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Emission factor, relative ozone formation potential and relative carcinogenic risk assessment of VOCs emitted from manufacturing industries

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Abstract

Manufacturing industries are one of the important emission sectors of anthropogenic volatile organic compounds (VOCs). In this study, VOC emission factors, relative ozone formation potential (ROFP) and relative carcinogenic risk (RCR) were estimated for manufacturing industries ($n = 13$) located in central Taiwan. Emission samples were collected in stainless steel canisters and were analyzed with a system of gas chromatography-mass spectroscopy. Higher emission factors of total VOCs (Σ VOCs) were observed for stencil printing ($423 \text{ mg-VOC kg}^{-1}$) compared to other emission industries. Alkanes constituted the most prominent group of VOCs for steel foundry (42%), aluminum foundry (25%) and synthetic resin industries (25%). Oxygenated VOCs were the most abundant group in the organic solvent (80%), polyester resin (80%) and polyurethane (75%) industries. Moreover, emissions from acrylic resin manufacturing had a major contribution from aromatic compounds ($> 95\%$). Toluene was the topmost compound in terms of its contribution to Σ VOCs in plastic tape manufacturing (44%), aluminum foundry (40%), steel foundry (12%), plastic coating (64%) and stencil printing (35%). Analysis of ozone formation potentials showed that the metal product and machinery acrylic resin manufacturing and stencil printing had a higher normalized relative ozone formation potential (ROFP) index and belonged to Level-I emission sources. However, in terms of the relative carcinogenic risk (RCR), integrated iron and steel manufacturing had the highest normalized RCR index that belonged to level-I emission sources. Level-I represents the most important VOC emission sources. This study provides a reactivity- and carcinogenicity-based approach to identify high-priority VOC emission sources. The results of this study would help formulate emission reduction policies and strategies for manufacturing industries.

Keywords: Volatile organic compounds, Manufacturing sources, Relative ozone formation potential, Relative carcinogenic risk, Potential source comparison

Introduction

Manufacturing industries are important stationary emission sources of air pollutants worldwide. These emission sources have become one of the major contributors to air pollution due to a substantial increase in industrial production [1–3]. The pollutants such as particulate

matter, oxides of carbon, oxides of nitrogen, polycyclic aromatic hydrocarbons and volatile organic compounds (VOCs) pose threats to human health and the environment [4–7]. VOCs are of interest in part because they participate in atmospheric photochemical reactions that contribute to ozone formation [8]. Tropospheric ozone is formed by chemical reactions involving airborne VOCs, airborne nitrogen oxides, and sunlight [9]. The oxidation products of VOCs may also get absorbed by the atmospheric aerosols [10]. VOCs contain several

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hundreds of species; each species can react with different rates and reaction mechanisms and have different potential for ozone formation [11]. Ozone formation potential (OFP) estimates the contribution of individual VOC species to ozone formation. Developing control strategies for VOC emission sources requires considering not only the emission amount of VOCs but also the chemical reactivity (i.e., maximum incremental reactivity, MIR) of VOC species [12]. The MIR based approach has been recommended by U.S. EPA [13]. Reactivity-based control strategies can be applied to various industrial emission sources to identify the highly reactive VOC emission sources that contribute more to the ozone formation. For example, in Europe, reactivity-based strategies for stationary emission sources resulted in the reduction of tropospheric ozone formation compared to simple mass-based strategies [14].

VOC lifespan in the atmosphere could range from a few minutes to several months. So, some of the VOCs may travel over large distances and enter the human body mainly through inhalation or skin absorption causing varieties of health effects [15]. Human health effects can vary among VOC species, ranging from irritants to cancerous illnesses [16–18]. For example, exposure to BTEX (i.e., benzene, toluene, ethylbenzene and xylene) has been associated with toxicological effects such as depression, respiratory diseases, damage to the circulatory system and cancer [19–22]. Benzene, and 1, 3-butadiene have been identified as carcinogens [23], and well-known risk factors for various types of cancers [24]. The main carcinogenic risks are associated with the blood (leukemia and non-Hodgkin lymphoma), lung, liver and biliary tract cancer [25–27]. With regard to these risks, the International Agency for Research on Cancer (IARC) has classified benzene as a Group-1 human carcinogen [24]. Moreover, other VOCs such as trichloroethylene and 1,2-dibromoethane are the probable human carcinogens (Group 2A, IARC), ethylbenzene and chloroform are possibly carcinogenic to human (Group 2B, IARC).

Several studies have been conducted on VOC emissions from sources such as road traffic, petrochemical industries, coal burning, biomass burning and solvent use [28–30]. These studies have reported significant differences in the source compositions between different regions. However, studies on VOC emissions from manufacturing industries are still limited [29, 31–33]. The major VOC emission sources include fossil fuel combustion, petrochemical, printing and solvent usage [29, 31, 34, 35]. Wang et al. [35] studied the distribution of VOCs emitted from solvent usage in furniture paint, auto paint and printing ink. Their study indicated that the largest contributing groups among the measured VOCs were aromatics (52%) followed by alkanes (32%) and alkenes (16%). Aromatic compounds such as

benzene has been found to be a common byproduct of the chemical manufacturing, petrochemical industries, production of xylene, toluene and other aromatic compounds, industrial solvent and printing sectors [23, 24]. Yuan et al. [29] identified alkanes and aromatic compounds as the most contributing groups in the printing sector. Tsai et al. [36] reported toluene, 1,2,4-trimethyl benzene, *m/p*-xylene, 1-butene, ethylbenzene, and benzene predominantly emitted from an integrated iron and steel plant located in Southern Taiwan.

VOC emissions from the manufacturing industries have a significant impact on air quality and human health. Biological evidence supports the causal link between VOC species and certain cancer. For instance, exposure to benzene and 1,3-butadiene increases the risk of leukemia [21, 37–39]. Toluene causes neurological disorders [40]. Long-term exposure to xylene can cause headaches, tremors and impaired concentration [41]. Occupational epidemiological studies of petrochemical industry workers indicate that benzene may cause lung cancer, multiple myeloma and acute myelogenous leukemia [42, 43]. Increased rates of leukemia risk have been shown in workers of synthetic rubber industries [37].

Stack emissions from different industries might differ greatly in the VOC species compositions. Thus, the emissions from different sources might play roles in atmospheric chemistry and human health hazards in different ways. It is essential to characterize VOC emission sectors, not only in terms of VOC emission concentrations but also in their chemical reactivity and associated health hazards. However, such data are still not sufficient for industrial emission sources. In this study, a few important industrial emission sources were investigated on the basis of emission factors, ROFP and RCR VOCs.

Materials and methods

Description of emission sources

In this study, the following thirteen types of VOC emission sources were selected: organic solvent manufacturing, synthetic resin manufacturing, acrylic resin manufacturing, polyester resin manufacturing, plastic tape manufacturing, aluminum foundry, steel foundry, metal products and machinery industries, integrated iron and steel manufacturing, non-ferrous metal-based manufacturing, polyurethane (PU) leather manufacturing, plastic coating and stencil printing. All of the selected emission sources were located within Taichung city, Taiwan. The sample industries were selected to represent the major industrial emission sources located within Taichung city. The selected emission sources contributed to 73% of total VOC emissions within the city in the year 2016 [44]. The selected emission sources were grouped into the following five sectors on the basis

of U.S. EPA's North American Industrial Classification System (NAICS): chemical manufacturing sector (NAICS S 325), plastics products manufacturing sector (NAICS 326), metals manufacturing sector: primary (NAICS 331) and fabricated metal product manufacturing (NAICS 332), leather manufacturing (NAICS 313) and printing and related support activities sector (NAICS 323).

The chemical manufacturing sector incorporates the chemical transformation of organic and inorganic raw materials and the formation of products. In the present study, this sector was represented by the industries that handled organic solvents and various types of resins. The plastic product manufacturing sector incorporated the industry that manufactured adhesive plastic tapes. The metal (primary and fabricated) manufacturing sector included iron and steel industries, metal casting industries, and nonferrous metal industries. In this study, only the sintering process of the integrated iron and steel industry was investigated. The leather/textile manufacturing sector consisted of the facility that handled synthetic leather, spinning natural and manmade fibers into yarns and threads. The printing sector included plastic coating, stencil printing, plate-making and bookbinding.

Detailed information about selected emission sources can be found in Table 1.

VOCs sampling and analysis

VOC emissions from manufacturing industries can be categorized into fugitive emissions and stack emissions. The current study was conducted only for stack emissions. Emission samples were collected using 6 L fused silica stainless steel canisters (Entech Instruments, Catalog# 29–10,622) that had been pre-cleaned with high purity-nitrogen and evacuated with an automated canister cleaner. A flow controller and Teflon tubing were used to extract the exhaust gas from emission stacks to the evacuated canisters. The volume of flue gas was measured using a gas flowmeter. The selection of the sampling location in the stack is important to obtain representative samples. To minimize the effects of process variables, monitoring was performed when there was constant flow through stacks. Stack-ports were set by the local environmental protection body for routine monitoring.

