Journal of Cleaner Production 142 (2017) 2965–2972

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Life cycle assessment of polyvinyl chloride production and its recyclability in China

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ARTICLE INFO

Article history:
Received 11 July 2016
Received in revised form
4 October 2016
Accepted 27 October 2016
Available online 29 October 2016

Keywords:
Life cycle assessment
Environmental impact
Primary PVC
Recycled PVC
Energy

ABSTRACT

Polyvinyl chloride (PVC), the second most widely consumed plastic, is a 21st century material generally used in pipes, cables, and other construction applications. Life cycle assessment (LCA) of polyvinyl chloride production and its recyclability in China was conducted to investigate the environmental impact generated from PVC industry. Uncertainty analysis was conducted using the Monte Carlo simulation. Results showed that the key materials contributing to the general environmental burden were chlorine, carbon dioxide, and nitrogen oxides for both scenarios. The primary PVC scenario had an overwhelmingly great environmental impact in most categories except for agricultural land occupation. The impact on climate change can be decreased by 36.21% and 15.53% respectively in producing 1 ton of primary PVC considering alternative energy sources, such as proportionally replacing coal-based electricity generation by hydropower and hybrid power according to the State Grid structure. The key factors in reducing the overall environmental impact of PVC production are promoting the use of recycled PVC, reducing NMVOC emissions, and raising the renewable energy ratio.

1. Introduction

Plastics have played an irreplaceable role in human life and production as the most important material of the 21st century. These materials consist of macromolecules made from monomer, such as ethylene, through addition or condensation polymerization. Plastics are widely used in many parts of civil life, industrial production, and aerospace technology because of their superior material properties, including low cost, lightweight, and durability (PlasticsEurope, 2015). The plastic industry crosslinks to several other parts (e.g., building and construction, packaging, transportation, and electronic) of the entire industry. Thus, the increase of plastic production resulted in the prosperity of other industries. From 2009 to 2013, worldwide plastic production increased slowly with a huge quantity of 250–299 Mton. The plastic production of China also increased to top position at the same time (Plastics-The Facts, 2015). According to Chinese statistics, the annual plastic production of China was approximately 54.74, 57.82, and 61.89 Mton in 2011, 2012, and 2013, respectively. This production accounts for over 20% of global plastic production. Moreover, China produced 73.88 Mton of plastics in 2014 making a rapid 19% increase to the plastic production in 2013 (National Bureau of Statistics of China, 2015). Specifically, polyvinylchloride (PVC) is one of the world's top five raw materials for general synthetic resin with a yield ranking second only behind polyethylene (PE) in the world of plastics. PVC presents a production of 13.0 (23.7%), 13.3 (22.9%), and 15.3 (20.7%) Mton in 2011, 2012, and 2013 in China, respectively (China Plastics Industry Yearbook, 2013).

. To degrade completely plastic takes a long time because plastic is a chemically stable materials (Garcia et al., 2006). Large amounts of persisting waste plastic are consumed and discarded. This condition results in plastic or white pollution. Plastic pollution causes several environmental problems, such as solid waste occupying land and impacting the esthetic sense, ocean pollutant affecting organisms in oceans as food or barriers, and as collective organic chemical pollutants (Gross, 2015; Wilcox et al., 2015). Furthermore, plastic production requires crude oil as materials and consumes great amount of non-renewable resources, which enhance the energy crisis (Thompson et al., 2009). Thus, a thorough inquiry of the environmental impact of plastic production is necessary. Moreover, plastic pollutants need to be managed in an improved and efficient scientific approach (Quartey et al., 2015). Additionally, plastic recycling is the process of recovering waste plastic into useful plastic product. This method saves energy and material to

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http://dx.doi.org/10.1016/j.jclepro.2016.10.171
0959-6526/

solve the white pollution. Recycled plastic is meaningful and vastly promising for future development of great prosperity (Sadat-Shojai and Bakhshandeh, 2011). However, recycling plastics is yet to be developed sufficiently in China. The officially measured total of recovered plastics was 9 Mton, 25.7% recovery (China Plastics Industry Yearbook, 2011). Recycling has been considered by the public to manage the plastic volume (Hopewell et al., 2009; WBCSD, 2000). This study aims to determine whether the recycled PVC is more environmentally friendly than primary PVC or the primary PVC objectively and thoroughly is the basis of proper sustainable development.

