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Study on Low Carbon Transition for Hazardous Chemical Packaging Based on Life Cycle Assessment and Grey Model

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Abstract: The purpose of this paper was to analyze the development trend of hazardous chemical packaging towards low carbon economy from both qualitative and quantitative perspectives. Four types of relatively small volume packaging with volume/weight less than 450L/400kg, respectively, and three intermediate bulk containers (IBCs), which are widely used for hazardous chemicals were studied to calculate the carbon footprint (CF) from cradle to grave using life cycle assessment (LCA) method and to predict the future carbon emission of hazardous chemical packaging in the next five years (2016-2020), based on the export data of Tianjin Port in China. Grey model (GM) was adopted in the prediction. The results showed that majority of IBCs have lower carbon footprint than other types when the packaging contained same amount of same hazardous chemical. With the development of international trading, the demand of hazardous chemicals will increase as well. As the result, carbon emission generated by hazardous chemical packaging will increase accordingly. However, based on GM simulation result, increasing the amount of IBC use will effectively reduce the relative amount of carbon emission.

Keywords: packaging; hazardous chemicals; life cycle assessment (LCA); grey model (GM); IBCs; carbon footprint (CF)

1. Introduction

Since 17th century, industrial revolution has brought huge development to human civilization. Packaging industry achieved great development by leaps and bounds [1, 2]. However, modern packaging industry exploited resources in an inappropriate way and also adopted a high energy consumption, pollution and emission production mode, which increased scarcity of global resources and worsened the global environment. Under the background of low carbon economy, a broader awareness of sustainable development of packaging has been aroused [3]. Low carbon economy is a human rational choice in accordance with the fundamental interests of human development [4].

The earliest research of LCA started from packaging field, which can date back to 1969 when the Coca-cola Company described the different resources consumption and environmental release regarding to different containers of drinking. Therefore, in recent 50 years, the research achievements of fruitful package field mainly focus on the food package field, including packaging for cheese products [5], alcohol products [6] as well as fruit and vegetable packaging [7], etc. Through comparative study, packaging products more friendly to the environment will be innovated. Feng, etc. [8] conducted research to compare the life cycle for fiberboard IBCs and fiberboard boxes, and showed that fiberboard IBCs has obvious advantages over the fiberboard boxes in the comparative analysis of life cycle, including 11 categories of impact on the environment. Among them, the biggest gap is ozone depletion damage, only 60% of the fiberboard boxes, while the smallest is the acidification/eutrophication, 90% of the fiberboard boxes. On terms of life-cycle stages, IBC has greatest advantages in the raw material production phase, while minimum in use phase. Researchers preferred to assess carbon footprint by using LCA in recent years. The research of packaging carbon footprint focused on food packaging [9-11] and the related one in the field of consumption concept and consumption behavior [12, 13].

According to the 'UN Transport of dangerous goods model regulations' [14], there are almost 2830 UN numbers to represent the different of dangerous goods, of which about 90% are hazardous chemicals. Hazardous chemicals have had a profound impact on health, environment, economy, etc. [15]. Meanwhile, the hazardous chemical accidents, such as the huge chemical explosion at the Chinese port of Tianjin on Aug.12th 2015, called for the control on different life cycle stages of dangerous chemicals [16]. As a special part of commodity packaging, hazardous chemical packaging has gained much attention, since its characteristics are inflammable, explosive and corrosive which could bring adverse impact on human being and environment. Research on hazardous chemical packaging was mainly focused on the influential ensure product safety [17-19], such as safety test technology, product design, etc. However, there have been fewer studies on life cycle and carbon footprint. One study on life cycle assessment for fiberboard box and fiberboard IBCs in the loading amount of hazardous chemicals showed that fiberboard IBCs was more environmental friendly.

Tianjin port as one of the largest ports in north of China [20], could be a very good representative for the status of the import and export of hazardous chemicals in packaging batch, type, quantity, etc. in China. Using the export data from Tianjin Port could better reveal the influence from the development of type, material, quantity of hazardous chemical packaging on the low carbon economy. This paper used Tianjin port exported hazardous chemical packaging from 2012 to 2015 as the research object and chose seven common types of packaging (4 kinds of small volume packaging, 3 kinds of IBCs) to conduct product life cycle analysis and quantitative calculation of their carbon footprint.