The collected samples were analyzed with the Gas Chromatography (7890) Mass Spectroscopy (5977B) system (GC/MS, Agilent Technologies). The details of the

Table 1 Information about emission sectors and sources included in the present study

Number	Sectors	Emission sources	No. of samples ($n = 21$)	Raw material	Activity
1	Chemical manufacturing sector (NAICS 325)	Organic solvent	$n = 4$	Solvent	Organic solvent
		Synthetic resin	$n = 2$	Plastic pellets, resin	Plastic, chemical
		Acrylic resin	$n = 2$	Acrylic polymer resin	Acrylic resin
		Polyester resin	$n = 1$	Polyester resin	Plastic product
2	Plastics products manufacturing sector (NAICS 326)	Plastic tape	$n = 1$	Ethyl acetate	Tape manufacturing
3	Metals manufacturing sector: Primary (NAICS 331) and fabricated metal product manufacturing NAICS 332)	Integrated iron and steel	$n = 1$	Sinter	Steel
		Aluminum foundry	$n = 3$	Aluminum alloy ingot	Mechanical equipment, locomotive parts
		Steel foundry	$n = 2$	Stainless steel ingot	Metal product
		Metal products and machinery	$n = 1$	Metal-hardware parts	Metal product
		Non-ferrous metal	$n = 1$	–	Mechanical equipment
4	Leather manufacturing sector (NAICS 313)	PU leather	$n = 1$	Aqueous solvent resin	Artificial leather
5	Printing and related support activities sector (NAICS 323)	Plastic coating	$n = 1$	Polyester foil film	Plastic coating
		Stencil printing	$n = 1$	Ink	Printing and data storage media production

GC/MS analysis is described elsewhere [45]. The internal calibration method was applied for the quantification of the VOCs. The standard mixture of gases (A715.15B) from Taiwan National Institute for Environmental Analysis was used as the external standard. Bromochloromethane, 1,4-difluorobenzene, chlorobenzene-d5 and 4-bromofluorobenzene were used as internal standards. A total of 72 VOC species were quantified in this study. Based on the functional groups, these VOCs were classified as alkanes (24 species), alkenes (8 species), aromatics (18 species), oxygenated VOCs (8 species), halocarbons (13 species) and others (1 species) (Table 2).

Emission factors of the detected VOC species were calculated for each of the emission sources by using Eq. (1).

$$\text{Emission factor} = \frac{\text{VOC con.} \times \text{Exhaust volume (dry basis)}}{\text{Raw material unit} \times \text{Sampling duration}} \quad (1)$$

The calculated emission factor of each VOC species was normalized ($x_{i,j}$) to the Σ VOCs emission factors in the source sample for each emission source. The detailed concentrations and emission factors can be found in Additional file 1 (Table S1 and Table S2 of Supplemental Materials).

Quality assurance and quality control (QA/QC)

The canisters were pre-cleaned before sampling with ultra-pure nitrogen (99.999%) to remove water vapor and contaminants. Canisters were cleaned for 12 cycles of filling and evacuation using a canister cleaning system (3100A, Entech). Replicates were performed for each sample to minimize analytical errors. The blank analysis was run before each sample analysis.

ROFP

The absolute OFP of VOC species is usually calculated by multiplying its concentration by its MIR value [46, 47]. However, it is usually the relative importance of each VOC species in comparison with the other emission sources that is of more practical significance. Knowing the relative importance of different VOCs allows for targeting more reactive VOCs sources, hence more efficient and flexible for sources comparing strategies. Therefore, ROFP was calculated on the basis of the VOC emission factor (normalized to 1) and the MIR value of each VOC (Eq. (2)).

$$\text{ROFP}_j = \sum_{i=1}^n x_{i,j} \times \text{MIR}_i \quad (2)$$

where, ROFP_j is for source j ($\text{g-O}_3 \text{ g-VOCs}^{-1}$), $x_{i,j}$ is the

Table 2 List of the target VOC species

No.	Species	No.	Species	No.	Species	No.	Species
	Alkanes ($n = 24$)	20	<i>n</i> -Octane	38	Styrene	57	Methyl methacrylate
1	Isobutane	21	<i>n</i> -Nonane	39	<i>o</i> -Xylene	58	Methyl Isobutyl Ketone
2	<i>n</i> -Butane	22	<i>n</i> -Decane	40	Isopropyl benzene		Halocarbons ($n = 13$)
3	Isopentane	23	<i>n</i> -Undecane	41	<i>n</i> -Propyl benzene	59	Methylene chloride
4	2,2-Dimethylbutane	24	<i>n</i> -Dodecane	42	<i>m</i> -Ethyl toluene	60	Chloroform
5	2,3-Dimethylbutane		Alkenes ($n = 8$)	43	<i>p</i> -Ethyl toluene	61	Tetrahydrofuran
6	2-Methylpentane	25	Propene	44	1,3,5-Trimethylbenzene	62	1,2-Dichloroethane
7	3-Methylpentane	26	1-Butene	45	<i>o</i> -Ethyl toluene	63	Trichloroethylene
8	<i>n</i> -Hexane	27	1,3-Butadiene	46	1,2,4-Trimethylbenzene	64	1,2-Dichloropropane
9	2,4-Dimethylpentane	28	Cis-2-butene	47	1,2,3-Trimethylbenzene	65	Tetrachloroethylene
10	Methylcyclopentane	29	1-Pentene	48	<i>m</i> -Diethyl benzene	66	Chlorobenzene
11	2-Methylhexane	30	Trans-2-pentene	49	<i>p</i> -Diethyl benzene	67	Bromoform
12	Cyclohexane	31	Isoprene	50	Naphthalene	68	1,1,2,2-Tetrachloroethane
13	2,3-Dimethylpentane	32	1-Hexene		Oxygenated VOCs ($n = 8$)	69	1,3-Dichlorobenzene
14	3-Methylhexane		Aromatics ($n = 18$)	51	Ethanol	70	1,4-Dichlorobenzene
15	<i>n</i> -Heptane	33	Benzene	52	Acrolein	71	1,2-Dichlorobenzene
16	Methylcyclohexane	34	Toluene	53	Acetone		Others (1)
17	2,3,4-Trimethylpentane	35	Ethylbenzene	54	Isopropyl alcohol	72	Carbon disulfide
18	2-Methylheptane	36	<i>m</i> -Xylene	55	Methyl Ethyl Ketone		
19	3-Methylheptane	37	<i>p</i> -Xylene	56	Ethyl acetate		

ratio of EF of VOC species i to Σ VOCs for source j , and MIR_i is the value of species i as proposed by Carter [11].

RCR

The absolute carcinogenic risk is usually estimated by multiplying the actual VOC concentration and its carcinogenic risk factor [48]. However, to ensure comparability among different emission sources, carcinogenicity was calculated for each emission source on a relative basis (Eq. (3)).

$$RCR_j = \sum_{i=1}^n x_{i,j} \times UR_i \times f_i \tag{3}$$

where, RCR_j is the source j $\text{mg}^{-1} \text{m}^3$, $x_{i,j}$ is the ratio of emission factor of VOC species i to Σ VOCs for source j , UR_i is the carcinogenic risk factor for VOC species i ($\mu\text{g m}^{-3}$) $^{-1}$, and f_i is the unit conversion factor. The U.S. EPA developed Integrated Risk Information System to provide carcinogenic risk factors for VOCs (Additional file 1: Table S3).

Normalized ROFP and RCR

After obtaining the ROFP and RCR values for different emission sources, they were sorted from high to low.

The normalized ROFP (NROFP) index and normalized RCR (NRCCR) index were calculated using the Eqs. (4) and (5).

$$NROFP_j = \frac{ROFP_j - ROFP_{min}}{ROFP_{max} - ROFP_{min}} \tag{4}$$

$$NRCCR_j = \frac{RCR_j - RCR_{min}}{RCR_{max} - RCR_{min}} \tag{5}$$

where, $NROFP_j$ is the normalized ROFP index of source j , $ROFP_{min}$ is the minimum $ROFP_j$ among VOC sources, $ROFP_{max}$ is the maximum $ROFP_j$ among VOC sources, $NRCCR_j$ is the normalized RCR index of sources j , RCR_{min} is the minimum RCR_j among VOC sources, RCR_{max} is the maximum RCR_j among VOC sources.

Results and discussion

Emission factors

The Σ VOCs emission factors of the manufacturing sectors are shown in Fig. 1. The sequence of Σ VOC emission factors for the five groups of manufacturing sectors was printing > plastic > metal > chemical > leather. The Σ VOCs emission factors of manufacturing sectors were observed to be ranging from 0.00267 to 423 mg-VOC kg^{-1} . Among all sectors, the maximum emission factors

