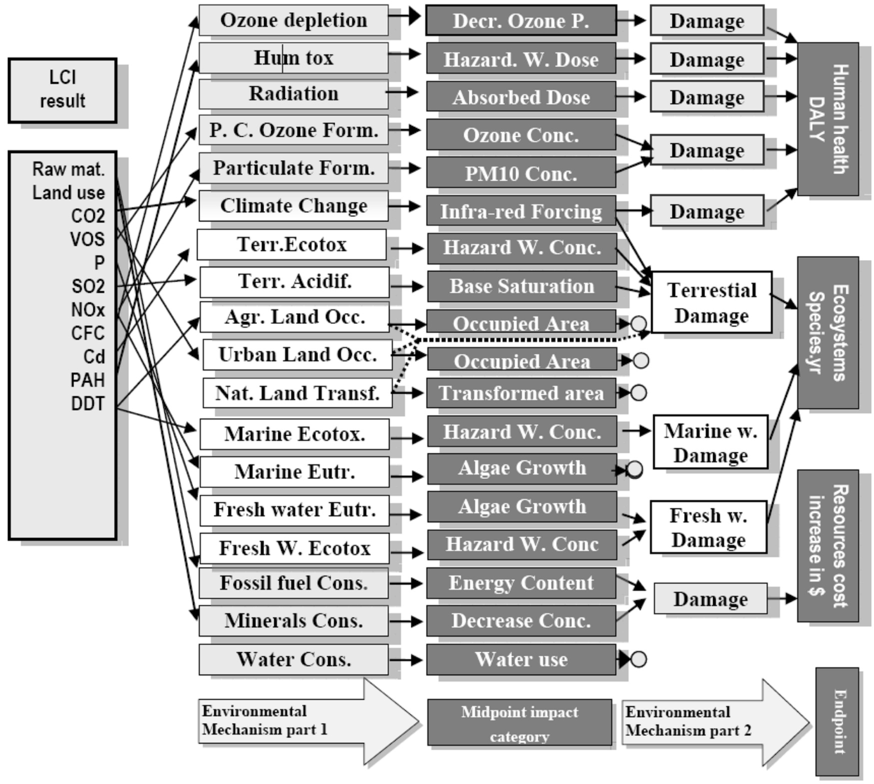


Fig. 10 The framework of ReCiPe 2008 method (Goedkoop et al. 2009)

Table 1 Overview of the reviewed studies

Author, year, location	Title	Impact categories	Main findings
Alston and Arnold, 2011, UK	Environmental impact of pyrolysis of mixed WEEE plastics part 2: LCA	CML: HTP, FAETP, MAETP, TETP, AP, EP, ADPEco99: Human health, ecosystemES06: Carbon deposit	Pyrolysis is a strong compromise option for WEEE plastics treatment compared with incineration and landfill
Andreola et al. 2005, Italy	CRT glass recycling: an example of clean technology	Human health, ecosystem, resources depletion	CRT glass glaze production demonstrated a reduction of environmental impacts compared with the standard one
Apisitpuvakul et al. 2008, Thailand	LCA of spent fluorescent lamps in Thailand at various rates of recycling	Carcinogens, respiratory organics, respiratory inorganic, climate change, radiation, ozone layer, eco-toxicity, acidification/eutrophication, land use and minerals	Cement production is the main contributor to the environmental impacts for spent fluorescent lamps recycling in Thailand
Biganzoli et al. 2015, Italy	Mass balance and LCA of the WEEE management system implemented in Lombardia Region (Italy)	Climate change, ozone depletion, human toxicity-cancer effects, human toxicity-non-cancer effects, particulate matter, photochemical ozone formation, acidification, terrestrial eutrophication, freshwater eutrophication, marine eutrophication, freshwater eco-toxicity, water resource depletion, and mineral and fossil resource depletion	The overall benefits of WEEE management are closely concerned with the recovery of metals, plastic, and glass
Barba-Gutierrez et al. 2008, Europe	An analysis of some environmental consequences of European electrical and electronic waste regulation	Human health, ecosystem, resources depletion	WEEE recycling is not as environmental friendly as expected, which depends on the collection distance
Bientinesi and Petarca 2009, Italy	Comparative environmental analysis of waste brominated plastic thermal treatments	Eco99: Human health, ecosystem, resources depletionImpact 2002+: Carcinogens, respiratory organics, climate change, radiation, ozone layer, eco-toxicity, acidification/eutrophication, land use, minerals, fossil fuels	Staged-gasification treatment of WEEE plastics had a potentially smaller environmental impact than co-combustion
Bigum et al. 2012, Sweden	Metal recovery from high-grade WEEE: A LCA	Acidification, eco-toxicity, global warming, human toxicity, nutrient enrichment, photochemical ozone formation, stratospheric ozone depletion	The metal recovery from WEEE causes significant environmental savings
Dodbiba et al. 2008, Japan	The recycling of plastic wastes from discarded TV sets: Comparing energy recovery with mechanical recycling in the context of LCA	ADP, GWP, AP, POCP, EP, HTP	Mechanical recycling of TV plastics is a better treatment option in environmental terms than incineration for energy recovery
Dodbiba et al. 2012, Japan	Leaching of indium from obsolete LCDs: Comparing grinding with electrical disintegration in context of LCA	ADP, GWP, AP, POCP, EP, HTP	The electrical disintegration was the most effective liberation method for indium leaching
Gamberini et al. 2010, Italy	On the integration of planning and environmental impact assessment for a WEEE transportation network: A case study	Human health, ecosystem, resources depletion	The fossil fuels and respiratory inorganic are the most critical impact categories
Hibbert and Ogunseitan 2014, USA	Risks of toxic ash from artisanal mining of discarded cell phones	USEtox: Ecotoxic-biological, human non-cancer, cancer	Incineration of e-waste can cause contamination and adverse public health impacts
Hischier et al. 2005, Switzerland	Does WEEE recycling make sense from an environmental perspective? The environmental impacts of the Swiss take-back and recycling systems for WEEE	CML: AP, GWP, EP, POCP, ODP, ARD, FAETP, HTP, TETP, FSETP, MSETP	The recycling system for WEEE in Switzerland has clear environmental advantages compared with incineration