With the existing data, grey model (GM) was used to calculate carbon footprint changing trend of the studied packaging products in Tianjin port during five years from 2016 to 2020. By analyzing the change in the relationship between hazardous chemical packaging type and its carbon footprint, a sustainable development model with lower carbon footprint - more friendly to environment could be established for hazardous chemical packaging industry. Furthermore, this would help realize the economic and social sustainable development. Therefore, research on industrial structure change on hazardous chemical packaging will be significant for the whole packaging industry.

2. Methodologies

2.1. Life Cycle Assessment

Based on the conception of life cycle, life cycle assessment (LCA) is regarded as a useful tool to estimate and assess the environmental impacts of a product or process by identifying and quantifying energy and materials used and wastes released to the environment, from 'cradle to grave' [21]. In addition, a cradle to cradle perspective [22] and a gate to gate assessment have also been introduced in recent years, when analyzing specific production processes or systems. Therefore, conducting a whole life cycle analysis of each packaging will give a comprehensive comparison in the field of hazardous chemical packaging.

The interest in LCA has grown rapidly in last decades because of the increasing awareness of environment protection and sustainable development. Now, it has been used in a wide range of research areas to evaluate environmental impacts. The main phrase of LCA can be divided into 4 steps according the international standards [23]:1) Goal and Scope definition; 2) Inventory analysis; 3) Impact assessment; 4) Interpretation. Figure 1 illustrates the conception framework of common LCA analysis. And it includes different models to evaluate different items, for example, IPCC used in this study is for carbon emissions and Eco-indicator 99 is for general environmental impacts.

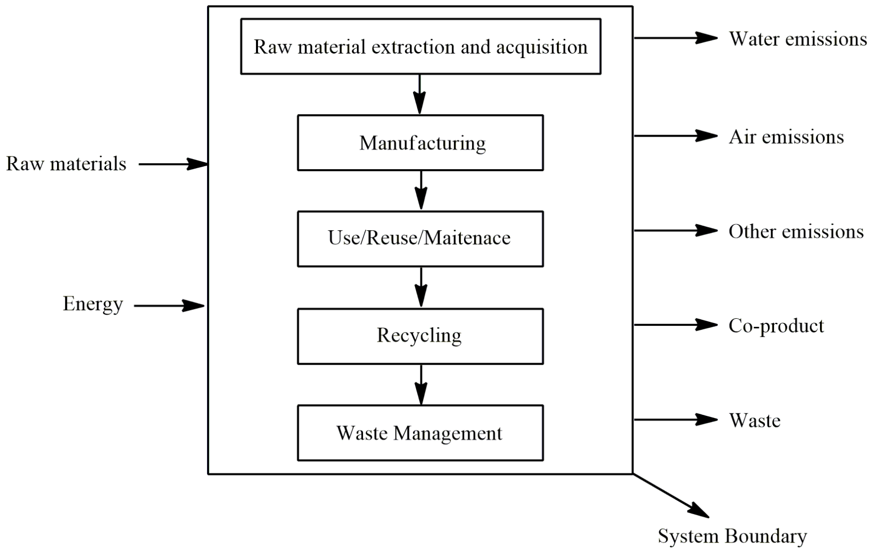

Figure 1. Scope of Life Cycle Assessment [23].

2.2. Carbon Footprint

Originated from LCA, carbon footprint is a worldwide standardized indicator of greenhouse gas (GHG) emissions through the whole life cycle of a particular product, process or activity [24]. Carbon dioxide is regarded as the largest contributor to climate change [25]. Therefore, CF is expressed in carbon dioxide equivalent (CO_2 eq.) [26], measuring the total greenhouse gas emissions directly caused by individual, activity, organization or product [27]. So it is necessary to analyze the CF, since it is one of the highlights of all concerns related to environmental issues, of representative dangerous chemicals' packages. It is useful to quantify the impact of human activities on the environment and global climate by assessing the quantity of emission from different carbon emitting sectors [28]. LCA model is used in this study to calculate the CF for covering the entire life cycle of the analyzed product.