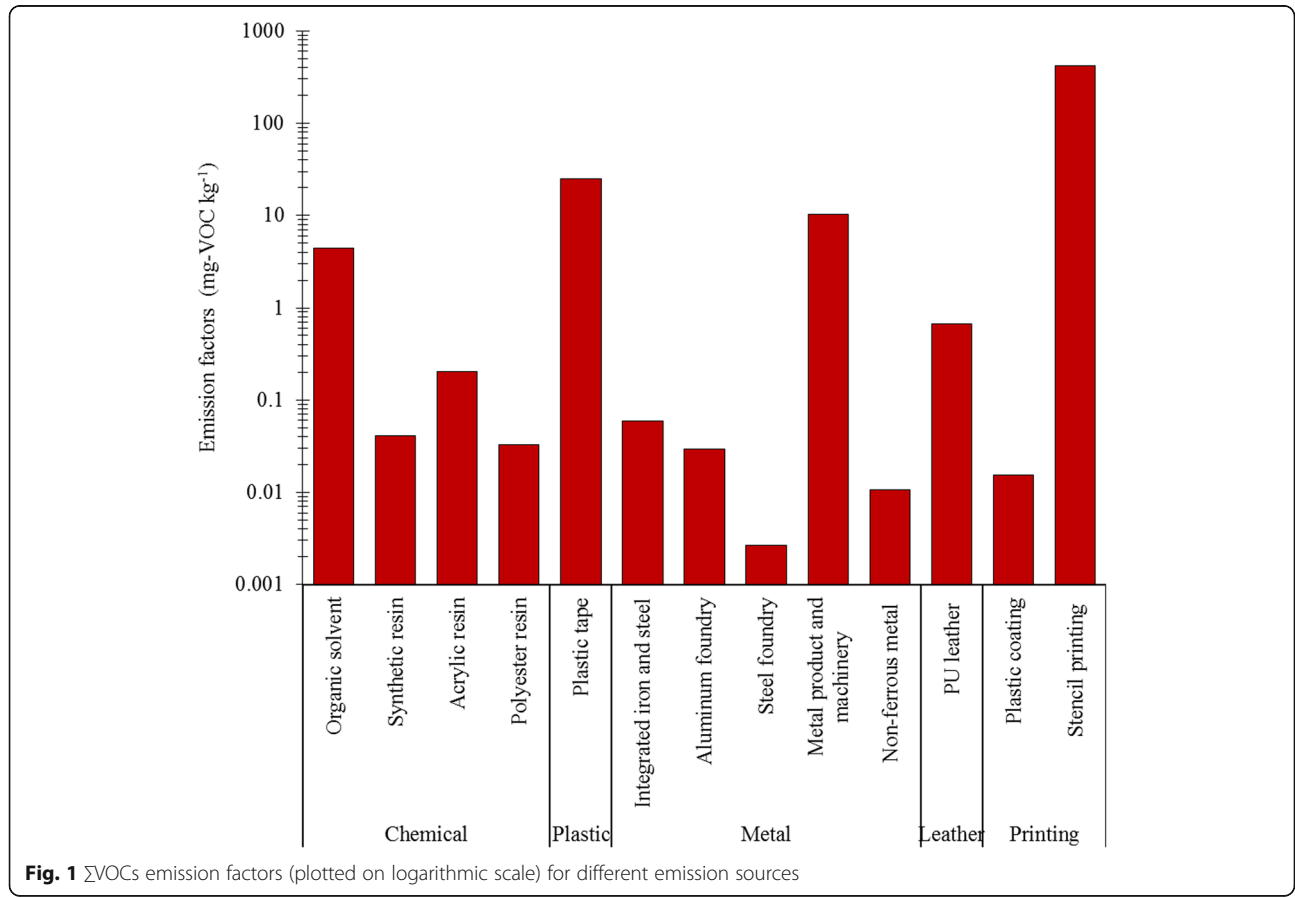


Fig. 1 Σ VOCs emission factors (plotted on logarithmic scale) for different emission sources

of Σ VOC were observed for stencil printing ($423 \text{ mg-VOC kg}^{-1}$) followed by plastic tape ($24.9 \text{ mg-VOC kg}^{-1}$), metal product and machinery ($10.3 \text{ mg-VOC kg}^{-1}$) and organic solvent ($4.4 \text{ mg-VOC kg}^{-1}$). For synthetic resin, acrylic resin, polyester resin, integrated iron and steel, aluminum foundry, steel foundry, non-ferrous metal, and polyurethane (PU) leather and plastic coating, Σ VOCs emission factors were found $\leq 1 \text{ mg-VOC kg}^{-1}$. Stencil printing had the highest emission factor which could be due to the presence of a large number of organic compounds in printing inks. Toluene was the most abundant VOC species measured in emissions from a Chinese printing industry [49]. In general, toluene, ethylbenzene, xylenes and ethyl acetate were common components in ink solvents [34, 49]. Some other organic compounds such as acetate, glycolic acid butyl ester, butyl glycol were also used in printing inks [50], but their percentage varied largely due to the heavy use of various solvent-based inks and paint solvents. Printing inks are made up of pigments, dyes, additives and carrier solvents. Different types of printing sectors have variable ink flow properties, which range from extremely thin watery through highly viscous to dry powder.

VOC species compositions

The VOC emission factors have been expressed as the percentage of each species relative to Σ VOCs emission factors. The identified VOCs were classified into the following five categories: alkanes, alkenes, aromatics, halocarbons and oxygenated VOCs. As presented in Fig. 2, alkanes formed the dominant VOC group in steel foundry (42%), aluminum foundry (25%) and synthetic resin (25%). A higher proportion of alkenes were observed for metal products and machinery (60%) followed by other emission sectors. Zhao et al. [33] observed a high percentage of alkanes (26%) followed by alkynes (16%), aromatics (14%) and alkenes (11%) in the emissions from iron and steel sectors. In the integrated iron and steel sector, aromatic compounds were the dominant (84%) VOC group followed by oxygenated VOC and alkenes. Similar results were reported by Tsai et al. [36] that showed a high contribution (45–70%) of aromatic compounds from integrated iron and steel industry.

The higher proportion of alkanes and alkenes emissions indicates insufficient oxidation of volatile components released from the fuels [46]. Chemical sectors such as organic solvent and polyester resin

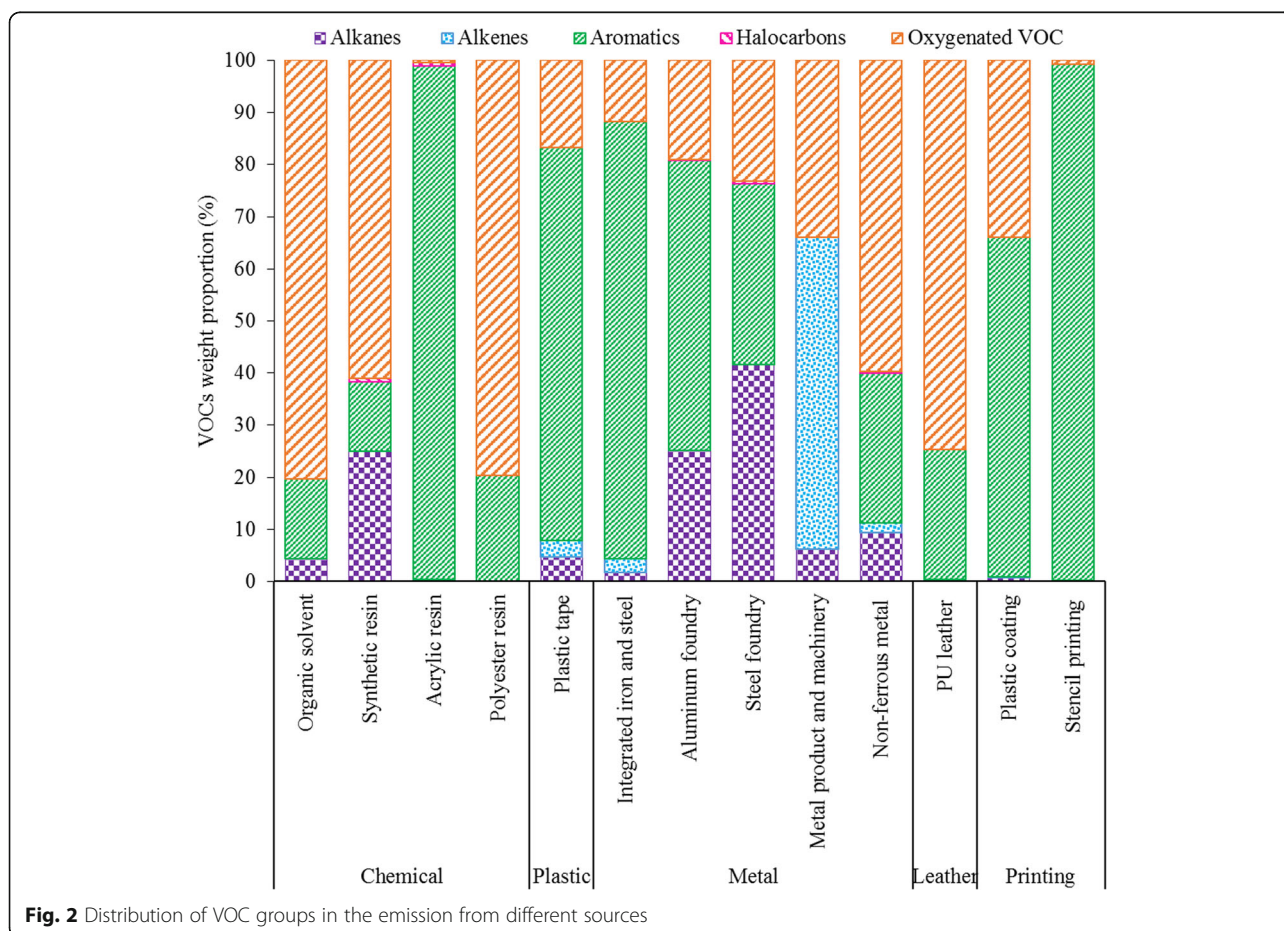


Fig. 2 Distribution of VOC groups in the emission from different sources

manufacturing were found to have more than 75% Σ VOCs contributed by oxygenated VOCs. Acrylic resin, plastic tape, integrated iron and steel, plastic coating and stencil printing sectors showed the major fraction of Σ VOCs contributed by aromatics (65–99%). Tsai et al. [36] reported the high abundance of aromatic species, including, toluene, 1,2,4 trimethylbenzene, xylene and benzene in the emissions from an integrated iron and steel industry. Yuan et al. [29] reported that the aromatics were the most abundant VOC group in the emissions from solvent usage in auto-painting, architectural painting and printing. The results provide only the functional groups of VOCs for different manufacturing sectors showed the VOCs emission characteristics from different product processes in three plants. Detailed profiles of the VOCs (top 5 contributors) for each manufacturing sector are presented in Table 3 and discussed in the following subsections.

