Analysis of the influencing factors of PAEs volatilization from typical plastic products

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ABSTRACT

The primary emphasis of this research was to investigate the foundations of phthalate (PAEs) pollutant source researches and then firstly confirmed the concept of the coefficient of volatile strength, namely phthalate total content in per unit mass and unit surface area of pollutant sources. Through surveying and evaluating the coefficient of volatile strength of PAEs from typical plastic products, this research carried out reasonable classification of PAEs pollutant sources into three categories and then investigated the relationship amongst the coefficient of volatile strength as well as other environmental factors and the concentration level of total PAEs in indoor air measured in environment chambers. Research obtained phthalate concentration results under different temperature, humidity, the coefficient of volatile strength and the closed time through the chamber experiment. In addition, this study further explored the correlation and ratio of influencing factors that affect the concentration level of total PAEs in environment chambers, including environmental factors, the coefficient of volatile strengths of PAEs and contents of total PAEs in plastic products. The research created an improved database system of phthalate the coefficient of volatile strengths of each type of plastic goods, and tentatively revealed that the volatile patterns of PAEs from different typical plastic goods, finally confirmed that the coefficient of volatile strengths of PAEs is a major factor that affects the indoor air total PAEs concentration, which laid a solid foundation for further establishing the volatile equation of PAEs from plastic products.

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Introduction

Over the past half-century, in the wake of societal economic development with the improvement of living standards amongst the general populace, there has been a tremendous change in the materials used in internal renovations and decorations, as well as a string of daily items. A new type of semi-volatile organic pollutant, known as phthalate esters (PAEs), has begun to penetrate into people's lives. It acts as an endocrine interferon, and has a disrupting effect on the male hormone testosterone. It can be seen that phthalates have an incredibly harmful effect on the health of the human body, and consequently relevant research has led to the arousal of enormous concern.

Contemporary research on phthalates concentrates on two points: measurement of PAEs concentration level and the pollutant sources investigation. America, Sweden, Japan, Germany, and other developed nations followed closely in

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carrying out indoor phthalate contamination level researches since 1991. Rudel et al. (2003) measured the indoor air samples from 120 American residences, and the study demonstrated that there are 88 types of endocrine interferon, as well as showed that phthalates were a common existence in indoor residential air. Kanazawa et al. (2010) researched the phthalate contamination concentration levels from 41 residences in Sapporo, Japan and assessed their relationship with Sick Building Syndrome. Fromme et al. (2004) measured the concentration levels of phthalate in 59 German apartments, with all samples resulting in finding of diethyl phthalate (DEP), dibutyl phthalate (DBP), and diethylhexyl phthalate (DEHP), amongst which the concentration of DBP was the highest, at 1083 ng/m^3; and within indoor dust, DEHP concentration was the highest, at 703 mg/kg, making up 80% of phthalates in the dust. The data above are the concentration levels of phthalate contamination within residential environments, and of course there also have corresponding researches of phthalate contamination concentration investigation in indoor air from public places, with PAEs concentration levels being equally contemptible. Becker et al. (2009), in a German kindergarten during 2003, discovered that children who are exposed to phthalates are subjected to even larger health effects, its metabolism resulting in concentration levels 3–5 times higher than adults. Henceforth, domestic and international scholars have launched extensive research on phthalate exposure to babies and children. Bergh et al. (2011) undertook research in Stockholm (Sweden), on phthalate levels in indoor air and indoor dust from three different types of indoor environments (residential, kindergarten, office), and discovered uniform detection of phthalate in all samples, with phthalate concentration levels in indoor air from the kindergarten ranging between 1200 and 5600 ng/m^3, and average concentration is 2500 ng/m^3, with total phthalate contamination level both in indoor air and indoor dust being lowest in residences, and highest in offices. These researches well illustrated concentration levels of indoor air phthalates which lead to serious indoor air contamination and thus investigating the PAEs volatilization features from pollutant sources is of great importance and necessary.

The main sources of phthalates in indoor environment mainly are construction materials, renovation and decoration materials, daily items and so on. According to statistics, every year thousand tons of phthalates are added into several hundred types of Polyvinyl chloride (PVC) products, and other consumer goods, from polythene flooring and wallpaper, toys, food packaging materials, medical blood bags to rubber tubing, nail polish, shampoo and so on (Bouma and Schakel, 2002; Kavlock et al., 2002). The content of phthalates in plastic goods exists in the range of 10%–60% (Rudel and Perovich, 2009). Uhde et al. (2001) investigated the emissions of phthalates from plastic wallpapers, with results showing that plastic wallpapers can emit diisobutyl phthalate (DIBP), DBP, DEHP, diisononyl phthalate (DINP), and dipentyl phthalate (DPP), at concentrations of 0.94–5.1 μg/m^3. Afshari et al. (2004) carried out evaluations on the emission concentration of phthalates from PVC flooring and electric cabling materials, with results finding that PVC flooring released higher level concentrations of DBP and DEHP. Stringer et al. (2000) tested types and content distributions of phthalate from 72 types of

toys purchased from 17 countries (of which 64 types were PVC materials or possibly contained PVC materials), with results showing that phthalates commonly exist in these toys, mainly DINP and DEHP, while toys from some countries also had the high addition of di-iso-decyl phthalate (DIDP). The data from current researches are varied and chaotic, and we preliminary found that the emission concentration was closely related to the surface area of different pollutant sources which can explained why PVC flooring and wallpapers emitted higher PAEs concentration compared to other pollutant sources.