2.3. Structure and Steps

In this study, LCA was used to analyze and compare the CF of seven hazardous chemical packaging (fiberboard boxes, steel drums, plastic drums, plastic woven bags, flexible IBCs, fiberboard IBCs and steel-plastic composite IBCs), aiming to give replacement trend in this field in order to achieve low-carbon economy. According to the process of LCA, CF was calculated in four steps in this paper, which was illustrated in Figure 2. And IPCC 2013 model was chosen to assess the carbon footprint of each packaging through its whole life cycle. IPCC 2013 is an assessment model established by Intergovernmental Panel on Climate Change [25], with the purpose of giving a comprehensive evaluation of all types of greenhouse gases which have global warming potential. Its results can be present by three indicators: GWP 20a, GWP 100a and GWP 500a, which presenting greenhouse effect of short-term, medium-term and long-term respectively. Since the work was to analyze and predict the CF of each packaging in a short time period, GWP 20a was used in this study.

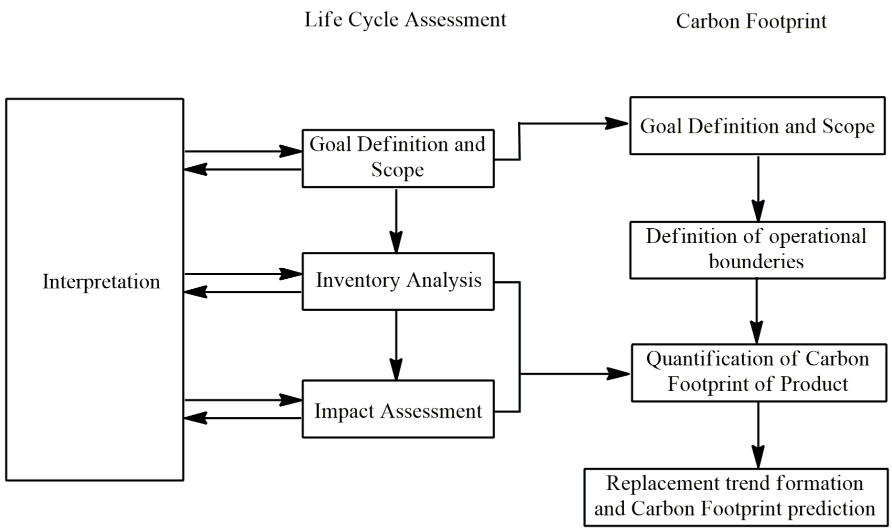

Figure 2. Four Steps to Assess Carbon Footprint.

2.4. Grey Model

Grey model is based on grey system theory, which aims to predict the behavior of systems with limited data [29]. It was first introduced by Deng in 1982 [30]. Different from common statistical models, grey model is an alternative forecasting tool for those systems of complex, uncertain and chaotic structure [31]. A limited amount of data is required to predict the behaviors of unknown systems [32]. Using grey model to make a grey prediction basically has three operations: accumulated generating operation (AGO), inverse accumulated generating operation (IAGO) and grey modeling. Although, there are many different grey prediction models, the most commonly used one is GM (1,1) [33]. And steps of setting up GM (1,1), which was used to forecast the carbon emission trend of hazardous chemical packaging for the next 5 years in this study with the help of

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Matlab, are as following:

Set the non-negative time-sequence data:

Calculating the AGO:

where, k=1, 2, …, n;

, k=1, 2, …, n;

Then, the GM (1,1) is as follows:

where, "a" is called "develop parameter" and "b" is called "grey input".

Estimating the with the least square method:

where,

and

Then response equation can be:

The response equation of GM (1,1) can be:

, k=1, 2, …, n.

While, k=1, 2, …, n.

And the predicted value can be:

, k=1, 2, …, n.

3. Data Source and Studied Packaging

3.1. Data Source

This work was based on the export data of Tianjin port from the statistic data of Tianjin Entry-Exit Inspection and Quarantine Bureau and selected export quantity in practical use of fiberboard boxes, steel drums, plastic drums, plastic woven bags, flexible IBCs, fiberboard IBCs and steel-plastic composite IBCs. These seven type packaging were chosen as the research object based on the volume and category of export dangerous goods of Tianjin in 2014. They accounted for about 88.6% of the whole export dangerous goods packaging, taking an absolutely big share in this field (see Table 1).