Life cycle assessment (LCA) is an assessment and management set for the environment focusing on one production through its entire life. LCA includes material procurement, manufacturing, transportation, usage, and discarding or recycling (ISO 14040, 2006; ISO 14044, 2006). To date, LCA is the most scientific, effective approach in evaluating environmental impact recommended by numerous scholars and associations. Observing the entire life flow is a key in problem solving. Moreover, LCA helps in determining the most contaminative process and pollutant source of production easily. The LCA of plastics has been extensively studied (Potting and van der Harst, 2015; Vahidi et al., 2015). Obtaining the environmental impact of one single type of plastic production (e.g., PE, polystyrene (PS), recycled low density polyethylene (LDPE), or polyamide (PA)) (Gironi and Piemonte, 2011; Potting and van der Harst, 2015; Siracusa et al., 2011), and of one process in the recycled plastic production, i.e., the recovery process (Vahidi et al., 2015) is simple considering the various types of plastics and their different paths ending in recycling or discarding. However, the overall cognition of the environmental impact of the plastic production industry is a difficult to derive. In addition, none of LCA in Chinese polyvinyl chloride (PVC) production has been introduced in international peer-reviewed journals. Moreover, most studies on recycled plastic with an LCA approach simply focus on plastic production, such as PVC window frames (Stichnothe and Azapagic, 2013; Wang et al., 2014) and PVC container (Navajas et al., 2013). Given that recycling plastics include a vast prospect for the plastic industry and a potential in reducing pollutant emissions, increasing our expert knowledge on the impact of recycled plastic production to the environment and the potential for less emissions is essential. Furthermore, the aforementioned LCA studies barely considered uncertainty although uncertainty analysis is the basic information for decision making. Thus, studying these issues using the LCA approach provides answers, as well as a reasonable ideology to measure the reduction and gradual elimination of the pollutants generated by the PVC industry. This study conducted LCA to evaluate the environmental impact of primary and recycled PVC production in China to determine and qualify the key factor, including the key substance and production process. Uncertainty analysis based on the Monte Carlo simulation was used to provide a reliable assessment and decide whether the recycled PVC is more environmental friendly than the primary PVC in each impact category.

2. Materials and methods

2.1. Functional unit

A functional unit is a reference unit that enables alternative product, process, or activity to be compared and analyzed. In this study, a ton of primary and recycled PVC plastic production was selected subsequently as the functional unit. This method provides the counting base of all the production flows as the two systems consider the completed PVC material production with the same use.

2.2. System boundaries

Fig. 1 shows the system boundaries of primary and recycled PVC production. Both scenarios established the general process of raw material input, energy consumption, transport, technological process flows, waste treatment, and direct emissions to the environment based on the functional unit. The production flow of the primary PVC scenario includes two main technological steps—first is vinyl chloride monomer (VCM) production and second is primary PVC production. Similarly, the recycled PVC scenario contains two main processes—recycled PVC particles and recycled PVC productions. Both scenarios involve waste treatment and direct emissions.