From the practical experience, this study ascertained that pollutant sources can be classified into two categories based on the numerous current researches, namely construction or decoration materials (wallpaper, paintings, PVC flooring, etc.), and daily items (packaging materials, plastic cups, plastic bowls, etc.). This study chose daily items as research objects.

In summary, the main focus of current research on investigating the pollutant sources was only evaluating the phthalate content in the contamination sources, but as to different contamination sources in varied environmental conditions, the volatility process isnot actually that clear. In other words, these researches did not establish the relationship or mathematical model between the phthalate content in sources and the volatile concentration level from sources in different environmental situation, sometimes only under certain one condition which lacking of universality. From the further exploring, this study found that volatile process and concentration were closely related to the exposed surface area of pollutant sources. Based on the above consideration, this study defined the coefficient of volatile strength of phthalate (K_{vs}) as total phthalate contents from per unit exposed surface area and unit mass of pollutant sources. In addition to comprehensively investigating the effectiveness of this coefficient as well as some environmental factors, this study primarily determined the main factors that affect volatile process and concentrations, which laid a solid foundation for further establishing the volatile models of PAEs from plastic products.

1. Materials and methods

1.1. Chemicals and materials

High performance liquid chromatography (HPLC) grade chemicals and solvents were used for all extraction and gas chromatography flame ionization detector (GC-FID) analysis. Standard mixtures of M-8060 phthalates, including dimethyl phthalate (DMP), DEP, DBP, butylbenzyl phthalate (BBP), di(2-ethylhexyl) phthalate (DEHP) and di-n-octyl phthalate (DnOP), were purchased from AccuStandard (New Haven, CT, USA) as stock solutions in isooctane; all had concentrations of 2.0 mg/mL for each phthalate.

1.2. Indoor air samples collection

Before sampling, all the sampling tubes and the glass fiber filters were baked at 400°C in the muffle furnace (KS60-6.5-12G, Shanghai, China) to remove any previously

adsorbed organic compounds and these instruments were then stored in aluminum foil.

Indoor air samples were collected from the environmental chambers (28 cm × 28 cm × 28 cm) under different environmental circumstances. The samples were collected into a plexiglass sampling head with a glass fiber filter (37 mm in diameter, pore size of 0.45 μm, Staplex, Brooklyn, N.Y., USA) and subsequently a glass tube packed with 2 g XAD-2 adsorbent (Sigma-Aldrich, St. Louis, MO, USA), using an electronically controlled air sampler (PC-A, Hengda, Zhejiang, China). The sampling device was set 1.5 m above the floor, with a sampling time of 8 to 10 hr, and sampling flow of 1.0 L/min (air pump changes in the range of less than 5% before and after sampling). When sampling was completed, both ends of the sampling device remained sealed, and samples were returned to the laboratory for immediate processing. Temperature, humidity, and air pressure were synchronously recorded using an electronic temperature and humidity instrument (HTC-1, Boyang, Zhengzhou, China) and digital air pressure equipment (BY-2003P, Taishi, Suzhou, China) (Table 1).

1.3. Sample pretreatment and analysis

1.3.1. Indoor air samples
Samples were extracted from XAD-2 and a glass fiber filter by an ultrasonic cleaner (SK250HP, Shanghai Kudos Ultrasonic Equipment Co., China) for 30 and 25 min, respectively, with a 10 mL mixture of dichloromethane/acetone (V/V, 1:1) as the extraction solvent. Then 5 mL of supernatant was transferred into a cuvette with 30 μL dimethylsulfoxide into the solution before evaporation by a high purity nitrogen concentrator (MTN-2800W, Automatic Science, China); then 970 μL methyl alcohol was added into the cuvette. The solution was filtered with a 0.22 μm organic filter, and transferred into a 1 mL glass vial. The sample was analyzed using a gas chromatograph (FULI9790, Wenling, China) with a DB-5 capillary column (30 m × 0.25 mm (ID) × 0.25 μm, Agilent Technology Inc., USA). The analysis was performed, using the pulsed splitless mode with an injection volume of 2 μL. High purity nitrogen was used as the carrier gas. The column condition was held at 60°C for 2 min, rose to 240°C with a rate of 15°C/min, followed by an increase to 280°C at a rate of 5°C/min and held for 10 min.

1.3.2. Contents of PAEs from different plastic items
After breaking the sample down in a 50 mL Erlenmeyer flask, into uniform fragments of approximately 0.2 g, record the corresponding surface area, then add 25 mL of dichloromethane and treat with ultrasound for 10 min, use organic microfiltration (0.45 μm) to filter into a 50 mL measuring

flask, and use dichloromethane to rinse out the remaining residue, combine the rinsing fluid into the measuring glass, after noting volume put the sample on the testing apparatus (in Summer, when the temperature is high, one may place an ice cube on the ultrasound apparatus to bring the temperature down, in order to lessen the volatility of the dichloromethane). The sample was analyzed using a gas chromatograph (FULI9790, Wenling, China) with a DB-5 capillary column (30 m × 0.25 mm (ID) × 0.25 μm, Agilent Technology Inc., USA). The analysis was performed; using the pulsed splitless mode with an injection volume of 2 μL. High purity nitrogen was used as the carrier gas. The column condition was held at 60°C for 2 min, rose to 240°C with a rate of 15°C/min, followed by an increase to 280°C at a rate of 5°C/min and held for 10 min.