Table 1. Volume & category of export dangerous goods of Tianjin in 2014

Category of packaging	Packaging	Batch	Percentage (%)
Small volume packaging with volume/weight less than 450L/400kg, respectively	Fiberboard boxes	1097	17.12
	Fiberboard drums	63	0.98
	Steel drums	1703	26.58
	Steel jerricans	29	0.45
	Plastic drums	1257	19.6
	Plastic jerricans	417	6.51
	Plastic woven bags	932	14.54
	Paper bags	108	1.69

	Steel-plastic composite drums	23	0.36
	Wood boxes	3	0.05
	Plywood boxes	26	0.41
Intermediate bulk containers （IBCs）	Fiberboard IBCs	14	0.22
	Flexible IBCs	415	6.48
	Steel-plastic composite IBCs	232	3.62
	Wood IBCs	2	0.03
Small gas pressure vessels	Small gas pressure vessels	87	1.36
Total		**6408**	**100**

3.2. Studied Packaging

We selected the above seven type packaging products of the specifications of the representative model as the research object, as demonstrated in Table 2. Product life cycle data were collected from several production enterprises in Tianjin region, respectively. When choosing the enterprises, on one hand, packaging production enterprises with larger export quota were chosen as the research object to ensure the representation of the data. On the other hand, data of packaging made of same material were collected from the same enterprise to ensure the comparability of different types of packaging.

Table 2. Life Cycle Data Acquisition Packaging Specifications and Companies List.

Category of packaging	Packaging	Specification and dimension	Related enterprise
Small volume packaging with volume/weight less than 450L/400kg, respectively	Fiberboard boxes	25kg double corrugated carton box	Seven Industrial (Tianjin) co., Ltd.
	Steel drums	216.5l [34]（ϕ 590mm，H 900mm）weight 11kg	Tianjin DaTian Packaging Container Co., Ltd
	Plastic drums	220l [35]（ϕ581mm，H 935mm）weight 8.5kg	Schuetz Container Systems (Tianjin) Co., Ltd.
	Plastic woven bags	25kg three layers of plastic woven bags	Tianjin XuHui HengYuan Plastic Packaging Corp.
Intermediate bulk containers （IBCs）	Fiberboard IBCs	1t,seven layers of corrugated cardboard （1100mm×1100mm×1100mm）	Seven Industrial (Tianjin) co., Ltd.
	Flexible IBCs	1t three layer , compilation plastic	Tianjin XuHui HengYuan Plastic Packaging Corp.
	Steel-plastic composite IBCs	1050l Steel-plastic composite IBCs	Schuetz Container Systems (Tianjin) Co., Ltd.

4. Analysis of hazardous chemical packaging

4.1. Goal and Scope

The first step of LCA is to define goal and scope, i.e., define the objectives and setting the system boundaries [36]. The objective of this study was to assess and compare the carbon footprint of seven hazardous chemical packaging and to forecast their carbon emission trends in Tianjin Port in the next five years, which provides assistance to package industry transition towards low carbon economy.

The selected types of packaging are fiberboard boxes, fiberboard IBCs, plastic woven bags, flexible IBCs, steel drums, plastic drums and steel-plastic composite IBCs. The whole life cycle of each packaging type from cradle to grave was analyzed in this study. Since Functional unit is the basis for comparison among the packaging, and the chosen packaging could work for both liquid and solid, unit loading weight capacity of 1 kg was chosen as the modeling basis in the case.

4.2. Inventory Analysis

In this study, the whole life cycle of packages was involved, from cradle to grave. Most inputs and outputs for each process were listed in Table 3, except for unavailable and uncertain data which almost do not affect the whole analysis. The modes of recycled packages vary according to their characteristics of material. Because of different materials of the packaging, the analyzing boundaries covered waste management phase according to the average level in China, and disposal was considered as the end of a single-used life cycle on site without transportation. Moreover, we chose the concrete with nearest density in the database of SimaPro. To conduct the carbon footprint analysis across with the life cycle, the assessment was made based on IPCC2013 GWP 20a. During the use of the packaging, there were minimal input and output related to the CF. Therefore, the inventory did not include the stage of use.

Table 3. Life Cycle Inventory of Packages.