2.3. Life-cycle impact assessment methodology

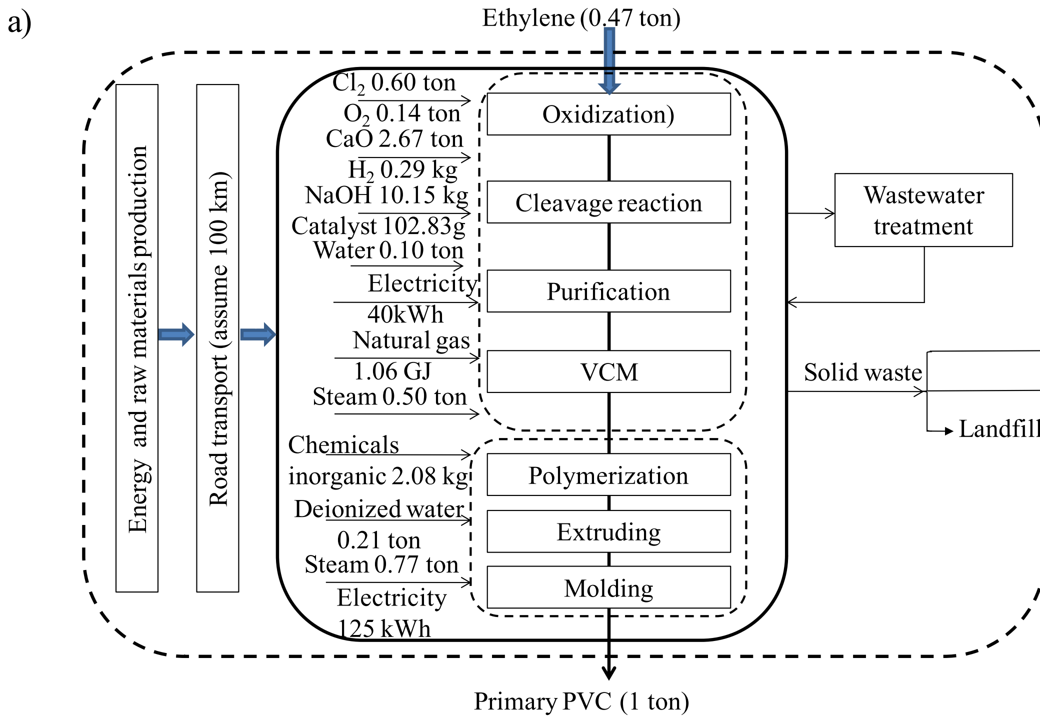
Life cycle impact assessment (LCIA) is calculated using the ReCiPe method, the latest and one of the most widely used method that combines indicator 99(Goedkoop and Spriensma, 2000)and LCA guide 2001 (Guinée et al., 2001). This integrated methodology derives LCIA results on the two levels illustrated by the environmental category indicators, namely, level one–18 midpoint indicators including climate change, ozone depletion, human toxicity, photochemical oxidant formation, particulate matter formation, ionising radiation, terrestrial acidification, freshwater eutrophication, marine eutrophication, terrestrial ecotoxicity, freshwater ecotoxicity, marine ecotoxicity, agricultural land occupation, urban land occupation, natural land transformation, water depletion, metal depletion, and fossil depletion; level two –3 endpoint indicators, including damage to human health, to ecosystems, and to resource availability. Normalization, equals to the ratio of the impact per unit of emission divided by the per capita world impact value of the year 2000, is conducted to compare different midpoint impact categories and to intuitively and efficiently determine the respective shares to overall impact. For more available details, view the website of Institute of Environmental Science in Leiden University of Nederland (http://www.cml.leiden.edu/research/industrialecology/researchprojects/finished/recipe.html).

2.4. Data sources

The primary data of the two scenarios were taken from typical production factories. The primary and recycled PVC factories were located in the provinces of Yunnan and Anhui in China, respectively. The primary PVC production factory included an annual PVC output of 1.5×10^5 ton. The 2013 annual primary data of this enterprise is mentioned in this study. The recycled PVC data referred to the 2015 factory data. The upstream data (i.e., chlorine, lime, hydrogen, sodium hydroxide, transport, electricity, steam, direct emission from PVC production, national coal-based electricity generation, industrial hazardous waste disposal, MSW sanitary landfill, and wastewater treatment) were primarily taken from the Chinese process-based life cycle inventory database(CPLCID), which involved the reviewed process-based life cycle inventory (LCI) of the key enterprises in China (Zhang et al., 2016). As a result of the lack of Chinese data, a more complete data (i.e., liquid oxygen, ethylene, catalyst, and natural gas) from Europe (Ecoinventcentre, 2015) was used in this study. To reduce the influence of the regionalized effect from the Europe, Chinese data involved in the CPLCID database on road transportation and national coal-based electricity generation were used to adapt European data to the Chinese situation.

2.5. Life-cycle inventory

The LCI results of both scenarios are shown in Table 1. This LCI table based on the functional unit summarized of all inputs and