1.3.2.1. Quality assurance and quality control.   The 0.5 mL of the newly prepared 1000 μg/mL standard mixture of PAEs was accurately transferred to a 50 mL bottle for dilution with dichloromethane. After shaking till the mixture was evenly blended, a standard mixed standard stock solution of phthalates with a concentration of 10 mg/L was produced. Then the 10 mg/L mixed standard stock solution was diluted to prepare 0.2, 0.4, 0.6, 0.8, 1.0, 2.0, 4.0, 8.0 and 10.0 mg/L solutions, which were used to draw the standard curves of each phthalate.

Based on the standard curve of each phthalate drawn with peak areas, the y and x refer to peak area and concentration of each PAEs, respectively in Table 2. The correlation coefficients were all relatively high and retention time were clear and definite (Table 2).

Table 2 – The calibration curve of phthalates.

Peak sequence	PAEs	Standard curve	R^2	Retention time (min)
1	DMP	$y = 1793.1x − 1350$	0.999	12.107
2	DEP	$y = 3139.01x − 3326$	0.998	16.290
3	DBP	$y = 4017.1x − 3550$	0.998	20.432
4	BBP	$y = 3608x − 2995$	0.999	22.490
5	DEHP	$y = 4365.01x − 1944$	0.998	25.298
6	DnOP	$y = 3698x − 2026$	0.999	28.240

DMP: dimethyl phthalate; DEP: diethyl phthalate; DBP: dibutyl phthalate; BBP: benzyl butyl phthalate; DEHP: bis(2-ethylhexyl) phthalate; DnOP: di-n-octyl phthalate; PAEs: phthalate esters.

Table 1 – The statistics of impact factors.

Impact factor	Min	Max	Mean	SD
Temperature (°C)	15	35	25	6
RH (%)	32.0	93.0	67.5	9.7
Pressure (kPa)	98.3	104.1	101.2	0.9

SD: standard deviation; RH: relative humidity.

Table 3 – Characteristic of the PAEs analytical method.

PAEs	R (%)	MDL (mg/L)	RSD (%)
DMP	100.9333	0.00106	2.608864
DEP	97.44667	0.00112	2.288333
DBP	108.7955	0.00105	4.590583
BBP	97.33	0.00109	7.370659
DEHP	97.8765	0.00097	6.347501
DnOP	106.9633	0.00101	7.519507

R: recovery rate; MDL: method detection limit; RSD: relative standard deviation.

Table 4 – The phthalate content in different plastic products (unit: mg/g).

Materials	DMP		DEP		DBP		BBP		DEHP		DnOP		∑PAEs
	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	Mean	Range	
Plastic bag	0.286	0.106–1.607	0.263	0.15–1.984	0.987	0.374–1.601	0.706	0.453–0.959	3.583	2.115–4.051	0.743	0.269–1.217	6.568
Plastic cup	0.469	0.311–1.227	0.103	n.d.–0.753	0.7085	n.d.–1.383	0.8355	n.d.–1.634	1.089	0.927–1.151	n.d.	n.d.	3.205
Plastic bowl	0.122	0.104–1.388	0.94	0.658–2.433	0.336	n.d.–1.156	0.384	n.d.–0.644	1.027	0.899–2.112	0.25	0.13–1.667	3.059
Plastic bucket	0.979	n.d.–1.854	0.298	0.277–0.319	n.d.	n.d.	0.232	0.101–0.872	1.417	1.11–1.78	n.d.	n.d.	2.926
Polyvinyl chloride (PVC) bag	0.765	0.587–1.463	0.599	0.433–1.55	0.533	n.d.–0.865	0.845	0.628–1.103	1.875	1.456–2.169	1.05	n.d.–1.85	5.667
PVC-based plastic film	0.969	0.487–1.552	0.372	0.155–1.29	n.d.	n.d.	0.979	0.527–2.031	1.444	0.516–1.724	0.589	0.335–0.844	4.354

n.d.: not detected.

In order to ensure the reliability of this method, rigorous quality control is demanded in data collection and analysis. The recovery rates (R), relative standard deviation (RSD), method detection limit (MDL) of PAEs were measured in Table 3.

R and RSD of the measurement approach: 0.5 mL of the mixture standard solutions of phthalate with concentrations of 0.4, 1.0, 4.0 and 10.0 μg/mL were then processed using the pre-processing method depicted above. Furthermore, the recovery and RSD of samples were then calculated. For detailed results, please refer to MDL which was measured by the methods of EPA, which means to measure the detectable minimum concentration that is of 99% confidence level when the concentration of analyte is above 0: 0.01 μg/mL mixed standard solution was added into 20 portions of blank samples. Based on the above measurement method, the MDL was calculated according to the standard deviation of the analytic result of parallel samples by:

$$\mathrm{MDL} = t_{(n-1, 1-\alpha = 0.99)} \times \mathrm{SD} \tag{1}$$

where, n is the number of samples being repeatedly measured; SD is the standard deviation of test results of standard addition samples with 20 times; t represents the value when the degree of freedom is $n - 1$, which is 3.143, and $1 - \alpha$ is the confidence level.