Packaging		Fiberboard boxes	Fiberboard IBCs	Plastic woven bags	Flexible IBCs	Steel drums	Plastic drums	Steel-plastic composite IBCs
Capacity		25kg	1000kg	25kg	1000kg	208kg	210kg	1050kg
Production	Material	Fiberboard (g)	Fiberboard (g)	PP (g)	PP (g)	Cold steel (g)	HDPE (g)	HDPE (g)
	Amount	600.75	14000	79	2140	20180	9500	16070
	Material	Flat filament (g)	Flat filament (g)	– –	– –	Coatings (g)	PP (g)	Steel tube (g)
	Amount	2.3229	40.6	– –	– –	250	33	38000
	Material	Print ink (g)	Print ink (g)	– –	– –	Adhesive (g)	– –	– –
	Amount	2.0025	35	– –	– –	20	– –	– –
	Material	PE (g)	PE (g)	– –	– –	Natural gas (m^3)	– –	– –
	Amount	0.75	500	– –	– –	0.3	– –	– –
	Energy	Electricity (kWh)	Electricity (kWh)	Electricity (kWh)	Electricity (kWh)	Electricity (kWh)	Electricity (kWh)	Electricity (kWh)
	Amount	0.03602	0.96	0.02	0.107	1.9	13.86	8.5
Transportation	Vehicle	Trucks (8t)	Trucks (8t)	Trucks (10.5t)	Trucks (10.5t)	Trucks (35t)	Trucks (35t)	Trucks (35t)
	Loading	4000	250	130000	5500	500	580	117
	Distance	60km	60km	115km	115km	100km	150km	150km
Disposal	Recycle	30%	30%	15%	15%	2.50%	15%	50%
	Landfill	40%	40%	40%	40%	2.50%	– –	– –
	Incineration	30%	30%	45%	45%	95%	85%	50%

4.3. Quantification of Carbon Footprint of Product

Simapro was used to evaluate the carbon footprint of each analyzed package for a single-use life cycle. The result is illustrated in Figure 3. It is clear that normal IBCs have lower carbon footprint than other packages with similar material. For example, flexible IBCs exhaust GHG 6.07*10^{-3}kg CO_2 eq. when loading 1kg solid, while plastic woven bags exhaust 9.8*10^{-3} CO_2 eq. It should be mentioned that steel drums have lower carbon footprint than steel-plastic composite IBCs, and the reason may be attributed to its high recycle level. However, according to practical situation, drum cleaning is a difficult task. Drums will hold residual liquid, resulting in adverse tore cycle again. Hence, steel-plastic composite IBCs will be a better choice when meeting the demand for re-use, although it has a little higher carbon footprint. Moreover, the steel-plastic composite IBCs are the most reused ones in fact, which can be reused 3 times every 3 years. It can be imagining that if reuse phase is added into consideration, the carbon footprint of steel-plastic composite IBCs will get lower, since recycling of steel is one of responsible factors for environmental advantage.

The key factor to determine the carbon footprint of a packaging is the type and amount of the material that is used to make the packaging. Compared with rigid plastic packaging, flexible plastic packaging uses relatively less material with higher recycle rate, so generally it is the best choice for hazardous chemicals. When containing same amount of chemicals, the flexible IBCs are more environmental friendly due to its less consumption of raw material.

Packaging recycling is also an important factor in determining the carbon footprint. Carbon emission in the production of plastic material is lower than production of steel, but the steel scrap can be used directly for smelting, and its recycle rate is higher. On the other hand, the plastic packaging, especially rigid plastic packaging, recycle rate is low, so the plastic drum shows the highest carbon footprint (Figure 3).

Another factor to determine the carbon footprint is the number of use. Cleaning and maintenance of packaging consume much less energy than producing a new packaging so that for a package used for N times, its carbon footprint becomes 1/N. This is equivalent to reduce the material consumption for one packaging to N times less when the package can be used for N times.

Also, it can be seen from Figure 3, the packaging for solid product always achieves a better environmental performance, i.e., producing fewer GHG emissions than the one applicable for liquid. This may be caused by the fact that packaging for liquid need higher and more special performance and requirements so that its need more material consumption and environmental impacts can be much more.