Chemical manufacturing

The top five VOC species emitted from four chemical manufacturing sectors, such as organic solvent, synthetic resin, polyester resin and acrylic resin industries are shown in Table 3. The VOCs emitted from organic solvent manufacturing were mainly oxygenated VOCs, such as ethyl acetate and acetone, accounting for > 65% of Σ VOCs. Methyl isobutyl ketone, toluene and isopropyl alcohol accounted for a minor fraction of Σ VOCs. Synthetic and polyester resin manufacturing sectors predominantly emitted oxygenated VOCs like acetone (56%, 0.023 mg-VOC kg⁻¹) and ethyl acetate (80%, 0.026 mg-VOC kg⁻¹). However, the acrylic resin industry had higher contributions from aromatics (> 95% of Σ VOCs) such as *m/p/o*-xylene, ethylbenzene, and toluene. Most organic resins are solvent-borne, which contain a mixture of organic solvents, many of which are VOCs. The common solvents used in resins contain toluene, xylene, benzene, ethyl ketone, and methyl isobutyl ketone. Acrylic resin is widely used in paint formulations, and the paints emit predominantly aromatics compounds, such as benzene, toluene, ethylbenzene and xylene [28, 51]. However, the polyester resin was found to have the emission contributions mainly from oxygenated VOCs, as they are formed by the reaction of dibasic organic acids and polyhydric alcohols [52]. The difference in VOC emissions was probably related to the raw materials and products originating from the chemical manufacturing sectors.

Plastic tape manufacturing

The VOC species emitted from the plastic tape manufacturing industry were mainly aromatics such as toluene, ethyl acetate, *m/p*-xylene and ethylbenzene, accounting for 44% (11 mg-VOC kg⁻¹), 16% (4.0 mg-

VOC kg⁻¹), 10% (2.5 mg-VOC kg⁻¹), 10% (2.5 mg-VOC kg⁻¹) and 5% (1.3 mg-VOC kg⁻¹) of Σ VOCs emission factors, respectively. The reason for the high emission of toluene may be related to the nature of raw material used in plastic tape manufacturing. Plastic tape products included petroleum, petroleum by-products, natural rubber, acrylic resins, silicone rubber, dispersions, polymers and solvents. Solvent-based adhesive tape applications require high-stress resistance. There is no solvent-free adhesive tape available that shows equivalent properties. Therefore, there is no alternative to solvent-based adhesives in the high-quality range. All stages of the tape manufacturing process included hot melts releasing VOCs into the atmosphere. Tsubaki et al. [53] found toluene to be the major VOC species emitted from the double-sided pressure-sensitive adhesive tape.

Metal manufacturing

Toluene, ethyl acetate, acetone, 1-butene, *n*-butane, cis-2-butene, benzene, and ethanol were the main VOC species emitted from the metal-based manufacturing industries. Toluene was the most abundant VOC species in the emissions from both aluminum and steel foundries, accounting for 40% (0.012 mg-VOC kg⁻¹) and 12% (0.00031 mg-VOC kg⁻¹) of the Σ VOCs emission factors, respectively. Benzene had the highest contribution (41%, 0.024 mg-VOC kg⁻¹) in the integrated iron and steel sector. Samples from metal product and machinery and non-ferrous metal showed the major fractions of 1-butene and ethyl acetate emissions, accounting for 40% (4.2 mg-VOC kg⁻¹) and 38% (0.0041 mg-VOC kg⁻¹) of the Σ VOCs emission factors, respectively (Table 3). VOC compositions in the emissions from the integrated iron and steel manufacturing sector were similar to those reported by the previous work [36] for four processes of the integrated iron and steel industries. The study reported benzene, toluene, xylene, *n*-butane and 2-methylpentane for the sintering process as the major VOCs. Toluene, 1,2,4-trimethyl benzene, isopentane, *m/p*-xylene, 1-butene, ethylbenzene, benzene, trichloroethylene, *n*-hexane and *n*-pentane were the major VOC species in coke making exhausts [36].

Leather manufacturing

The major VOCs emitted from PU leather industry were methyl ethyl ketone, toluene and methyl methacrylate, accounting for 60% (0.40 mg-VOC kg⁻¹), 24% (0.16 mg-VOC kg⁻¹) and 13% (0.085 mg-VOC kg⁻¹) of Σ VOCs, respectively. The contributions of major VOC species detected in this study were similar to those reported in the earlier studies. Chang and Lin [54] obtained a higher amount of toluene and methyl ethyl ketone in emissions from coating, drying and surface treating processes of the PU leather industry. Wang et al. [55] reported a high

Table 3 Comparison of top-five VOC species obtained in this study with literature

Industry	Manufacturing	Percentage distribution (%) and Emission factors (mg-VOC kg ⁻¹) of the top 5 VOC species					References
		1st	2nd	3rd	4th	5th	
Chemical	Organic solvent	Ethyl acetate ^c 51% (2.3 mg-VOC kg ⁻¹)	Acetone ^c 14% (0.64 mg-VOC kg ⁻¹)	Methyl isobutyl ketone ^c 8% (0.35 mg-VOC kg ⁻¹)	Toluene ^b 6% (0.25 mg-VOC kg ⁻¹)	Isopropyl alcohol ^c 4% (0.16 mg-VOC kg ⁻¹)	This study
	Synthetic resin	Acetone ^c 56% (0.023 mg-VOC kg ⁻¹)	Methylcyclohexane ^a 16% (0.0067 mg-VOC kg ⁻¹)	Toluene ^b 8% (0.0033 mg-VOC kg ⁻¹)	Methyl ethyl ketone ^c 3% (0.0011 mg-VOC kg ⁻¹)	3-Methylpentane ^a 2% (0.0091 mg-VOC kg ⁻¹)	This study
Plastic	Acrylic resin	<i>m</i> -Xylene ^b 42% (0.087 mg-VOC kg ⁻¹)	<i>p</i> -Xylene ^b 28% (0.058 mg-VOC kg ⁻¹)	<i>o</i> -Xylene ^b 16% (0.033 mg-VOC kg ⁻¹)	Ethylbenzene ^b 10% (0.020 mg-VOC kg ⁻¹)	Toluene ^b 1% (0.0026 mg-VOC kg ⁻¹)	This study
	Polyester resin	Ethyl acetate ^c 80% (0.026 mg-VOC kg ⁻¹)	Toluene ^b 16% (0.0053 mg-VOC kg ⁻¹)	<i>o</i> -Ethyltoluene ^b 1% (0.00027 mg-VOC kg ⁻¹)	<i>p</i> -Ethyltoluene ^b 1% (0.00027 mg-VOC kg ⁻¹)	<i>m</i> -Ethyltoluene ^b 1% (0.00024 mg-VOC kg ⁻¹)	This study
Metal	Plastic tape	Toluene ^b 44% (11 mg-VOC kg ⁻¹)	Ethyl acetate ^c 16% (4.0 mg-VOC kg ⁻¹)	<i>m</i> -Xylene ^b 10% (2.5 mg-VOC kg ⁻¹)	<i>p</i> -Xylene ^b 10% (2.5 mg-VOC kg ⁻¹)	Ethylbenzene ^b 5% (1.3 mg-VOC kg ⁻¹)	This study
	Integrated iron and steel	Benzene ^b 41% (0.024 mg-VOC kg ⁻¹)	Toluene ^b 38% (0.023 mg-VOC kg ⁻¹)	Methyl ethyl ketone ^c 7% (0.0043 mg-VOC kg ⁻¹)	1,3-Butadiene ⁺ 2% (0.0012 mg-VOC kg ⁻¹)	Ethyl acetate ^c 2% (0.0011 mg-VOC kg ⁻¹)	This study
Leather	Aluminum foundry	Toluene ^b 40% (0.012 mg-VOC kg ⁻¹)	Ethyl acetate ^c 10% (0.0029 mg-VOC kg ⁻¹)	<i>n</i> -Nonane ^a 7% (0.0021 mg-VOC kg ⁻¹)	<i>n</i> -Octane ^a 4% (0.0013 mg-VOC kg ⁻¹)	2,3,4-Trimethylpentane ^a 4% (0.0013 mg-VOC kg ⁻¹)	This study
	Steel foundry	Toluene ^b 12% (0.00031 mg-VOC kg ⁻¹)	Acetone ^c 11% (0.00029 mg-VOC kg ⁻¹)	<i>n</i> -Butane ^a 8% (0.00023 mg-VOC kg ⁻¹)	Methyl ethyl ketone ^c 5% (0.00015 mg-VOC kg ⁻¹)	Ethanol ^c 5% (0.00014 mg-VOC kg ⁻¹)	This study
Printing	Metal products and machinery	1-Butene ⁺ 40% (4.2 mg-VOC kg ⁻¹)	Ethanol ^c 29% (2.9 mg-VOC kg ⁻¹)	<i>cis</i> -2-Butene ⁺ 18% (1.9 mg-VOC kg ⁻¹)	<i>n</i> -Butane ^a 6% (0.65 mg-VOC kg ⁻¹)	Acrolein ^c 5% (0.56 mg-VOC kg ⁻¹)	This study
	Non-ferrous metal	Ethyl acetate ^c 38% (0.0041 mg-VOC kg ⁻¹)	Acetone ^c 14% (0.0015 mg-VOC kg ⁻¹)	Toluene ^b 14% (0.0015 mg-VOC kg ⁻¹)	Methyl ethyl ketone ^c 7% (0.00078 mg-VOC kg ⁻¹)	<i>n</i> -Undecane ^a 3% (0.00027 mg-VOC kg ⁻¹)	This study
Coating	PU leather	Methyl ethyl ketone ^c 60% (0.40 mg-VOC kg ⁻¹)	Toluene ^b 24% (0.16 mg-VOC kg ⁻¹)	Methyl methacrylate ^c 13% (0.085 mg-VOC kg ⁻¹)	Ethyl acetate ^c 2% (0.011 mg-VOC kg ⁻¹)	Acetone ^c 1% (0.0018 mg-VOC kg ⁻¹)	This study
	Plastic coating	Toluene ^b 64% (0.0099 mg-VOC kg ⁻¹)	Acetone ^c 25% (0.0039 mg-VOC kg ⁻¹)	Methyl ethyl ketone ^c 8% (0.0012 mg-VOC kg ⁻¹)	Ethyl acetate ^c 1% (0.00013 mg-VOC kg ⁻¹)	2-Methylhexane ^a 1% (0.000038 mg-VOC kg ⁻¹)	This study
Printing	Stencil printing	Toluene ^b 35% (149 mg-VOC kg ⁻¹)	1,2,4-Trimethylbenzene ^b 20% (85 mg-VOC kg ⁻¹)	<i>m</i> -Ethyltoluene ^b 10% (42 mg-VOC kg ⁻¹)	1,3,5-Trimethylbenzene ^b 7% (31 mg-VOC kg ⁻¹)	1,2,3-Trimethylbenzene ^b 6% (26 mg-VOC kg ⁻¹)	This study
	Gravure printing	Ethyl acetate 64%	Isopropyl alcohol 14%	Methylene chloride 7%	<i>n</i> -Propyl acetate 4%	Toluene 4%	[28]
Coating	Letterpress printing	Benzene 15%	Toluene 13%	Ethylbenzene 5%	1,2-Dichloropropane 5%	Acetic acid, methyl ester 4%	[28]
	Wood furniture	Styrene 20%	Ethyl acetate 16%	Acetic acid, butyl ester 10%	Toluene 7%	<i>m/p</i> -Xylene 6%	[28]