Table 1 continued

Author, year, location	Title	Impact categories	Main findings
Hong et al. 2015, China	LCA of electronic waste treatment	Human toxicity, photochemical oxidant formation, particulate matter formation, ionizing radiation, climate change, ozone depletion, and so on	The environmental impact of the e-waste treatment without end-life disposal is significantly higher than that of the treatment with end-life disposal
Johansson and Bjorklund 2010, Sweden	Reducing life cycle environmental impacts of WEEE recycling	ADP and GWP	Disassembly before shredding can reduce the abiotic depletion and global warming potential
Kang et al. 2013, USA	Potential environmental and human health impacts of rechargeable lithium batteries in electronic waste	Resource depletion, human toxicity, eco-toxicity	The resource depletion and human toxicity of lithium batteries is mainly from cobalt, copper, nickel, thallium, and silver, whereas the eco-toxicity potential is primarily from cobalt, copper, nickel, thallium, and silver
Lim et al. 2011, USA	Potential environmental impacts of LEDs: Metallic resources, toxicity, and hazardous waste classification	Hazardous waste potential, resource depletion potentials, toxicity potentials	The resource depletion potentials of LEDs mainly derives from gold and silver, whereas the toxicity potentials is mainly from arsenic, copper, nickel, lead, iron, and silver
Lim et al. 2013, USA	Potential environmental impacts from the metals in incandescent, CFL, and LED bulbs	Hazardous waste potential, resource depletion potentials, toxicity potentials	The CFLs and LEDs have higher resource depletion and toxicity potentials than the incandescent bulb
Lu et al. 2006, Taiwan	Balancing the life cycle impacts of notebook computers: Taiwan's experience	Human health, ecosystem, resources depletion	Manufacturers should be responsible for the recycling technologies development and redesign rather than recovery should be stressed
Mayers et al. 2005, UK	Extended producer responsibility for waste electronics: An example of printer recycling in the United Kingdom	Depletion of non-renewable resources, air acidification, POCP, EP, GWP, ODP, human, terrestrial, and aquatic toxicity	Specific environmental objectives and operating standards should be studied apart from the mass-based recycling and recovery targets
Menikpura et al. 2014, Japan	Assessing the climate co-benefits from WEEE recycling in Japan	Greenhouse gas emissions	A significant amount of greenhouse gas emissions can be avoided by implementing an appropriate WEEE recycling program
Moraes et al. 2014, Brazil	LCA of cell phones in Brazil based on two reverse logistics scenarios	GWP, ODP, POCP, AP, EP, non-renewable energy	Full treatment of cell phone in Brazil reduces acidification, photochemical oxidation, and eutrophication
Noon et al. 2011, USA	A LCA of end-of-life computer monitor management in the Seattle metropolitan region	GWP, total energy consumption, total fossil fuel consumption, total select air pollution, mercury, lead	LCD monitor disposal had lower environmental impacts than CRT monitor disposal except for the mercury management
Rocchetti et al. 2013, Europe	Environmental impact assessment of hydrometallurgical processes for metal recovery from WEEE residues using a portable prototype plant	ADP, AP, EP, GWP, ODP, POCP	The category of global warming potential was the most critical impact category, and metal extraction steps have the highest impacts
Rocchetti and Beolchini 2014, Italy	Environmental burdens in the management of end-of-life CRTs	ADP, AP, EP, GWP, ODP, POCP	CRTs recycling confirms the environmental advantage by secondary raw material recovery
Soares Rubin et al. 2014, Brazil	Utilization of LCA methodology to compare two strategies for recovery of copper from PCB scrap	EDIP: GWP, SOD, AEP, AE, TE	The process of using aqua regia for Cu recovery from PCBs has better environmental performance than using sulfuric acid
Sole et al. 2012, Spain	Proposal of a new model to improve the collection of small WEEE: A pilot project for the recovery and recycling of toys	ADP, AP, EP, GWP, POCP	The collection campaign for electronic toys in Spain was environmentally beneficial