2. Results and discussion

2.1. Ratios of contamination concentration in standard plastic goods

This study has collected several types of plastic goods often seen in markets with 10 samples from each type of plastic goods, recorded the mean value and range of each phthalate content in different plastic products and furthermore evaluated the total phthalate content as shown in Table 4.

By comparing contents of different kinds of PAEs in plastic products, as can be seen, DMP, DEP, BBP, and DEHP were found in all plastic samples. DBP were not detected in plastic bags and plastic bowls. DnOP were not detected in plastic bowls and PVC bags. PAEs total content in plastic products could be ranked as: plastic bags > PVC bags > PVC films > plastic cups > plastic bowls > plastic bottles. The range of PAEs total contents was 2.926–6.568 mg/g.

In conclusion, different types of plastic products contain different types of PAEs. In addition, DEHP is found in all plastic products with the highest content and a range of concentrations between 1.027 and 3.583 mg/g.

The study took a further step to choose a few typical plastic products for detailed vertical comparisons and analyzed the proportions of different PAEs in each product. Fig. 1 showed content ratio of different PAEs in plastic bags, PVC bags and plastic bowl, with six kinds of PAEs all detected. Compare the proportions of all kinds of PAEs in this three products and the trend are: DEHP > DBP > DnOP > BBP > DMP > DEP in plastic bags, DEHP > DnOP > BBP > DMP > DEP > DBP in PVC bags, DEHP > DEP > BBP > DBP > DnOP > DMP in plastic bowls.

Furthermore, this study calculated the coefficient of volatile strengths of phthalate ($K_{vs \sum PAEs}$) using above values. Moreover, this study carried out a preliminary classification in
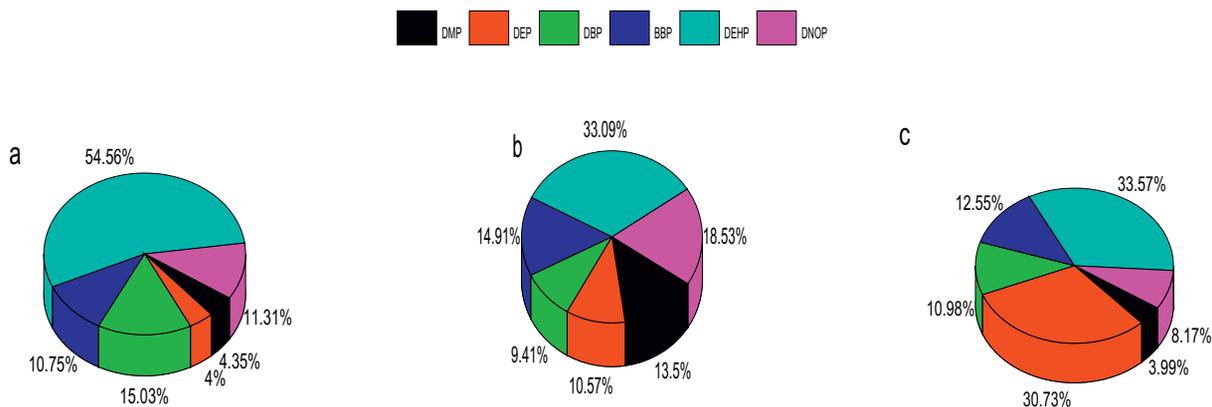
Fig. 1 – Content ratio of different PAEs in plastic bags (a), Polyvinyl chloride (PVC) bags (b) and plastic bowl (c).

relation to contamination sources based on the value of $K_{vs\sum PAEs}$, and then chose several more representative plastic products to continue environmental chamber experiments.

Table 5 and Fig. 2 demonstrated that most plastic goods can be divided into three categories based on the coefficient of volatile strengths. Plastic goods with the coefficient of volatile strength of more than 5000 mg/(g·m²) are considered to hold high content of phthalate, most of which are plastic film-like plastic goods, due to the requirements of increase plastic flexibility. In the case of plastic goods within 4000–5000 mg/(g·m²), these are considered to hold a medium content of phthalate, most of these have PVC-type plastic film, and finally, plastic goods with less than 4000 mg/(g·m²) coefficient of volatile strength are considered to hold a low content of phthalate, they are mostly plastic buckets which have structural invariance property and are of a relatively hard quality.

2.2. Concentration level analysis of phthalate contamination in environment cabin

In order to investigate the relationship between the main influencing factors (the coefficient of volatile strength $K_{vs\sum PAEs}$, temperature T, the closed time t, relative humidity RH, etc.) and indoor air phthalate concentration levels, this study set up a confined environmental chamber to rule out interference from other sources of contamination, and to gain air samples from cabin under different temperature, humidity, confinement time, as well as with different pollutant sources.

This study selected several typical plastic goods (mainly plastic bags, PVC bags, plastic cups and plastic buckets) as experimental objects. In order to explore the phthalate volatile pattern, experimental objects were confined in an environment cabin under constant temperature control, with every temperature change interval of 5°C, and were given a closed time range of 1–20 days. The measurement results can be seen in following Fig. 3.

Fig. 3 demonstrated emission concentration tendency of PAEs from plastic bags, PVC bag, plastic cups, and plastic buckets in the environment chambers with different closed time at different temperatures. Fig. 3 also showed that under the same temperature, with the increase of closed time, total concentration of PAEs in the environment cabin is also present gradually rising trend, which can be determined primarily that closed time positively related with total concentration of PAEs in the environment cabin.