Table 3 Comparison of top-five VOC species obtained in this study with literature (Continued)

Industry	Manufacturing	Percentage distribution (%) and Emission factors (mg-VOC kg ⁻¹) of the top 5 VOC species					References
		1st	2nd	3rd	4th	5th	
Paint manufacturing	Metal surface	Styrene 23%	Methyl isobutyl ketone 8%	Toluene 8%	1,2-Dichloroethane 5%	Ethyl acetate 5%	[28]
	-	Ethyl acetate 11%	Acetic acid, butyl ester 9%	Ethyl-benzene 7%	Toluene 5%	m/p-Xylene 5%	[28]
Shoemaking	-	2-Butanone 29%	Acetone 19%	Ethyl acetate 19%	Toluene 7%	Cyclohexane 5%	[28]
	Integrated iron and steel industry ^d	Toluene 16 ± 10	1,2,4-Trimethylbenzene 5.5 ± 1.5	m/p-Xylene 3.4 ± 1.8	Ethylbenzene 2.6 ± 1.3	Trichloroethylene 2.6 ± 1.1	[36]
Solvent use	Sintering	Toluene 63 ± 73	Benzene 13 ± 14	Isopentane 13 ± 8.8	m/p-Xylene 13 ± 11	1,2,4-Trimethylbenzene 9.8 ± 9.1	[36]
	Hot forming	Carbon tetrachloride 7.5 ± 11	Toluene 1.7 ± 0.31	1,2,4-Trimethylbenzene 1.1 ± 0.24	m/p-Xylene 1.1 ± 0.18	Ethylbenzene 0.74 ± 0.14	[36]
PU factories	Cold forming	Toluene 15 ± 2.4	o-Xylene 4.7 ± 0.45	Benzene 3.8 ± 0.32	m/p-Xylene 3.8 ± 0.36	Isopentane 3.4 ± 2.4	[36]
	Printing factory	Architectural paints 20%	m/p-xylene 14%	Ethylbenzene 9%	o-Xylene 8%	Benzene 8%	[29]
Adhering	Printing shop	n-Decane 17%	n-Nonane 15%	n-Undecane 13%	n-Octane 7%	m/p-Xylene 6%	[29]
	Coating	i-Pentane 12%	n-Hexane 9%	Toluene 8%	m/p-xylene 6%	Ethane 5%	[29]
Adhering	Coating	Dimethyl formamide 2500 ± 1460 ppm	Toluene 1320 ± 210 ppm	Methyl ethyl ketone 570 ± 320 ppm	-	-	[51]
	Adhering	Dimethyl formamide 600 ± 100 ppm	Methyl ethyl ketone 250 ± 50 ppm	Toluene 150 ± 30 ppm	-	-	[51]

^a: Alkanes
^b: Aromatic
^c: Oxygenated VOC
^d: g/tonne-product (Emission factor)

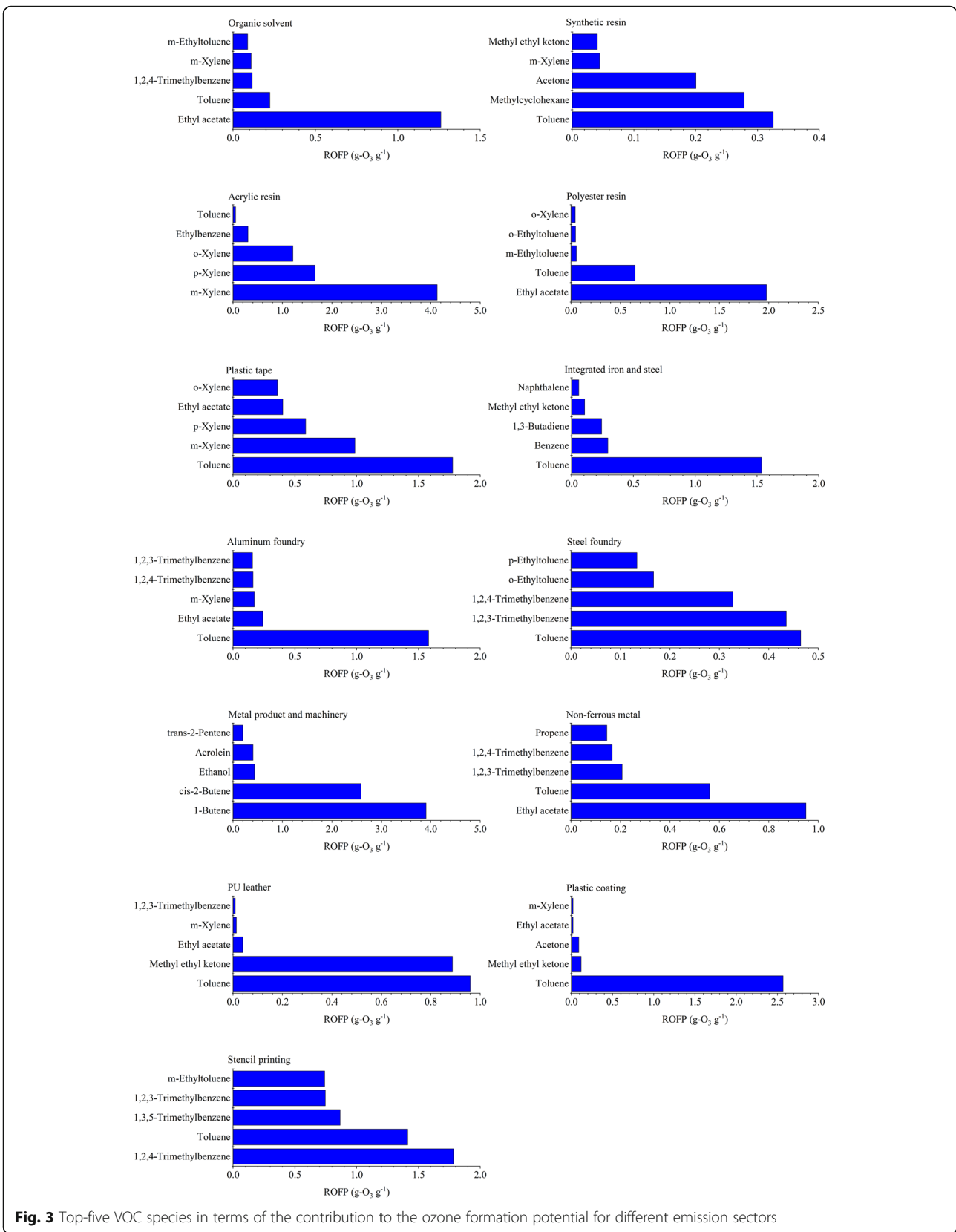


Fig. 3 Top-five VOC species in terms of the contribution to the ozone formation potential for different emission sectors

quantity of 2-butanone, toluene and ethyl acetate in different areas of the manufacturing facility such as manufacturing department, semi-finished raw material department, resin warehouses and outside vicinity of the industries. Organic solvents are widely used in the PU industries which could be a potential source of VOCs. The species of organic solvents include toluene, methyl ethyl ketone and dimethylformamide. Some solvents are added as thinners and additives to avoid excessive viscosity of polyurea-formaldehyde in PU industry [54]. These results showed that the VOC species compositions were attributable to the organic solvent and other raw materials used in PU industries.