Table 1 continued

Author, year, location	Title	Impact categories	Main findings
Song et al. 2013a, b, Macau	Sustainability evaluation of e-waste treatment based on emergy analysis and the LCA method: A case study of a trial project in Macau	Human health, ecosystem, resources depletion	The e-waste treatment trial project in Macau had low competitive ability because of its high-input emergy
Song et al. 2013a, b, China	The LCA of an e-waste treatment enterprise in China	CML: AP, GWP, EP, POCP, ODP, ARD, FAETP, HTP, TETPEco99: Human health, ecosystem, resources depletion	Recycled metal is an importance source of environmental benefits
Soo and Doolan, 2014, Malaysia and Australia	Recycling mobile phone impact on LCA	Impact 2002+2: Human health and ecosystem quality	The recycled materials demand, law enforcement, and e-waste recycling system are identified as the significant drivers for reducing the environmental impact of mobile phone recycling
Streicher-Porte et al. 2009, Colombia	One laptop per child, local refurbishment, or overseas donations? Sustainability assessment of computer supply scenarios for schools in Colombia	Use of energy, use of resources, amount of toxic emissions	Excessive refurbishments involving the replacement of larger electronic components can cause net environmental impacts
Wager et al. 2011, Switzerland	Environmental impacts of the Swiss collection and recovery systems for WEEE: A follow-up	CML: AP, GWP, EP, POCP, ODP, ARD, FAETP, HTP, TETPEco99: Human health, ecosystem, resources depletion	The environmental impacts of the recovery system in 2009 is lower than that in 2005 in Switzerland
Xu et al. 2013, USA	Environmental and economic evaluation of CRT funnel glass waste management options in the United States	CML: ADP, AP, EP, MAETP, FAETP, TETP, GWP, HTP, ODP, POCPEco99: Human health, ecosystem, resources depletion	Pyro-metallurgy and hydrometallurgy are the most feasible recycling options in the United States, considering both environmental and economic performances
Xue et al. 2015, China	Waste management of printed wiring boards: A LCA of the metals recycling chain from liberation through refining	GWP, AP, EP, ADP, FAETP, HTP, MAETP, POCP, TETP	The metal leaching in the refining stage posed most of the environmental impact in the recycling chain for waste PCBs

Table 2 Abbreviations used in Table 1

Abbreviations	Impact category
ADP	Abiotic depletion potential
AE	Aquatic eutrophication
AEP	Acidification
AP	Acidification potential
EP	Eutrophication potential
FAETP	Freshwater aquatic eco-toxicity potential
FSETP	Freshwater sediment eco-toxicity potential
GWP	Global warming potential
HTP	Human toxicity potential
MAETP	Marine aquatic eco-toxicity potential
MSETP	Marine sediment eco-toxicity potential
ODP	Ozone layer depletion potential
POCP	Photochemical ozone creation potential
SOD	Stratospheric ozone depletion
TE	Terrestrial eutrophication
TETP	Terrestrial eco-toxicity potential

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