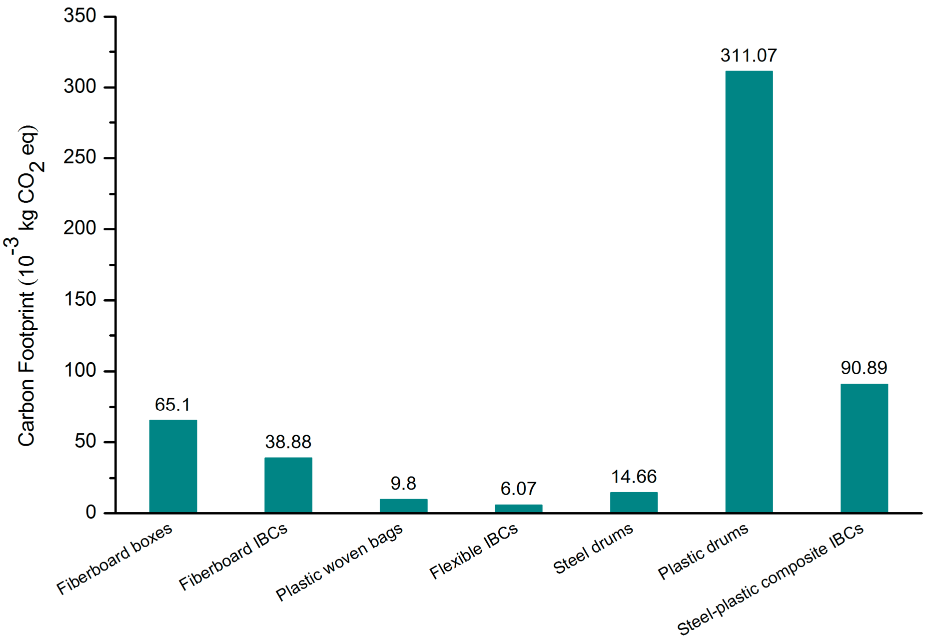

Figure 3. Carbon Footprint of Each Packaging With 1kg Loading Capacity.

Based on the analysis as above, IBCs shows great advantages than other types of small volume packaging in terms of raw material nature and consumption, recycle rate and reuse times. Therefore, when safety requirement during hazardous chemical storage and transportation can be fulfilled, increasing the ratio of IBCs among hazardous chemical packaging could help reduce the overall carbon footprint in hazardous chemical packaging industry.

4.4. Replacement Trend Formation and Carbon Footprint Prediction

The result of carbon footprint analysis as shown in Figure 3 was obtained based on same load capacity—1kg hazardous chemical goods. From the result of the carbon footprint for 1 kg of hazardous chemicals, the following trends which represent the package carbon emission can be estimated easily to meet other situation. Table 4 shows the data of packaging amount collected from Tianjin Port in 2012-2015 and the prediction in the next five years (2016-2020). Number of each analyzed package was predicted by Grey Model, and Matlab was used in the calculation.

Table 4. Amount of Packaging From 2012 to 2015 and Prediction in 2016.

Packing Type	Capacity	Number								
		2012	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**
Fiberboard boxes	25kg	419536	400346	492962	429665	469364	484318	499749	515672	532102
Fiberboard IBCs	1000kg	876	924	1278	1510	1923	2425	3057	3856	4862
Plastic woven bags	25kg	5671675	6925561	7018450	10879826	13366614	17280926	22341515	28884059	37342538

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flexible IBCs	1000kg	191016	225621	241779	288947	323309	367470	417663	474711	539551
Steel drums	208kg	689345	708439	752724	880061	970593	1085423	1213839	1357440	1518048
Plastic drums	210kg	116675	134810	137268	137872	139732	141302	142891	144497	146121
Steel-plastic composite IBCs	1050kg	20876	23497	25084	24730	25678	26325	26988	27669	28366