This study selected emission concentration values of PAEs from the plastic bag, PVC bag, plastic cups and plastic buckets with the closed time referring to 2, 10, and 20 days respectively. Fig. 4 demonstrated with the increase of temperature, at the same closed time, PAEs emission concentration showed a trend of rising gradually, namely positively related temperature and emission concentration of PAEs in the environment cabin.

The closed times which were selected are 2, 10 and 20 days respectively. At ambient temperature (25°C), the impacts of pollutant sources with different volatility strength coefficients on the concentrations of PAEs released in the environmental chamber were compared and can be found in Fig. 5. According to Fig. 5, a positive correlation was found between the $K_{vs\sum PAEs}$ value and the concentration of PAEs in the environmental chamber.

2.3. Correlation analysis

This study carried out correlation analysis on total phthalate concentration levels with correlating affecting factors in environmental chambers. Through Fig. 3, we can initially determine changes in overall phthalate concentration levels under uniform temperature conditions with different closed time, with the appearance of all changes in logarithmic function. As the result, through independent variable t
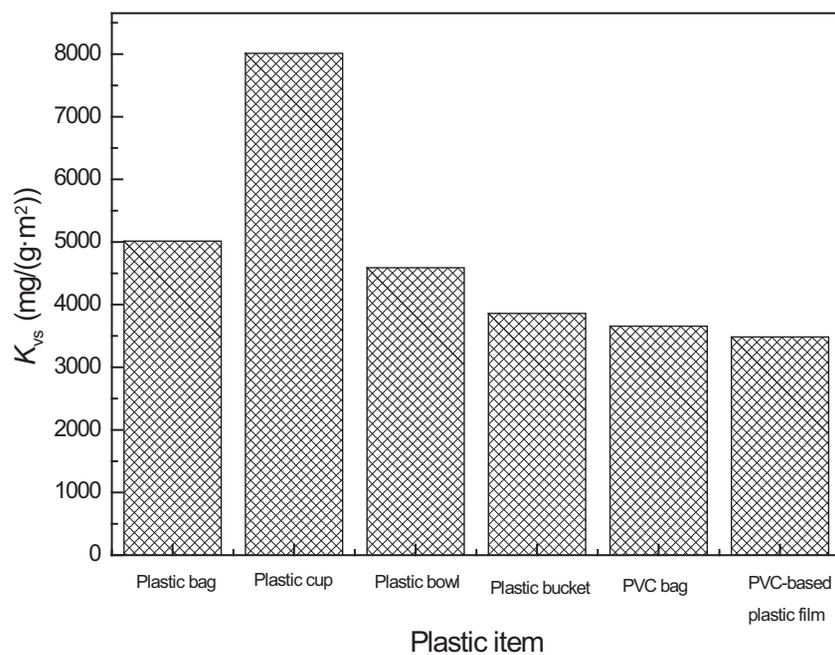
Table 5 – The coefficient of volatile strength of standard plastic goods $K_{vs\sum PAEs}$ (unit: mg/(g·m²)).

Materials	Mass (g)	Surface area (m²)	Sample number	Mean	$K_{vs\sum PAEs}$
Plastic bag	7.00	0.046	10	6.568	5013.8
Plastic cup	11.00	0.011	10	3.205	8012.5
Plastic bowl	12.00	0.020	10	3.059	4588.5
Plastic bucket	19.00	0.036	10	2.926	3860.7
PVC bag	8.50	0.066	10	5.667	3656.1
PVC-based plastic film	5.26	0.033	10	4.354	3483.2