Printing sectors

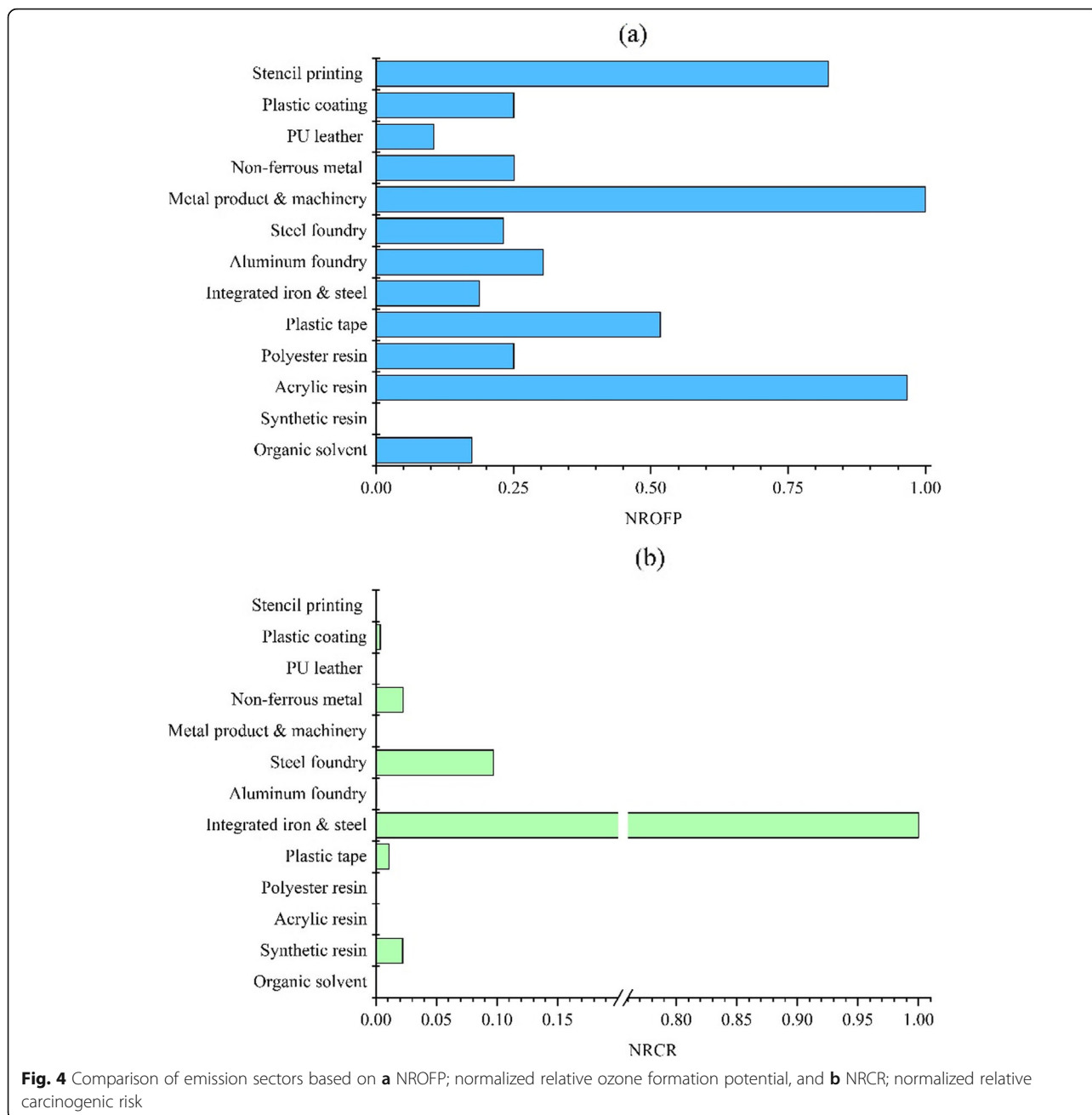
The printing sector in the present study included plastic coating and stencil printing (Table 3). Toluene was the most abundant species in the emissions of plastic coating and stencil printing, accounting for 64% ($0.0099 \text{ mg-VOC kg}^{-1}$) and 35% ($149 \text{ mg-VOC kg}^{-1}$) of Σ VOCs emission factors, respectively. However, methyl methacrylate, ethyl acetate, acetone, methyl ethyl ketone and 2-methyl hexane accounted for a minor fraction of Σ VOCs for both sectors. Organic solvents are widely used in plastic coating and ink printing [29] which could make an important source of aromatic compounds. Li et al. [34] obtained a higher percentage of alkanes (45%) and aromatics (47%) in printing ink. The study reported that VOC species emitted from the ink printing sectors were mainly, alkanes and aromatics. Some other studies found that toluene, benzene, and some oxygenated organics are the typical species emitted from printing sectors [28, 34, 56]. Zheng et al. [28] reported aromatics (e.g., benzene and toluene) as the major species of letterpress printing, while ethyl acetate and isopropyl alcohol were important VOCs in offset printing and gravure printing processes. Raw materials and derivatives might be the responsible factor for the observed differences in the emissions from different printing sectors.

ROFP

The top five VOCs in terms of their contributions to ROFP in different emission sectors are shown in Fig. 3. The top five VOC species for organic solvent included ethyl acetate, toluene, 1,2,4-trimethylbenzene, *m*-xylene and *m*-ethyl toluene that together accounted for 75% of the total ROFP. In synthetic resin industries, the top five ROFP VOCs accounted for 72% of the total ROFP. They included aromatics (toluene and *m*-xylene), alkanes (methylcyclohexane), and oxygenated VOCs (acetone and methyl ethyl ketone). In the polyester resin industry, oxygenated and aromatic species were predominant contributors to the total ROFP, whereas in the acrylic resin industry, the aromatic VOCs (*m/p/o*-xylene,

ethylbenzene and toluene) were the major contributors to ROFP. 1-butene and ethyl acetate were the dominant contributors to the total ROFP for metal product and machinery and non-ferrous metal sectors, respectively. Similarly, toluene was the highest contributor followed by *m/p*-xylene and ethyl acetate in the plastic tape manufacturing sector. Likewise, toluene was the dominant contributor of total ROFP for the aluminum foundry, steel foundry, integrated iron and steel, PU leather and plastic coating sectors. For the stencil printing sector, 1, 2,3-trimethyl benzene was the major contributor to the total ROFP. Moreover, several aromatic VOCs including 1,3,5-trimethyl benzene, 1,2,3-trimethylbenzene and *m*-ethyltoluene were also obtained as the top five VOCs contributing to the total ROFP in the stencil printing sector.

The ROFPs of VOCs varied widely across different emission sectors (Additional file 1: Fig. S1). The total ROFP of metal product and machinery emission was the highest ($7.6 \text{ g-O}_3 \text{ g-VOCs}^{-1}$) among all emission sources, followed by acrylic resin manufacturing ($7.4 \text{ g-O}_3 \text{ g-VOCs}^{-1}$), stencil printing ($6.5 \text{ g-O}_3 \text{ g-VOCs}^{-1}$), and plastic tape manufacturing ($4.6 \text{ g-O}_3 \text{ g-VOCs}^{-1}$). In the metal product and machinery sector, alkenes were the main contributors, accounting for 88% of total ROFP. However, in acrylic resin manufacturing, printing and plastic tape sectors, aromatics contributed to 99.9, 99.8 and 85% of total ROFP, respectively. The major aromatic VOCs for these emission sources were 1-butene, *m*-xylene, 1,2,4-trimethylbenzene and toluene. The total ROFP for synthetic resin manufacturing emissions was the lowest because the oxygenated VOCs with low reactivity accounted for the major fraction of Σ VOCs. The ROFP contributions for acrylic resin, plastic tape, metal manufacturing (integrated iron and steel, aluminum and steel foundries) and printing (plastic coating and stencil printing) emissions were mainly from aromatic VOCs. However, oxygenated VOCs were the major contributing group to the ROFP for other manufacturing sectors (i.e., organic solvent, polyester resin, non-ferrous metal and PU leather). Tsai et al. [36] reported toluene, 1-butene, *m/p*-xylene, *o*-xylene, 1,2,4-trimethylbenzene, ethylbenzene, 1,3,5-trimethylbenzene, 1,2,3-trimethylbenzene as the major VOCs in terms of OFP in the emissions from four process units of an integrated iron and steel plant. The sequence of OFP for four processes was as follows: cold forming \approx sintering > hot forming > cakemaking. Furthermore, OFP of cold forming and sintering process is about 4 and 5 times higher than that of hot forming and cakemaking processes, respectively. Ou et al. [57] reported that industrial solvents and gasoline vehicles contributed 33 and 18% of anthropogenic OFP of VOC emissions, respectively, whereas, motorcycles and industrial processes accounted for 14 and 13%, respectively. Li et al. [34] also reported a similar



VOC emission pattern for iron and steel and printing sectors. A detailed comparison of the results with literature can be found in the supplementary material (Additional file 1: Table S4). It should be noted that the ozone formation potential depends on the speciated VOC emission concentrations and their MIR values. Thus, VOCs with high emission factors may not always be the major contributors to ozone formation.