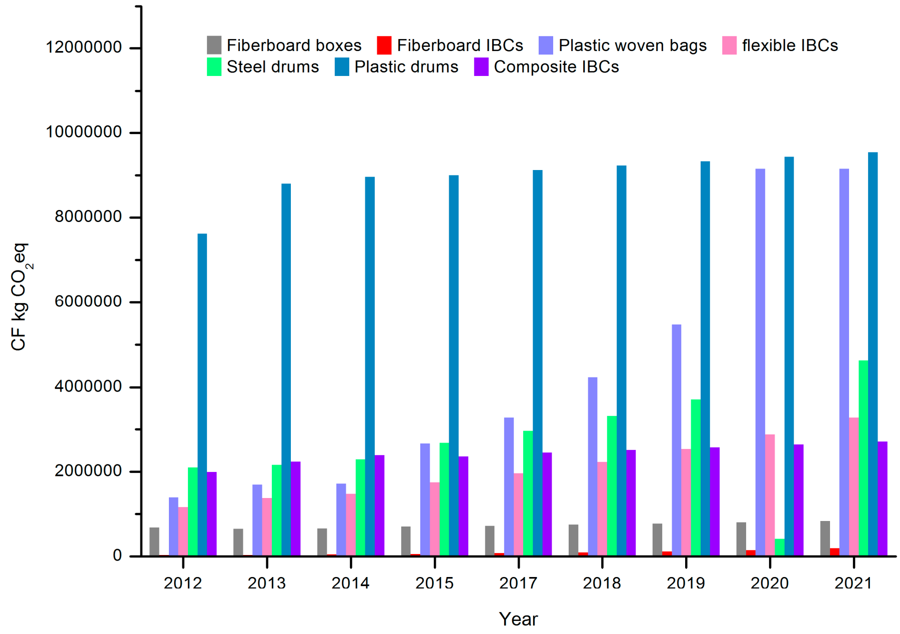

Figure 4. Growth Trend of Analyzed Packages From 2012 to 2020.

The prediction results show that the use of several kinds of packaging will grow fast in the next five years were plastic woven bag, fiberboard, flexible container bags and steel drums, while the use of plastic bucket will grow slowly. This basically meets the requirements of the sustainable development of the carbon footprint of hazardous chemical packaging. At the same time, it further confirms the impact of the carbon footprint by a number of factors, including material, consumption and recycling rate. The steel plastic composite IBCs showed no obvious advantage, and the main reason is that in the statistics analysis and calculation of the packaging, single use case is only considered. For multiple uses, statistics cannot be achieved at the same port, which caused the inaccuracy of carbon footprint calculation.

Since IBCs showed lower carbon footprint than other small volume packages, we can presume that if more IBCs could be used as hazardous chemical packaging, there would be less carbon footprint than general ones increasing the same amount. It is convinced that there is a significant drop in carbon emission when the numbers of IBC increased and the more it rises the more carbon emissions decline. Moreover, we made a carbon emission prediction on the basis of GM prediction. In the grey model results, different packages have various growth rates according to the historical data. Assuming that all packages would grow in the same rate (the average growth rate), the carbon footprint of

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2020 with the two kinds of growth rate was shown in Figure 5, where 2020′ stands for the results of the average growth rate ones. Among the predicted different growth rates in 2020 compared to 2015, IBCs generally have higher growth rate than general packages (as shown in the 2020 line in Figure 5). When they share a same growth rate (2020′ in Figure 5), which means IBCs grow slowly but general ones more quickly, and the total carbon footprint as shown in the Figure 5 can be more than the predicted one of varied growth rate. Hence, promoting the use of IBCs can lead the industry of hazardous chemicals' packaging to a low-carbon economy, achieving much more sustainable development.

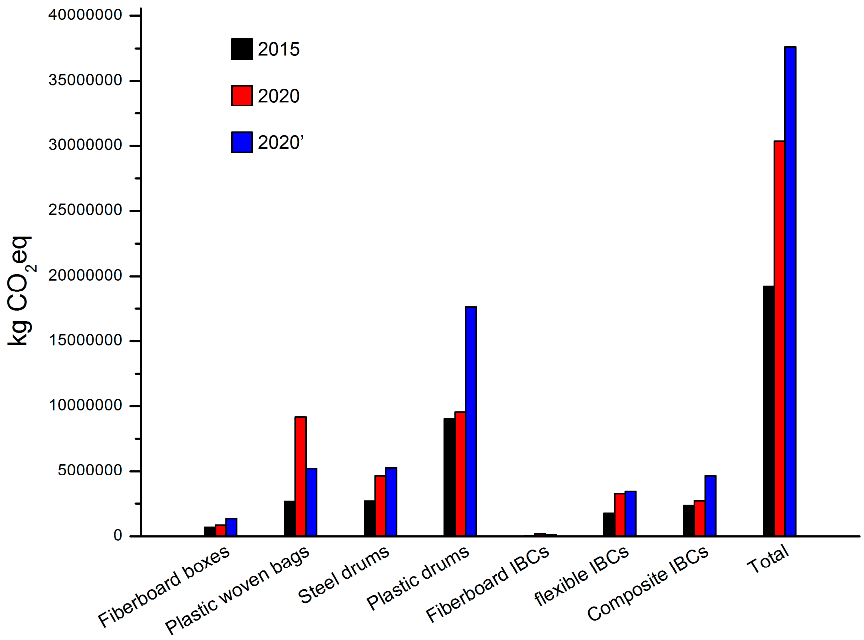

Figure 5. Carbon Emission Prediction (2020) With GM and Same Growth Rate Compared With 2015.