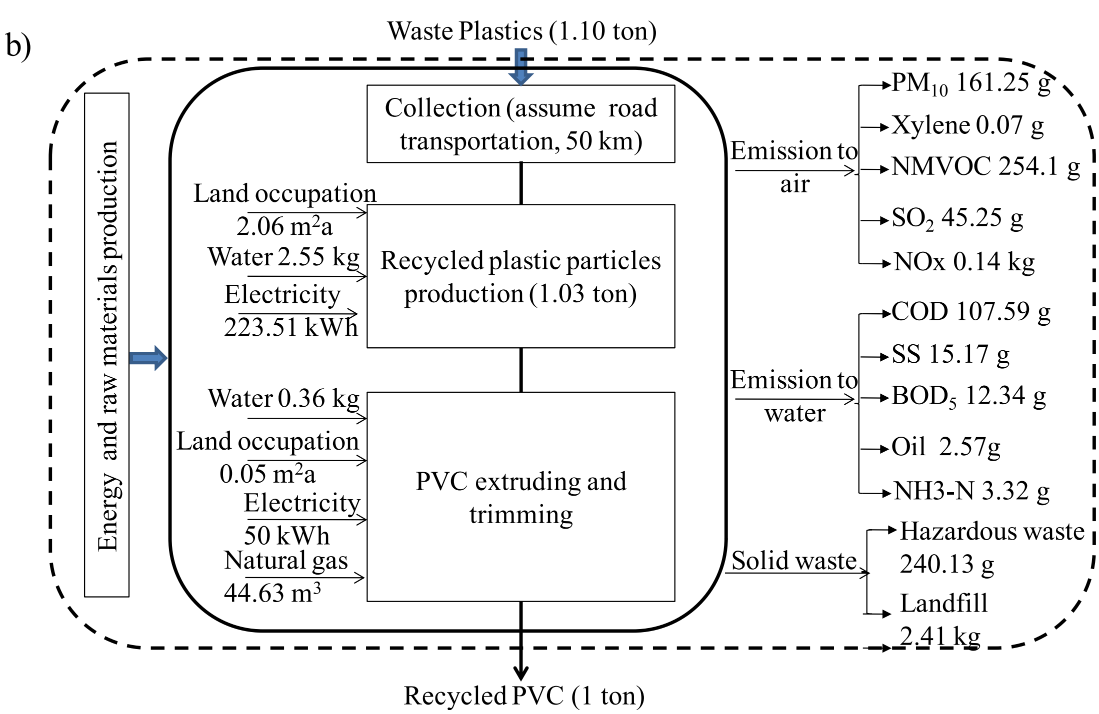


Fig. 1. System boundaries of a) primary PVC, b) recycled PVC.

outputs for the two scenarios.

3. Results

3.1. LCIA results

The LCIA midpoints led to the two scenarios presented in Table 2, with their respective GSD^2 (squared geometric standard deviation) values. The GSD^2 value on the climate change in the primary PVC was 1.43. This result indicates that GSD^2 value corresponds to an integrating potential score in the range of 1.97×10^3–4.03×10^3 kg CO_2eq with a 95% confidence interval. Similarly, tendencies can be calculated with the rest of categories for both scenarios. The primary PVC scenario generally has higher

Table 1
Life cycle inventories of primary and recycled PVC production. Values are presented per functional unit.

	Categories	Unit	Primary PVC	Recycled PVC
Raw materials	Ethylene	ton	0.47	–
	Waste Plastics	ton	–	1.10
	Catalyst	g	2.18×10^3	–
	Cl_2	ton	0.60	–
	O_2	ton	0.14	–
	CaO	g	26.73	–
	H_2	kg	0.29	–
	NaOH	kg	10.15	–
	Deionized water	ton	0.21	–
	Water	kg	5.84×10^3	2.91
Energy consumption	Electricity	kWh	165.00	273.51
	Natural gas	m^3	29.61	44.63
	Occupation	m^2a	0.08	2.11
	Steam	ton	1.27	–
Air emissions	SO_2	kg	0.43	0.04
	NOx	kg	0.43	0.14
	Particulates	kg	0.21	0.16
	Cl_2	mg	93.28	–
	HCl	mg	2.33	–
	VCM	mg	6.02	–
	Xylene	g	–	0.07
	NMVOC	kg	–	0.25
Emissions to water	SS	g	9.13	15.17
	BOD_5	g	9.35	12.34
	COD	g	48.91	107.59
	Hg	mg	0.56	–
	Chloride	mg	38.87	–
	Oil	g	–	2.57
	NH_3	g	–	3.32
Waste to treatment	Industrial Hazardous Waste	g	–	240.13
	Landfill	g	19.43	2.41×10^3
	Wastewater	ton	1.46	0.36

environmental impact scores on each category compared with recycled PVC scenario.

Fig. 2 presents the normalized midpoint results of primary and recycled PVC scenarios to determine the respective shares to overall impact. The impacts in the primary PVC scenario were mainly attributed to human toxicity, terrestrial ecotoxicity, marine ecotoxicity, and fossil depletion. The remaining categories minimally contributed to the overall environmental burden. The climate change, human toxicity, and fossil depletion count as the dominant environmental impacts for recycled PVC scenario, whereas the impacts contributing to the rest of the categories were small.

3.2. Main contributors

Fig. 3 and Fig. 4 displays the key substances and processes of aforementioned key categories. The potential impact of climate change, a common concern of LCA researchers, was also involved in Fig. 4. For both scenarios, chlorine was the most significant substance contributing to terrestrial and marine ecotoxicity. The top three contributors to fossil depletion were oil, natural gas, and coal.

