**assessment of VOCs emitted from manufacturing industries**

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## Abstract

In this study, a few important manufacturing industries located in Central Taiwan were studied ($n$ = 13) for the emission of volatile organic compounds (VOCs), relative ozone formation potential (ROFP) and relative carcinogenic risk (RCR). Higher emission factors of total VOCs (∑VOCs) were observed for stencil printing (423 mg-VOC kg$^{-1}$) compared to other emission sectors. Alkanes formed the most dominant group of VOCs for steel foundry (41.6%), aluminum foundry (25.1%) and synthetic resin manufacturing (25.0%). However, for the chemical sector (synthetic and polyester resin), oxygenated organics like acetone (55.7%) and ethyl acetate (79.7%) were the predominant VOCs. Moreover, emissions from acrylic resin manufacturing had higher contributions from aromatic compounds (> 95%). Toluene was the topmost compound in terms of its contribution to ∑VOCs in plastic tape manufacturing (44.4%), aluminum foundry (39.6%), steel foundry (11.6%), plastic coating (64.3%) and stencil printing (35.3%). Analysis of ozone formation potentials showed that the metal product & machinery acrylic resin manufacturing and stencil printing had a higher normalized ROFP index and belonged to level-I emission sources. However, in terms of the RCR, integrated iron & steel manufacturing had the highest normalized RCR index belonged to level-I emission sources. Level-I represents the most important VOC emission sources.

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

## 1. Introduction

Manufacturing industries are the 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]. 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 human body mainly through inhalation or skin absorption causing varieties of health effects [11]. Health effects can vary by types of VOC species which include cancerous illnesses, respiratory irritation, central nervous system damage, eye and skin irritation [12]. Several VOCs have been classified by the International Agency for Research on Cancer (IARC) as Group 1 carcinogens for human [13]. Benzene, a known carcinogen, has been found to be a common byproduct of the chemical manufacturing, petrochemical industries, production of xylene, toluene and other aromatic compounds, printing sectors and industrial solvent usage [14,15].

Studies regarding VOC emissions from manufacturing sectors are still limited [14,16–18]. The major VOC emission sources include fossil fuel combustion, petrochemical, printing and solvent usage [16,17,19,20]. Wang et al. [20] 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 (51.9%) followed by alkanes (31.8%) and alkenes (16.3%). Yuan et al. [17] identified alkanes and aromatic compounds as the most contributing groups in the printing sector. Tsai et al. [21] 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.

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 their chemical reactivity and associated health hazards. However, such works are still limited for industrial emission sources. In this study, a few important industrial emission sources were investigated on the basis of emission factors, relative ozone formation potentials and relative carcinogenic risks of VOCs.

## 2. Materials and methods

### *2.1. 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 & machinery industries, integrated iron & 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 72.5% of total VOC emissions within the city in the year 2016 (Taiwan EPA). 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 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 covers the transformation of organic and inorganic raw materials by the chemical processes and the formation of products. The plastic product manufacturing sector includes facilities that make goods by processing plastic materials and raw rubber. The synthetic fiber industry involves the manufacturing of cellulosic, noncellulosic, and polyester fibers. The metal (primary and fabricated) manufacturing sector includes iron and steel industries, metal casting industries, and nonferrous metal industries. The leather/textile manufacturing sectors consist of establishments engaged in synthetic leather, spinning natural and manmade fibers into yarns and threads. The printing sector include plastic coating, stencil printing, plate-making and bookbinding. In this study, only the sintering process of integrated iron and steel industry was investigated. Detailed information about selected emission sources can be found in Table 1.

[Add Table 1]

*2.2. 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# 29-10622) 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 collected samples were analyzed with the Gas Chromatography (7890) Mass Spectroscopy (5977B) system (GC/MS, Agilent

Technologies). The details of the GC/MS analysis is described elsewhere [22]. Internal calibration method was applied for the quantification of the VOCs. A total of 72 VOC species were quantified in this study (Table S1). Taiwan NIEA (National Institute for Environmental Analysis) standard (A715.15B) was used as the external standard. Bromochloromethane, 1,4-difluorobenzene, chlorobenzene-d5 and 4-bromofluorobenzene (BFB) were used as the internal standards. Based on the functional groups, these VOCs were classified as alkanes, alkenes, aromatics, oxygenated VOCs and halocarbons. Emission factors of the detected VOC species were calculated for each of the emission sources by using Eq. (1).

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

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

*2.3. 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). Two replicate measurements were done for each sample. The blank analysis was run before each sample analysis.