From Figure 6, it can be seen that simply comparing the annual carbon footprint in the absolute value is not very helpful to understand the trend of the packaging change, since export quantity of hazardous chemicals increased year by year and the use of packaging was also increased. Therefore, Grey model is used to predict the total export amount of hazardous chemicals in 2020, and the carbon footprint using the proportion of various packaging type as in 2015 and using the proportion of various packaging type in 2020 predicted by Gray model 2020′, respectively. The results showed that with the packaging industry adjustment, great impact on the overall change of carbon footprint can be achieved - reducing the absolute carbon footprint of 13904751.95kg CO_2 eq., and the relative impact of 45.80%.

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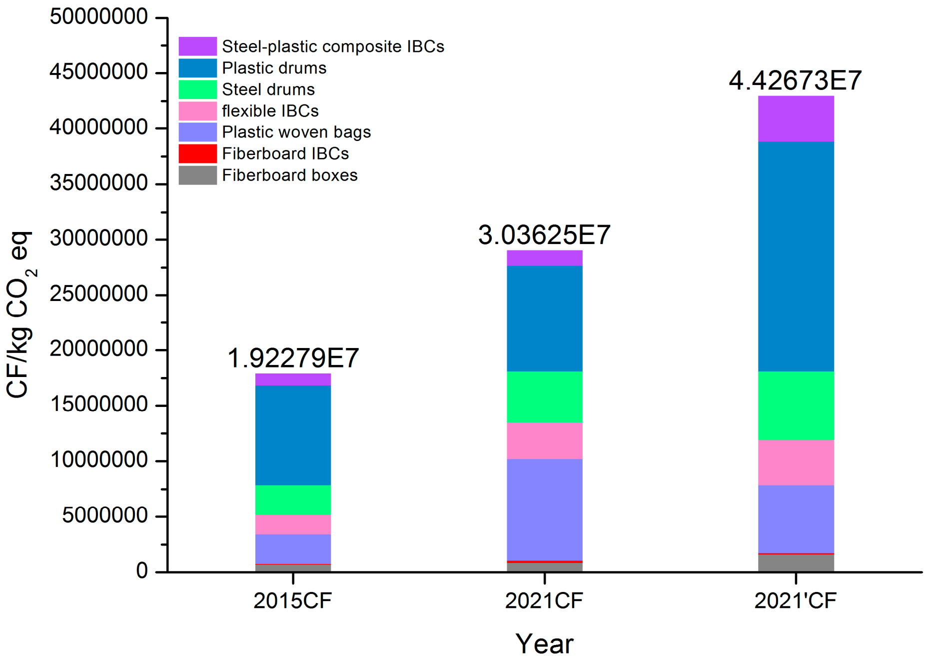

Figure 6. Carbon Emission Prediction (2020) With GM and Same Growth Rate 2015.

5. Conclusion

This study evaluated the carbon footprints of seven hazardous chemical packaging, with the conception of life cycle- from 'cradle-to-grave'. The findings presented in this paper revealed useful information for replacing trends in hazardous chemical packaging. In overall, packaging made of different materials and with different volumes will have different carbon footprint. In the premise of not affecting the safety of hazardous chemical storage and transportation, and not influencing their use, reasonably increasing packaging capacity, reducing packaging material, increasing the reuse of packaging and recycle rate of packaging material will help reduce overall carbon emissions of hazardous chemicals packaging.

IBCs appeared to be a better choice of lower carbon footprint than the other small volume packages made of similar material. Moreover, prediction on batches packaging usage and carbon emissions at Tianjin Port in 2016-2020 showed both of these two numbers increased. However, if the use of IBCs increases, carbon emissions in 2016-2020 decrease significantly. It can be concluded that IBCs can be a much more environmental-friendly choice in reducing the carbon emissions. In order to achieve the goal of low carbon economy, promoting the use of IBCs is a crucial change which must be made in the future.

This study still has limitations due to the focus on Tianjin Port, although it could well represent the status of hazardous chemical packaging use in North China. Further assessment should be carried out to cover more regions.

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