Table 2
LCIA midpoint results of primary PVC production and recycled PVC production. Values are presented per FU.

Categories	Unit	Primary PVC		Recycled PVC	
		Value	GSD^2	Value	GSD^2
Climate change	kg CO_2 eq	2.82×10^3	1.43	646.81	1.30
Ozone depletion	kg CFC-11 eq	9.30×10^{-5}	1.78	7.17×10^{-6}	2.07
Terrestrial acidification	kg SO_2 eq	9.59	1.46	1.82	1.26
Freshwater eutrophication	kg P eq	0.03	2.89	1.71×10^{-3}	1.94
Marine eutrophication	kg N eq	0.48	1.59	0.08	1.37
Human toxicity	kg 1,4-DB eq	428.42	1.74	59.17	1.89
Photochemical oxidant formation	kg NMVOC	12.29	1.55	2.19	1.35
Particulate matter formation	kg PM_{10} eq	3.58	1.47	0.84	1.69
Terrestrial ecotoxicity	kg 1,4-DB eq	14.99	1.95	0.13	1.98
Freshwater ecotoxicity	kg 1,4-DB eq	0.76	1.76	0.03	1.98
Marine ecotoxicity	kg 1,4-DB eq	6.29	1.85	0.12	1.51
Ionising radiation	kBq U235 eq	110.41	3.62	2.86	3.82
Agricultural land occupation	m^2a	10.34	3.42	5.28	1.93
Urban land occupation	m^2a	7.20	1.78	2.53	2.31
Natural land transformation	m^2	0.17	2.91	0.03	3.70
Water depletion	m^3	57.52	1.52	3.37	1.53
Metal depletion	kg Fe eq	48.48	2.35	3.38	1.92
Fossil depletion	kg oil eq	1.12×10^3	1.46	138.09	1.24

GSD^2: squared geometric standard deviation.

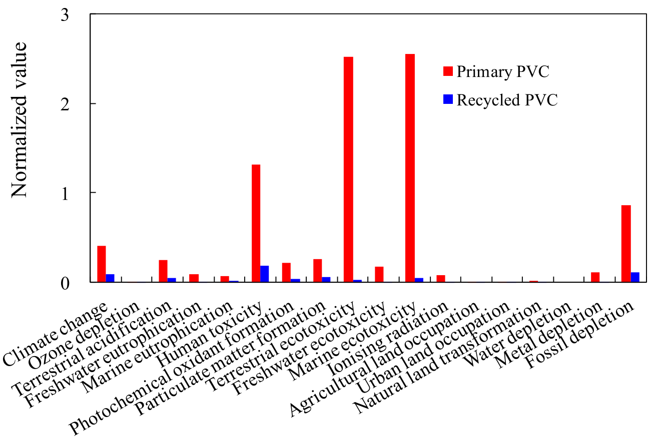


Fig. 2. Normalized midpoint results.

For the primary PVC scenario, the dominant substance contributing to human toxicity was chlorine and mercury. Moreover, mercury was accountable for the human toxicity in the recycled PVC scenario, whereas arsenic, cypermethrin, and copper exhibited an additional dominant contribution to the impact generated from human toxicity, terrestrial ecotoxicity, and marine ecotoxicity, respectively. For the primary PVC scenario, chlorine consumption for VCM production process dominated the impact on each key category described. In the remaining small proportion, mercury emitted from coal-based energy (i.e., steam and electricity) production process exhibited a relatively significant contribution to the impact on the categories. For the recycled PVC scenario, the aforementioned dominant substances emitted from the processes of electricity generation and hazardous waste disposal for recycled plastic particle production were the main contributor to most of the key categories. Natural gas production and coal-based electricity generation processes for PVC extruding and trimming exhibited an additional important contribution to the overall environmental burden.