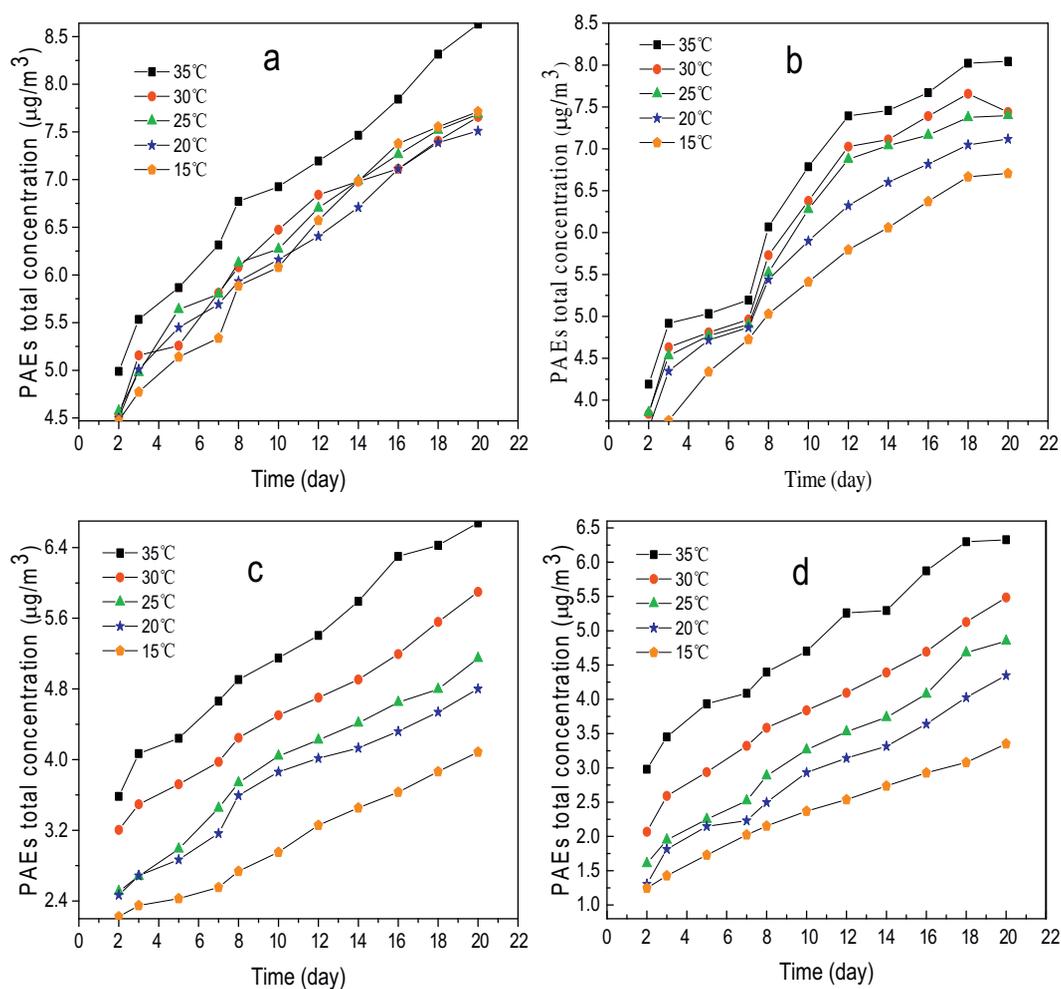Fig. 2 – $K_{vs\sum PAEs}$ values of different plastic items.

Fig. 3 – Emission concentration of total PAEs from plastic cups (a), plastic bags (b), plastic buckets (c) and Polyvinyl chloride (PVC) bag (d).
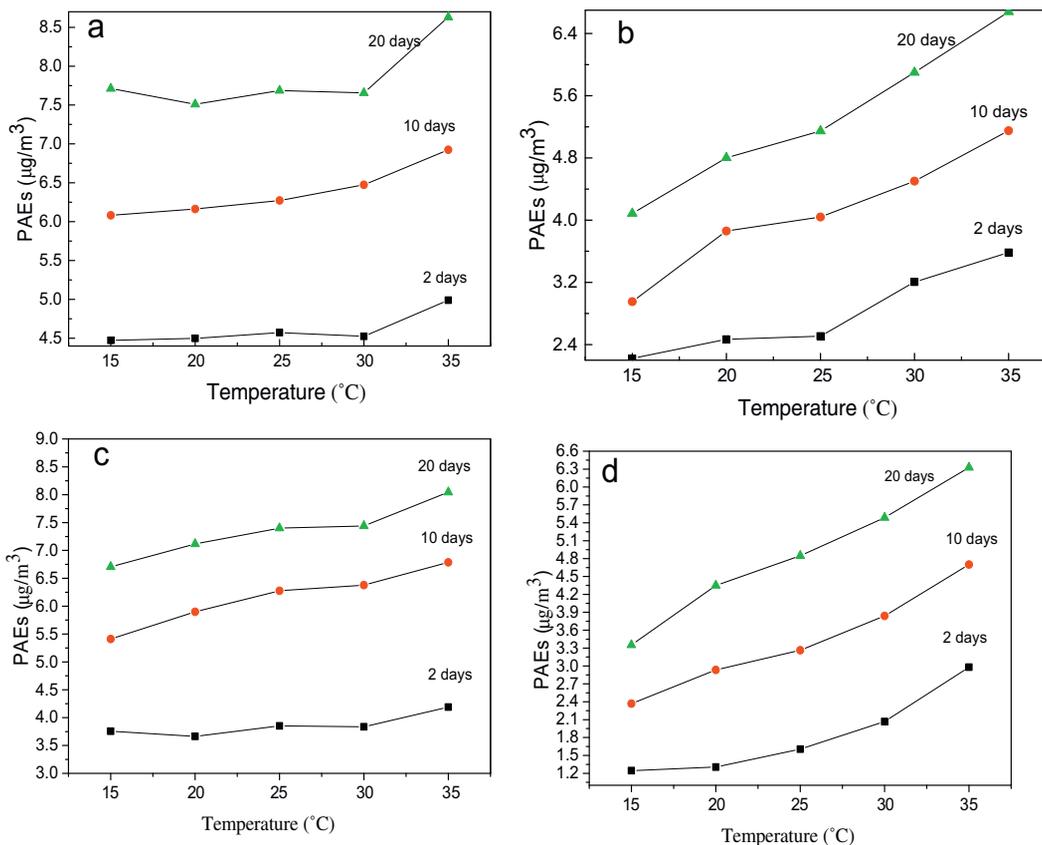
Fig. 4 – Emission concentrations of total PAEs from the plastic cups (a), plastic buckets (b), plastic bag (c), Polyvinyl chloride (PVC) bag (d) and in different closed times.