RCR

The RCR of each of the emission sources investigated in this study has been presented in Additional file 1: Fig.

S2. The RCR of emissions from the integrated iron and steel sector was the highest among all tested emission sources with the risk value of $41 \times 10^{-8} \text{ mg}^{-1} \text{ m}^3$, followed by steel foundry ($4.0 \times 10^{-8} \text{ mg}^{-1} \text{ m}^3$) and non-ferrous metal industry ($9.2 \times 10^{-9} \text{ mg}^{-1} \text{ m}^3$). RCR values of other emission sectors such as organic solvent, synthetic resin, acrylic resin, plastic tape, aluminum foundry, PU leather, plastic coating and stencil printing ranged from 1.2×10^{-10} – $9.1 \times 10^{-9} \text{ mg}^{-1} \text{ m}^3$. The RCRs were not calculated for polyester resin and metal product and machinery because of the unavailability of the carcinogenic risk factor values for the VOCs detected in

the emissions of those sources. The highest relative RCRs were observed for the integrated iron and steel manufacturing sector and steel foundry because those sources emitted a high amount of benzene. Several VOC species, including benzene, chloroform, trichloroethylene, bromoform and 1,3-butadiene are classified as carcinogenic compounds according to the Integrated Risk Information System. Industrial manufacturing sectors are reported as the major VOC emission sources [28, 36]. Several previous studies have assessed cancer risks for inhalation exposure to VOCs in industrial areas, but most of them focus on the ambient VOCs [58–60].

Specific potential emission sources

A comparison of potential VOC emission sources based on ROFP and RCR between different emission sectors is presented in Fig. 4. NROFP and NRCR were categorized into four levels: Level-I (0.75–1.00), Level-II (0.50–0.75), Level-III (0.25–0.50) and Level-IV (0–0.25) where Level-I represents the most important VOC emission sources and Level-IV represents the least important emission source in terms of NROFP and NRCR. Metal product and machinery, acrylic resin and stencil printing sectors belonged to the Level-I emission sources (NROFP index: > 0.75). However, in terms of the NRCR, it was found that the integrated iron and steel had the highest NRCR index that belonged to Level-I emission sources. Therefore, it can be concluded that not only the single factor such as OFP but also the cancer risk should be taken into consideration for the identification of potentially important VOC emission sources.

Conclusions

In this study, 13 types of stationary emission sources were investigated for emission factors of speciated VOCs and associated ROFP and RCR. ROFP and RCR were used for the identification of potentially important VOC emission sectors. The results showed that the maximum Σ VOCs emission factors were observed for stencil printing (423 mg-VOC kg⁻¹) among all emission sources. Alkanes formed the dominant VOC group in the steel foundry (42% of Σ VOCs emission factors), aluminum foundry (25% of Σ VOCs emission factors) and synthetic resin (25% of Σ VOCs emission factors). However, in the chemical sector (synthetic and polyester resin), oxygenated VOCs such as acetone (56% of Σ VOCs emission factors) and ethyl acetate (80% of Σ VOCs emission factors) were the major contributors to total VOCs. Xylene, ethylbenzene, and toluene formed > 95% of Σ VOCs in the emissions from acrylic resin manufacturing. Analysis of ROFP showed that metal product and machinery sector, acrylic resin manufacturing and stencil printing were potentially important emission sources in terms of OFP. In terms of the NRCR, integrated iron and steel sector

was the potentially important source with the highest NRCR index. The results suggested that the reactivity- and carcinogenicity-based approach is required for prioritizing the emission sources. Toluene, xylene, 1,2,4-trimethylbenzene and other high OFP-contributing species were the major reactive species that could be targeted while developing control strategies. In addition, carcinogenic VOCs such as benzene, chloroform, trichloroethylene, bromoform and 1, 3-butadiene should also be targeted for emission control.

Supplementary Information

The online version contains supplementary material available at <https://doi.org/10.1186/s42834-020-00068-2>.

Additional file 1 Table S1 Average concentrations of the VOC species identified in different manufacturing sectors. **Table S2** Emission factors of the VOC species identified in different manufacturing sectors. **Table S3** Carcinogenic inhalation risk factor of VOC species. **Table S4** Comparison of ozone formation potential of VOC obtained in this study and with previous studies. **Fig. S1** Relative ozone formation potential of VOCs for different emission sources. **Fig. S2** Relative carcinogenic risk of VOCs for different emission sources.

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HHY contributed to the study design, data analysis, drafting and editing manuscript. SKG and NBD led sampling, analysis and contributed to the study design, data analysis, drafting and editing manuscript. The authors read and approved the manuscript.

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Competing interests

The authors declare that they have no competing interests.

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References

- Hui LR, Liu XG, Tan QW, Feng M, An JL, Qu Y, et al. Characteristics, source apportionment and contribution of VOCs to ozone formation in Wuhan, Central China. *Atmos Environ*. 2018;192:55–71.
- Wei YG, Gu J, Wang HW, Yao T, Wu ZZ. Uncovering the culprits of air pollution: evidence from China's economic sectors and regional heterogeneities. *J Clean Prod* 2018;171:1481–93.
- Yang HH, Gupta SK, Dhital NB, Wang LC, Elumalai SP. Comparative investigation of coal- and oil-fired boilers based on emission factors, ozone and secondary organic aerosol formation potentials of VOCs. *J Environ Sci-China* 2020;92:245–55.