3.3. Sensitivity analysis

Sensitivity analysis is a way to predict the relationships between input and output variables in a system. In this study, a 5% input variables was assumed. Table 3 exhibits the results of a 5% variation to prominent processes on the key environmental impact categories to evaluate the significant influence on the LCIA results in this study. A 5% decrease in electricity occurred in both scenarios. This result is a common key process leading to middle variations on the presented categories. However, this condition obviously increased the cut off in the primary PVC scenario. Moreover, a dramatic decrease in VCM consumption demonstrated the highest variation in each category for the primary PVC scenario. Meanwhile, improving the catalyst consumption efficiency and the control of direct emission showed the lowest variation in the rest of the categories. For recycled PVC scenario, improving recycled plastic particle consumption efficiency yields the highest

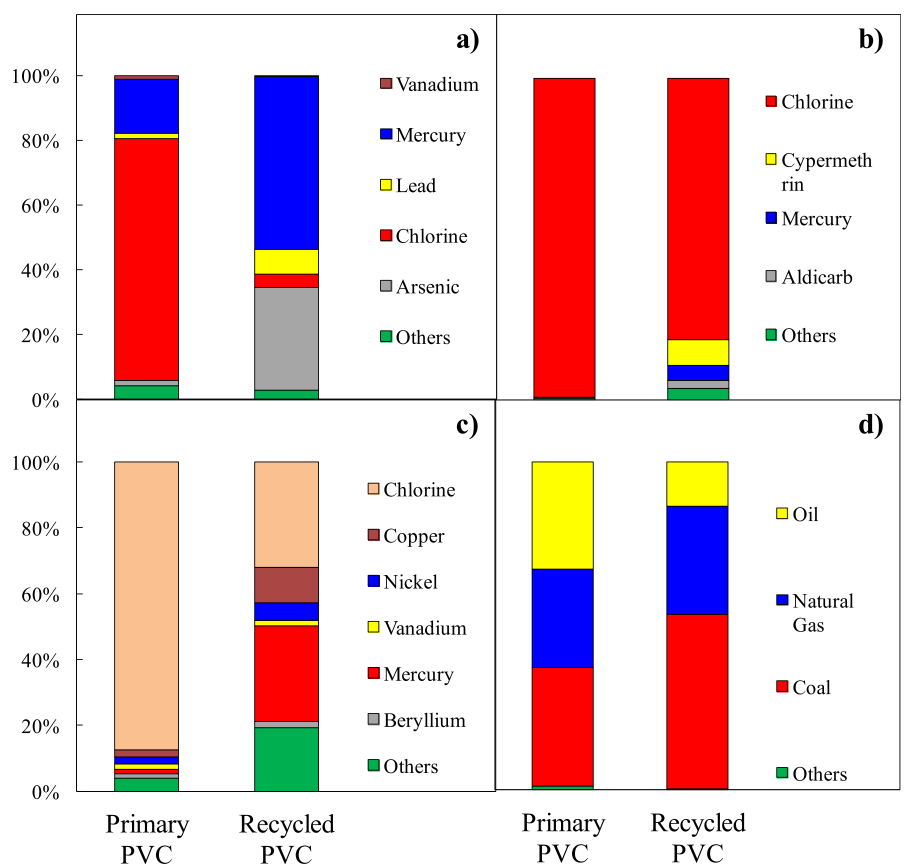


Fig. 3. Contributions of the most significant substances to key categories: a) human toxicity; b) terrestrial ecotoxicity; c) marine ecotoxicity; d) fossil depletion.

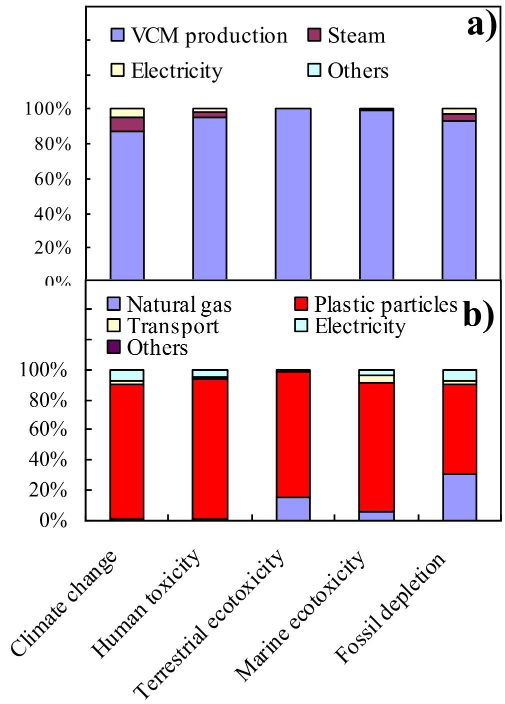


Fig. 4. Main processes that contribute to significantly affected categories: a) primary PVC; b) recycled PVC.

Table 3
Sensitivity analysis.