(confinement time) converted to lnt, we can carry out the correlation analysis with total phthalate concentration levels. Through Fig. 4, this study can also make preliminary determinations that the changes to total phthalate concentration level, with regard to temperature, are emerging perhaps as linear functions, exponential function and logarithmic function. To

Fig. 5 – Concentration of total PAEs from different pollutant sources with different volatility strength coefficients at ambient temperature (25°C).

further investigate temperature, this study modified the function form accordingly, with total phthalate concentration levels to carry out the correlation analysis. Finally, this study selected the different function form of K_{vs} with total PAEs concentration to carry out the correlation analysis.

Table 6 revealed correlation analysis results. Total phthalate concentration levels and containment time lnt (day); have extremely statistically significant correlations; with temperature $\ln(T + 273.15)$ they also have significant correlations; with different forms of RH however, the correlations are not significant; with linear correlation $K_{vs\sum PAEs}$ stronger than with linear correlation $\ln(K_{vs\sum PAEs})$.

As a result, acquiring all factors, together with total phthalate concentration levels, this study determined most optimal relevant form, laid a solid foundation for analysis of factors ratio.

2.4. Analysis of factors ratio

Apart from atmosphere pressure and humidity, all the factors mentioned above imposed significant influence on total PAEs concentration in the environmental chamber. When carrying out the analysis of factors ratio, in order to reflect the changing patterns of the total concentration of PAEs as comprehensively as possible, above influential factors ought to be considered. When merely taking into account the influence of temperatures and the closed time, based on the result of the above correlativity analysis, this study simply
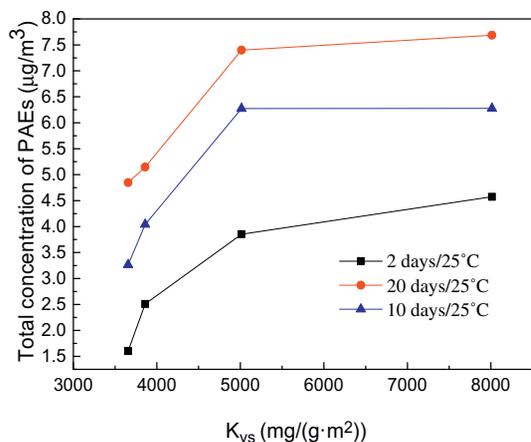
Table 6 – Correlation analysis on total phthalate concentration levels and correlating effecting factors.

		$\ln(T + 273.15)$	$(T + 273.15)^2$	$T + 273.15$	$\ln t$	K_{vs}	$\ln K_{vs}$
$C_{\sum PAEs}$	Correlation (r)	0.832	0.829	0.831	0.861	0.886	0.827
	p	0.021	0.023	0.022	0.000	0.114	0.173

adjusted individual environmental factor variances and matched then with the total concentration level of PAEs by Eviews. The final results are shown in Table 7, deriving the optimal expression form as:

$$C_{\sum PAEs} = 25.477 \times \ln(T + 273.15) + 1.465 \times \ln t - 143.63 \quad (2)$$

$$C_{\sum PAEs} = 25.477 \times \ln(T + 273.15) + 1.465 \times \ln t - 143.63 \quad (3)$$

where, $C_{\sum PAEs}$ ($\mu g/m^3$) is the content of total PAEs in entire pollutant sources; T (°C) is the temperature; and t (day) is the indicative of closed time.

In accordance with the correlation coefficient $R^2 = 0.446536$ in Table 7, the contribution rate of the two environmental influential factors used in the establishment of equation referring to the change of total PAEs concentration was roughly 44.65%. This cannot sufficiently explain the main reasons on the change of PAEs concentration. This is owing to the absence of consideration about feature of pollutant sources, reflecting that it may be the main factor that affects PAEs concentration. Such factor may have 55.35% influence on the total concentration of PAEs (assuming that feature of pollutant sources and the two environmental factors mentioned in the paper can basically explain all the influential factors of the change in total PAEs concentration).

According to the literature survey, the feature of pollutant sources can be demonstrated with two indictors: the content of total PAEs in pollutant sources and the volatility strength coefficient (K_{vs}) that calculated above (Section 2.1).

If the content of total PAEs (C_{PAEs}) in pollutant sources was taken into account along with the above two environmental influential factors being matched with the concentrations of PAEs measured in environmental chambers, the parameters of matching result are shown in Table 8.

$$C_{\sum PAEs} = C_1 \times \ln(T + 273.15) + C_2 \times \ln t + C_3 \times C_{PAEs} + C_4 \quad (4)$$

where, C_1, C_2, and C_3, are all parameters of ratio values and C_4 is a constant term. C_{PAEs} is the content of total PAEs in unit mass of pollutant sources.

Based on the previous analysis, when considering the factor of $K_{vs\sum PAEs}$ into fitting analysis and then using Eviews to conduct basic adjustments of all variables, including environmental factors and $K_{vs\sum PAEs}$, with total phthalate

concentration data, the optimum representational form can be seen as below with fitting result is demonstrated in Table 9:

$$C_{\sum PAEs} = C_1 \times \ln(T + 273.15) + C_2 \times \ln t + C_3 \times K_{vs\sum PAEs} + C_4 \quad (5)$$

where, T (°C) is the indoor air temperature, t (day) is the confinement time, $K_{vs\sum PAEs}$ is the coefficient of volatile strength.