4. Deng CX, Jin YJ, Zhang M, Liu XW, Yu ZM. Emission characteristics of VOCs from on-road vehicles in an urban tunnel in eastern China and predictions for 2017–2026. *Aerosol Air Qual Res* 2018;18:3025–34.
5. Saini J, Dutta M, Marques G. A comprehensive review on indoor air quality monitoring systems for enhanced public health. *Sustain Environ Res* 2020; 30:6.
6. Tsai JH, Chen SJ, Lin SL, Huang KL, Hsueh CK, Lin CC, et al. Emissions of PM_{2.5}-bound polycyclic aromatic hydrocarbons and metals from a diesel generator fueled with biodiesel converted from used cooking oil. *Aerosol Air Qual Res*. 2019;19:1555–65.
7. Garcia JA, Vallar E, Galvez MC, Bagtasa G. Application of the WRF/Chem v.3.6.1 on the reanalysis of criteria pollutants over Metro Manila. *Sustain Environ Res* 2019;29:38.
8. Tsai JH, Yao YC, Huang PH, Chiang HL. Fuel economy and volatile organic compound exhaust emission for motorcycles with various running mileages. *Aerosol Air Qual Res* 2018;18:3056–67.
9. Wu WJ, Zhao B, Wang SX, Hao JM. Ozone and secondary organic aerosol formation potential from anthropogenic volatile organic compounds emissions in China. *J Environ Sci-China* 2017;53:224–37.
10. Tajuelo M, Rodriguez A, Baeza-Romero MT, Aranda A, Diaz-de-Mera Y, Rodriguez D. Secondary organic aerosol formation from α -methylstyrene atmospheric degradation: role of NO_x level, relative humidity and inorganic seed aerosol. *Atmos Res* 2019;230:104631.
11. Carter WP. Updated maximum incremental reactivity scale and hydrocarbon bin reactivities for regulatory applications. 2010. <https://www3.arb.ca.gov/regact/2009/mir2009/mir10.pdf>. Accessed 27 Sep 2020.
12. Avery RJ. Reactivity-based VOC control for solvent products: more efficient ozone reduction strategies. *Environ Sci Technol* 2006;40:4845–50.
13. USEPA. Revisions to the California State Implementation Plan and Revision to the Definition of Volatile Organic Compounds (VOC)-Removal of VOC Exemptions for California's Aerosol Coating Products Reactivity-based Regulation. Washington, DC: US Environmental Protection Agency; 2005.
14. Derwent RG, Jenkin ME, Passant NR, Pilling MJ. Reactivity-based strategies for photochemical ozone control in Europe. *Environ Sci Policy* 2007;10:445–53.
15. Montero-Montoya R, Lopez-Vargas R, Arellano-Aguilar O. Volatile organic compounds in air: sources, distribution, exposure and associated illnesses in children. *Ann Glob Health* 2018;84:225–38.
16. Widiana DR, Wang YF, You SJ, Yang HH, Wang LC, Tsai JH, et al. Air pollution profiles and health risk assessment of ambient volatile organic compounds above a municipal wastewater treatment plant, Taiwan. *Aerosol Air Qual Res* 2019;19:375–82.
17. Lerner JEC, Sanchez EY, Sambeth JE, Porta AA. Characterization and health risk assessment of VOCs in occupational environments in Buenos Aires, Argentina *Atmos Environ* 2012;55:440–7.
18. Zhang ZJ, Yan XY, Gao FL, Thai P, Wang H, Chen D, et al. Emission and health risk assessment of volatile organic compounds in various processes of a petroleum refinery in the Pearl River Delta, China. *Environ Pollut* 2018; 238:452–61.
19. Lin CK, Hung HY, Christiani DC, Forastiere F, Lin RT. Lung cancer mortality of residents living near petrochemical industrial complexes: a meta-analysis. *Environ Health-Glob* 2017;16:101.
20. Alghamdi MA, Khoder M, Abdelmaksoud AS, Harrison RM, Hussein T, Lihavainen H, et al. Seasonal and diurnal variations of BTEX and their potential for ozone formation in the urban background atmosphere of the coastal city Jeddah, Saudi Arabia. *Air Qual Atmos Hlth* 2014;7:467–80.
21. Domingo JL, Marques M, Nadal M, Schuhmacher M. Health risks for the population living near petrochemical industrial complexes. 1. Cancer risks: a review of the scientific literature. *Environ Res* 2020;186:109495.
22. Durmusoglu E, Taspinar F, Karademir A. Health risk assessment of BTEX emissions in the landfill environment. *J Hazard Mater* 2010;176:870–7.
23. Gallego E, Roca FJ, Perales JF, Gadea E. Outdoor air 1,3-butadiene monitoring near a petrochemical industry (Tarragona region) and in several Catalan urban areas using active multi-sorbent bed tubes and analysis through TD-GC/MS. *Sci Total Environ* 2018;618:1440–8.
24. IARC. List of Classifications – IARC Monographs on the Identification of Carcinogenic Hazards to Humans. Lyon; 2019.
25. Divine BJ, Hartman CM. A cohort mortality study among workers at a 1,3 butadiene facility. *Chem Biol Interact* 2001;135:535–53.
26. Gun RT, Pratt N, Ryan P, Roder D. Update of mortality and cancer incidence in the Australian petroleum industry cohort. *Occup Environ Med* 2006;63: 476–81.
27. Ward E, Boffetta P, Andersen A, Colin D, Comba P, Daddens JA, et al. Update of the follow-up of mortality and cancer incidence among European workers employed in the vinyl chloride industry. *Epidemiology*. 2001;12:710–8.
28. Zheng JY, Yu YF, Mo ZW, Zhang Z, Wang XM, Yin SS, et al. Industrial sector-based volatile organic compound (VOC) source profiles measured in manufacturing facilities in the Pearl River Delta, China. *Sci Total Environ* 2013;456:127–36.
29. Yuan B, Shao M, Lu SH, Wang B. Source profiles of volatile organic compounds associated with solvent use in Beijing, China. *Atmos Environ* 2010;44:1919–26.
30. Liu Y, Shao M, Fu LL, Lu SH, Zeng LM, Tang DG. Source profiles of volatile organic compounds (VOCs) measured in China: part I. *Atmos Environ* 2008; 42:6247–60.
31. Beelen R, Raaschou-Nielsen O, Stafoggia M, Andersen ZJ, Weinmayr G, Hoffmann B, et al. Effects of long-term exposure to air pollution on natural-cause mortality: an analysis of 22 European cohorts within the multicentre ESCAPE project. *Lancet*. 2014;383:785–95.
32. Mo ZW, Shao M, Lu SH, Niu H, Zhou MY, Sun J. Characterization of non-methane hydrocarbons and their sources in an industrialized coastal city, Yangtze River Delta, China. *Sci Total Environ*. 2017;593:641–53.
33. Zhao Y, Mao P, Zhou YD, Yang Y, Zhang J, Wang SK, et al. Improved provincial emission inventory and speciation profiles of anthropogenic non-methane volatile organic compounds: a case study for Jiangsu, China. *Atmos Chem Phys*. 2017;17:7733–56.
34. Li GH, Wei W, Shao X, Nie L, Wang HL, Yan X, et al. A comprehensive classification method for VOC emission sources to tackle air pollution based on VOC species reactivity and emission amounts. *J Environ Sci-China* 2018; 67:78–88.
35. Wang HL, Qiao YZ, Chen CH, Lu J, Dai HX, Qiao LP, et al. Source profiles and chemical reactivity of volatile organic compounds from solvent use in Shanghai, China. *Aerosol Air Qual Res* 2014;14:301–10.
36. Tsai JH, Lin KH, Chen CY, Lai N, Ma SY, Chiang HL. Volatile organic compound constituents from an integrated iron and steel facility. *J Hazard Mater* 2008;157:569–78.
37. Cheng H, Sathiakumar N, Graff J, Matthews R, Delzell E. 1,3-butadiene and leukemia among synthetic rubber industry workers: exposure-response relationships. *Chem Biol Interact* 2007;166:15–24.
38. Zheng H, Kong SF, Yan YY, Chen N, Yao LQ, Liu X, et al. Compositions, sources and health risks of ambient volatile organic compounds (VOCs) at a petrochemical industrial park along the Yangtze River. *Sci Total Environ* 2020;703:135505.
39. Loomis D, Guyton KZ, Grosse Y, El Ghissassi F, Bouvard V, Benbrahim-Tallaa L, et al. Carcinogenicity of benzene. *Lancet Oncol* 2017;18:1574–75.
40. Filley CM, Halliday W, Kleinschmidt-DeMasters BK. The effects of toluene on the central nervous system. *J Neuropathol Exp Neurol* 2004;63:1–12.
41. Kandyala R, Raghavendra SPC, Rajasekharan ST. Xylene: an overview of its health hazards and preventive measures. *J Oral Maxill Pathol* 2010;14:1.
42. Kirkeleit J, Riise T, Bratveit M, Moen BE. Increased risk of acute myelogenous leukemia and multiple myeloma in a historical cohort of upstream petroleum workers exposed to crude oil. *Cancer Causes Control* 2008;19:13–23.
43. Lin CK, Hsu YT, Christiani DC, Hung HY, Lin RT. Risks and burden of lung cancer incidence for residential petrochemical industrial complexes: a meta-analysis and application. *Environ Int* 2018;121:404–14.
44. TEPA. Taiwan Emission Data System Version 10.1. Taipei: Taiwan Environmental Protection Administration; 2020. <https://teds.epa.gov.tw/TEDS.aspx> [in Chinese].
45. Dhital NB, Yang HH, Wang LC, Hsu YT, Zhang HY, Young LH, et al. VOCs emission characteristics in motorcycle exhaust with different emission control devices. *Atmos Pollut Res* 2019;10:1498–506.
46. Geng CM, Yang W, Sun XS, Wang X, Bai ZP, Zhang X. Emission factors, ozone and secondary organic aerosol formation potential of volatile organic compounds emitted from industrial biomass boilers. *J Environ Sci-China* 2019;83:64–72.
47. Zheng JY, Shao M, Che WW, Zhang LJ, Zhong LJ, Zhang YH, et al. Speciated VOC emission inventory and spatial patterns of ozone formation potential in the Pearl River Delta, China. *Environ Sci Technol* 2009;43:8580–6.
48. Tsai JH, Gu WT, Chung II, Chiang HL. Airborne air toxics characteristics and inhalation health risk assessment of a metropolitan industrial complex. *Aerosol Air Qual Res* 2019;19:2477–89.

49. Tang JH, Chu KW, Chan LY, Chen YJ. Non-methane hydrocarbon emission profiles from printing and electronic industrial processes and its implications on the ambient atmosphere in the Pearl River Delta, South China. *Atmos Pollut Res* 2014;5:151–60.
50. Kiurski JS, Maric BB, Aksentijevic SM, Oros IB, Kecic VS. Occupational hazards in printing industry. *Int J Environ Sci Te.* 2016;13:955–72.
51. Zhao P, Cheng YH, Lin CC, Cheng YL. Effect of resin content and substrate on the emission of BTEX and carbonyls from low-VOC water-based wall paint. *Environ Sci Pollut R* 2016;23:3799–808.
52. Bailey MA, Costin CR. Unsaturated polyester resin compositions comprising metallic monomers. Alexandria: US Patent and Trademark Office; 2002.
53. Tsubaki H, Inokuchi S, Hirose I, Kosaka T. Double-sided pressure-sensitive adhesive tape for fixing decorative panel. Alexandria: US Patent and Trademark Office; 2011.
54. Chang CT, Lin KL. Assessment of the strategies for reducing VOCs emission from polyurea-formaldehyde resin synthetic fiber leather industry in Taiwan. *Resour Conserv Recy* 2006;46:321–34.
55. Wang BG, Feng ZC, Zhou Y, Liu HX. VOC components in the air caused by the local polyurethane synthetic leather industries in the Pearl River Delta region. *China Environ Sci* 2009;29:914–8.
56. Liu BS, Liang DN, Yang JM, Dai QL, Bi XH, Feng YC, et al. Characterization and source apportionment of volatile organic compounds based on 1-year of observational data in Tianjin, China. *Environ Pollut* 2016;218:757–69.
57. Ou JM, Zheng JY, Li RR, Huang XB, Zhong ZM, Zhong LJ, et al. Speciated OVOOC and VOC emission inventories and their implications for reactivity-based ozone control strategy in the Pearl River Delta region, China. *Sci Total Environ* 2015;530:393–402.
58. Jaars K, Vestenius M, van Zyl PG, Beukes JP, Hellén H, Vakkari V, et al. Receptor modelling and risk assessment of volatile organic compounds measured at a regional background site in South Africa. *Atmos Environ* 2018;172:133–48.
59. Tong R, Ma X, Zhang Y, Shao G, Shi M. Source analysis and health risk-assessment of ambient volatile organic compounds in automobile manufacturing processes. *Hum Ecol Risk Assess Int J* 2018:1–25.
60. Wallace HW, Sanchez NP, Flynn JH, Erickson MH, Lefer BL, Griffin RJ. Source apportionment of particulate matter and trace gases near a major refinery near the Houston Ship Channel. *Atmos Environ* 2018;173:16–29.

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