Scenario	Process	Variation	Climate change (kg CO_2 eq)	Human toxicity (kg 1,4-DB eq)	Terrestrial ecotoxicity (kg 1,4-DB eq)	Marine ecotoxicity (kg 1,4-DB eq)	Fossil depletion (kg oil eq)
Primary PVC	VCM production	5%	122.46	20.33	0.75	0.31	51.86
	Catalyst	5%	0.20	1.98×10^{-2}	1.57×10^{-5}	2.07×10^{-4}	5.27×10^{-2}
	Steam	5%	12.17	0.68	1.52×10^{-4}	8.48×10^{-4}	2.64
	Direct emission	5%	0.10	2.77×10^{-3}	2.50×10^{-6}	2.70×10^{-5}	8.77×10^{-3}
	Electricity	5%	6.27	0.38	1.40×10^{-4}	5.90×10^{-4}	1.29
Recycled PVC	Transport	5%	0.61	2.81×10^{-2}	3.0×10^{-5}	2.5×10^{-4}	0.16
	Electricity	5%	2.51	0.15	5.49×10^{-5}	2.36×10^{-4}	0.52
	Natural gas	5%	0.31	2.59×10^{-2}	1.01×10^{-3}	3.87×10^{-4}	2.12
	Plastic particles	5%	28.88	2.74	5.61×10^{-3}	5.38×10^{-3}	4.10

environmental benefit in each category. By contrast, the natural gas process reduction presents the lowest environmental benefit in climate change and human toxicity, whereas the decreased transport process provides the lowest environmental benefit in terrestrial ecotoxicity and fossil depletion categories. For the rest of the categories, improving electricity consumption efficiency indicated the lowest variation.

3.4. Uncertainty analysis

Table 4 presents the probability via the Monte-Carlo simulation method based on Frischknecht et al. (2005) by using SimaPro8.2 software. The environmental impact of primary PVC is evidently significantly higher than that of recycled PVC; this is true in most categories except for the agricultural land occupation. Similar environmental effect was observed in both scenarios in terms of agricultural land occupation (see Table 2).

Table 4
Uncertainty analysis.

Categories	Probability (Primary PVC ≥ Recycled PVC)
Agricultural land occupation	80.7%
Climate change	100%
Fossil depletion	100%
Freshwater ecotoxicity	100%
Freshwater eutrophication	100%
Human toxicity	100%
Ionising radiation	100%
Marine ecotoxicity	100%
Marine eutrophication	97.5%
Metal depletion	100%
Natural land transformation	99.6%
Ozone depletion	100%
Particulate matter formation	97.6%
Photochemical oxidant formation	97.1%
Terrestrial acidification	96.7%
Terrestrial ecotoxicity	100%
Urban land occupation	99.9%
Water depletion	100%

4. Discussion

Wu et al. (2010a, 2010b) have reported the LCA of primary and recycled PVC production in China in separate studies (Table 5). The LCI values for the primary PVC in this study were generally smaller than the values reported by Wu et al., (2010a) wherein the acetylene-based VCM production of common intermediate products to produce PVC was applied. However, the ethylene-based VCM production is applied in this study. Ethylene-based VCM represents an improved technology because the use of mercury-based catalyst in acetylene-based VCM process can generate strong environmental pressure. Approximately 83%, 80%, 50%, 24%, and 49% of environmental benefits in the NO_X, SO_2, water consumption, electricity, and steam were respectively observed in this study compared with the Wu research. The waste PVC recycle process for the recycled PVC scenario is basically the same with that presented by Wu et al., (2010b). However, the air pollutant emission values (0.14 kg-NO_X/t and 0.04 kg-SO_2/t) presented in this study were lower than those reported by Wu et al., (2010b; 0.91 kg-NO_X/t and 0.74 kg-SO_2/t). Similarly, the energy consumption per ton of recycled PVC production was around 49% lower than that

Table 5
Emissions and energy consumption of primary and recycled PVC production.

		Emissions (kg)		Energy and materials consumption			
		NOx	SO_2	Electricity (MJ)	Steam (kg coal.eq)	Water (t)	
Primary PVC	In this study	0.43	0.43	589.29	123.37	5.84	–
	Wu et al., (2010a)	2.52	2.20	778.14	240.20	11.78	–
		NOx	SO_2	Electricity (MJ)	Oil (MJ)	Diesel (MJ)	Natural gas (MJ)
Recycled PVC	In this study	0.14	0.04	975.54	–	–	1606.68
	Wu et al., (2010b)	0.91	0.74	206.89	2929.60	1938.40	–