From Table 9, three variables can explain more than 94.6% of reasons for indoor total phthalate concentration change, with the remaining 5.4% of uncertainties mainly due to other particular factors (ventilation circumstances *etc.*). Data fitting results are predominantly able to show the main causes of total phthalate concentration levels change. The final expression can be seen as below:

$$C_{\sum PAEs} = 25.476 \times \ln(T + 273.15) + 1.4652 \times \ln t + 0.2188 \\ \times K_{vs\sum PAEs} - 142.8848 \quad (6)$$

where, T (°C) is the indoor air temperature, t (day) is the natural containment time of windows and doors, and $K_{vs\sum PAEs}$ is the coefficient of volatile strength.

Fig. 6 summarized the ratios of influence that individual factors have on the concentration levels of total PAEs. The volatility strength coefficient of PAEs ($K_{vs\sum PAEs}$) yields an influence ratio of around 48.75%, whereas closed time and temperature together are at 45.7%, as well as other factors at 5.55% in Fig. 6a. The content of total PAEs (C_{PAEs}) yields an influence ratio of around 42.5%, whereas closed time and temperature together are at 45.7%, as well as other factors at 11.8% in Fig. 6b. Therefore, the volatility strength coefficient of PAEs ($K_{vs\sum PAEs}$) is the most predominant influential factor of total PAEs volatile concentration.

3. Conclusions

(1) This study firstly defined and evaluated the coefficient of volatile strength of the phthalate from plastic goods (namely phthalate content from per unit mass and unit surface area of plastic goods), with range from 3483.2 to 8012.5 mg/(g·m²), which created an improved database system of phthalate the coefficient of volatile strengths of typical type plastic goods.

Table 7 – The fitting result of PAEs total concentration with environmental factors *T* and *t*.

Variable	Coefficient	Coefficient value	Std. error	t-Statistic	p
T	C_1	25.47680	5.363569	4.749971	0.0000
t	C_2	1.465192	0.178497	8.208485	0.0000
–	C_3	−143.6308	30.56059	−4.699871	0.0000
R^2	0.456691		F-statistic		44.9707
Adjusted R^2	0.446536		Durbin–Watson statistic		0.061252
p (F-statistic)	0.0000				
Dependent variable: $C_{\sum PAEs}$	Sample number: 110				

Table 8 – The fitting parameter of PAEs total concentration T, t and C_{PAEs}.

R^2	0.881306	F-statistic	113.8506
Adjusted R^2	0.873565	Durbin–Watson statistic	0.532715
p (F-statistic)	0.000		
Dependent variable: $C_{\sum PAEs}$	Sample number: 110		

(2) Correlation and ratio analysis of influencing factors in environmental chambers. The correlation between total phthalate concentration, temperature and the closed time respectively is distinctly higher than humidity and atmospheric pressure. These two environmental factors together accounted for 45.7% of influencing factors.

After considering the volatility strength coefficient of PAEs (K_{vs}) from different pollutant sources into study, three variables can explain 94.6% of indoor phthalate concentration change ($R^2 = 0.9445$). Therefore, the coefficient K_{vs} accounted for 48.75% of influencing factors. However, the value of total PAE contents in plastic products accounted for 42.5% of influencing factors. In conclusion, the factor K_{vs} is a major factor that affect the indoor air total PAEs concentration.

Acknowledgments

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Table 9 – The fitting result of PAEs total concentration T, t and $K_{vs\sum PAEs}$.

Variable	Coefficient	Coefficient value	Std. error	t-Statistic	p
T	C_1	25.47680	1.698050	15.00356	0.0000
t	C_2	1.465192	0.056510	25.92784	0.0000
$K_{vs\sum PAEs}$	C_3	0.2187820	1.698050	15.00356	0.0000
–	C_4	−142.8848	9.675195	−14.76815	0.0000
R^2	0.946054		F-statistic		619.6384
Adjusted R^2	0.944527		Durbin–Watson statistic		0.392231
p (F-statistic)	0.000				
Dependent variable: $C_{\sum PAEs}$	Sample number: 110				
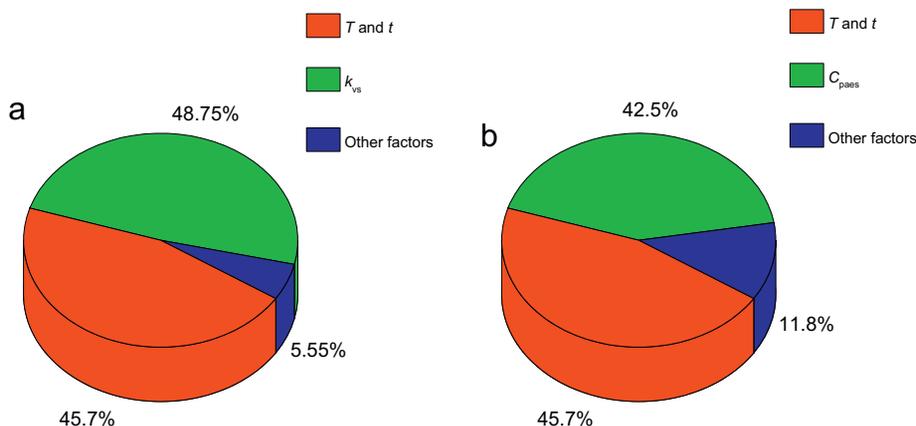
Fig. 6 – The ratios of different factors affecting the concentration levels change of total PAEs.

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