*2.4. Relative ozone formation potential (ROFP)*

The absolute ozone formation potential (OFP) of VOC species is usually calculated by multiplying the its concentration by its maximum incremental reactivity (MIR)

[23,24]. 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).

$$ROFP_j = \sum_{j=1}^{n} x_{i,j} \times MIR_i \qquad (2)$$

where, $ROFP_j$ is the relative ozone formation potential of VOCs for source $j$ (g-$O_3$ g-VOCs$^{-1}$), $x_{i,j}$ is the ratio of EF of VOC species $i$ to ∑VOCs for source $j$, and $MIR_i$ is the maximum incremental reactivity value of species $i$ as proposed by Carter [25].

*2.5.Relative carcinogenic risk (RCR)*

The absolute carcinogenic risk is usually estimated by multiplying the actual VOC concentration and its carcinogenic risk factor [26]. However, to ensure comparability among different emission sources, carcinogenicity was calculated for each emission sources on a relative basis (Eq. 3).

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

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

*2.6. 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 (NRCR) index were calculated using the Eqs. (4) and (5).

$$NROFP_j = \frac{ROFP_j - ROFP_{min}}{ROFP_{max} - ROFP_{min}} \quad (4)$$

$$NRCR_j = \frac{RCR_j - RCR_{min}}{RCR_{max} - RCR_{min}} \quad (5)$$

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, $NRCR_j$ 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.

## 3. Results and discussion

### *3.1. Emission factors*

The ∑VOCs emission factors of manufacturing sectors are shown in Fig. 1. The ∑VOCs emission factors of manufacturing sectors were observed to be ranging from 0.00267 mg-VOC/kg to 423 mg-VOC/kg. Among all sectors, the maximum emission factors of ∑VOC were observed for stencil printing (423 mg-VOC $kg^{-1}$) followed by plastic tape (24.9 mg-VOC $kg^{-1}$), metal product & machinery (10.3 mg-VOC $kg^{-1}$) and organic solvent (4.42 mg-VOC $kg^{-1}$). For synthetic resin, acrylic resin, polyester resin, integrated iron & steel, aluminum foundry, steel foundry, non-ferrous metal, PU leather and plastic coating, ∑VOCs emission factors were found ≤ 1 mg-VOC $kg^{-1}$. Stencil printing had the highest emission factor which could be due to the presence of large amount of organic compounds, including, xylene, ethyl benzene and ethyl acetate in printing inks [19]. Some other organic compounds such as acetate, glycolic acid butyl ester, butyl glycol were also used in printing inks [27]. 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.

[Add Figure 1]

*3.2. VOC species compositions*

The VOCs emission factors have been expressed as the percentage of each species relative to ∑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 (41.6%), aluminum foundry (25.1%) and synthetic resin (25.0%). The higher proportion of alkenes were observed for metal product & machinery (59.7%) followed by other emission sectors. Zhao et al. [18] observed a high percentage of alkanes (25.6%) followed by alkynes (15.5%), aromatics (13.6%) and alkenes (11.2%) in the emissions from iron and steel sectors.

[Add Figure 2]

The higher proportion of alkanes and alkenes emissions indicates insufficient oxidation of volatile components released from the fuels [23]. Chemical sectors such as organic solvent and polyester resin manufacturing were found to have more than 75% ∑VOCs contributed by oxygenated VOCs. Acrylic resin, plastic tape, integrated iron & steel, plastic coating and stencil printing sectors showed the major fraction of ∑VOCs contributed by aromatics (65.1% – 98.9%). Tsai et al. [21] 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. [17] 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. Detailed profiles of the

VOCs (top 5 contributors) for each manufacturing sector are presented in Table 2 and discussed in the following subsections.

[Add Table 2]

### *3.2.1. 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 2. The VOC species emitted from organic solvent manufacturing were mainly oxygenated VOCs, such as ethyl acetate and acetone, accounting for > 65% of ∑VOCs. Methyl isobutyl ketone, toluene and isopropyl alcohol, accounted for a minor fraction of ∑VOCs. Synthetic and polyester resin manufacturing sectors predominantly emitted oxygenated VOCs like acetone (55.7%, 0.0228 mg-VOC $kg^{-1}$) and ethyl acetate (79.7%, 0.0260 mg-VOC $kg^{-1}$). However, the acrylic resin industry had higher contributions from aromatics (> 95% of ∑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 [28,29]**.** However, polyester resin was found to have the emission contributions mainly from oxygenated VOCs, as it is formed by the reaction of dibasic organic acids and polyhydric alcohols [30]**.** The difference in VOC emissions was probably related to the raw materials and products originating from the chemical manufacturing sectors.