indicated by Wu et al., (2010b). These results indicate that the pollutant control and energy efficiency of the recent recycle PVC production in China have clearly improved. Additionally, whether the emission becomes more or less can be explained as most factories producing recycled PVC in China are individual small scale workshops. Furthermore, their innovativeness is not fully developed and their production of technology and environmental impact in China today can be improved. Moreover, Sabaliauskaite and Kliaugaite (2014) reported the global warming potential impact of the PVC wall panel production at 3.4 ton CO_2eq/ton in Lithuania. This result is higher than that observed in this study (2.8 t-CO_2eq/t). This difference was mainly attributed to the relatively high energy efficiency and natural gas-based energy structure used in the studied factory presented in this study. The environmental impact of a coal boiler-based PVC recycling production shows improved practical implications considering that most PVC recycling factories are small scale in China and they use coal rather than gas-fired boilers. The environmental impact generated from coal-fired boiler will be higher than that of natural gas-based PVC production in the climate change category if the coal-fired boiler was applied to replace gas-fired boiler in the present factory. Similar tendencies were observed for the rest of the categories based on uncertainty analysis (data not shown).

Notably, most factories producing recycled PVC in China are small scale and unequipped with an air control (e.g., dedusting, desulfurization and denitrification) system. Both coal- and gas-fired boilers in without-air-control situation generally present the relatively high impact tendency on each category and the same impact level on most categories. The only change is that the without-air-control situation indicated a greater higher impact value on photochemical oxidant formation than the with-an-air control system. This phenomenon is evident and is one of the significantly impacted categories in both situations and in both boiler cases. The non-methane volatile organic compound (NMVOC) and nitrogen oxides contribute nearly 100% on photochemical oxidant formation. As air control was applied, the NMVOC and nitrogen oxide emissions were reduced. Moreover, the impact value on this category decreased. Accordingly, improving the direct NMVOC and nitrogen oxide control system is highly important.

In addition, coal-based electricity generation, which is the dominant power generation method in China (National Bureau of Statistics of China, 2015), was considered in this study. However, hydropower, the secondary main contributor in electricity generation (China Energy Statistical Yearbook, 2014) and multiple electricity power merged into the State Grid of China as well. For instance, thermal-, hydro-, nuclear-, and wind-power accounted for 78.19%, 16.94%, 2.05%, and 2.60% of the national power generation in 2013, respectively (National Bureau of Statistics of China, 2015). Thus, determining the environmental impact change when coal-based electricity generation is replaced proportionally by hydropower and hybrid power is necessary. In general, the impact generated from primary and recycled PVC can be significantly reduced when the abovementioned alternatives are considered. Especially, the climate change potential score generated from electricity can be decreased by 36.21%, and 15.53% for the full life cycle process of primary PVC production by applying hydropower and hybrid power (Ecoinventcentre, 2015), respectively. Therefore, promoting an increased ratio of hydropower and adjusting energy structure can reduce environmental impact, especially on climate change.

5. Conclusion

This study focused on the pollutants generated through the life-cycle producing process of primary and recycled PVC, including the environmental impacts of each scenario and the potential for environmental improvement by evaluating the impact of applying alternative energy. Recycled PVC production was more environmental-friendly compared with the primary PVC production. Notable impacts on terrestrial ecotoxicity, human toxicity, marine ecotoxicity, and fossil depletion were observed. Uncertainty analysis indicated that primary PVC markedly has a greater impact than recycled PVC in most categories except for agricultural land occupation. The results revealed the superiority of recycled PVC in environmental improvement, as well as in directing the sufficient approach in controlling the recycled PVC impact by enhancing air control, specifically for the NMVOC and nitrogen oxide emissions. Moreover, optimizing boiler type and electricity generation structures was highly recommended. Related results in the current study will be included in the life cycle inventory database for PVC industry in China. Additionally, reasonable and efficient information for policymakers to estimate the environmental impacts of PVC industry and to adjust and conduct the PVC industries with less environmental impact will be provided. However, this study includes a number of limitations. PVC production varies in terms of technology, material input, and process control in China. Thus, such two cases cannot fully reflect the national levels of primary and recycled PVC productions. Further studies are suggested to investigate typical cases in different regions in order to analyze and complete the database in China.

Acknowledgments

We gratefully acknowledge financial support from National Natural Science Foundation of China (Grant no. 71671105), the Institute of the Fundamental Research Funds of Shandong University (2015JC016), the Institute of plateau meteorology, CMA, Chengdu, China (LPM2014002), and China Energy Conservation and Emission Reduction Co. Ltd (GJN-14-07).

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