### *3.2.2. 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 44.4% (11.1 mg-VOC kg$^{-1}$), 16.2% (4.04 mg-VOC kg$^{-1}$), 10.1% (2.52 mg-VOC kg$^{-1}$), 10.1% (2.50 mg-VOC kg$^{-1}$) and 5.24% (1.30 mg-VOC kg$^{-1}$) of ∑VOCs emission factors, respectively. Tsubaki et al. [31] found toluene to be the major VOC species emitted from the double-sided pressure-sensitive adhesive tape. Adhesive plastic tape products included petroleum, petroleum by-products, natural rubber, acrylic resins, silicone rubber, dispersions, polymers, solvents and other chemicals. Solvent-based adhesive tape applications require high stress resistance. There is no solvent-free adhesive tape available that show 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 melt that release VOCs into the atmosphere.

### *3.2.3. 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 39.6% (0.0116 mg-VOC kg$^{-1}$) and 11.6% (0.000285 mg-VOC kg$^{-1}$) of the ∑VOCs emission factors, respectively. Benzene had the highest contribution (40.8%, 0.0243 mg-VOC kg$^{-1}$) in the integrated iron & steel sector. Samples from metal product & machinery and non-ferrous metal showed the major fractions of 1-butene and ethyl acetate emissions, accounting for 40.1% (4.15 mg-VOC kg$^{-1}$ and 38.3% (0.00408 mg-VOC kg$^{-1}$) of the ∑VOCs emission factors, respectively (Table 2). VOC compositions in the emissions from the integrated iron & steel manufacturing sector were similar to those reported by the previous work [21] for four processes of integrated iron & steel industries. The study reported benzene, toluene, xylene, *n*-butane and 2-methyle pentane 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 [21].

### *3.2.4. Leather manufacturing*

The major VOCs emitted from PU leather industry were methyl ethyl ketone, toluene and methyl methacrylate, accounting for 60.0% (0.402 mg-VOC kg$^{-1}$), 24.0% (0.161 mg-VOC kg$^{-1}$) and 12.6% (0.0847 mg-VOC kg$^{-1}$) of ∑VOCs, respectively. The contributions of major VOC species detected in this study were similar to those reported in the earlier studies. Chang and Lin [32] obtained a higher amount of toluene and methyl ethyl ketone in the emissions from coating, drying and surface treating processes of the PU leather industry. Wang et al. [33] reported a high 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 [32]. These results showed that the VOC species compositions were attributable to the organic solvent and other raw materials used in PU industries.

### *3.2.5. Printing sectors*

The printing sector in the present study included plastic coating and stencil printing (Table 2). Toluene was the most abundant species in the emissions of plastic coating and stencil printing, accounting for 64.3% (0.00990 mg-VOC kg$^{-1}$) and 35.3% (149 mg-VOC kg$^{-1}$) of ∑VOCs emission factors, respectively. However, methyl methacrylate, ethyl acetate, acetone, methyl ethyl ketone and 2-methyl hexane accounted for a minor fraction of ∑VOCs for both sectors. Organic solvents are widely used in the plastic coating and ink printing [17] which could make an important source of aromatic compounds. Li et al. [19] obtained a higher percentage of alkanes (44.8%) and aromatics (47.4%) 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 form printing sectors [19,29,34]. Zheng et al. [29] 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.

### *3.3. Relative ozone formation potential*

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 75.1% of the total ROFP. In synthetic resin industries, the top five ROFP VOCs accounted for 71.7% 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 & 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 & steel, PU leather and plastic coating sectors. For the stencil printing sector, 1,2,3-trimethyl benzene was the major contributor of the total ROFP. Moreover, several aromatic VOCs including 1,3,5-trimethyl benzene, 1,2,3-trimethylebenzene and *m*-ethyltoluene were also obtained as the top five VOCs contributing to the total ROFP in the stencil printing sector.

[Add Figure 3]

The ROFPs of VOCs varied widely across different emission sectors (Fig. S1). The total ROFP of metal product & machinery emission was the highest (7.61 g-$O_3$ g-VOCs$^{-1}$) among all emission sources, followed by acrylic resin manufacturing (7.40 g-$O_3$ g-VOCs$^{-1}$), stencil printing (6.50 g-$O_3$ g-VOCs$^{-1}$), and plastic tape manufacturing (4.56 g-$O_3$ g-VOCs$^{-1}$). In the metal product & machinery sector, alkenes were the main contributors, accounting for 88.0% of total ROFP. However, in acrylic resin manufacturing, printing and plastic tape sectors, aromatics contributed to 99.9%, 99.8% and 85.3% 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 were lowest because the oxygenated VOCs with low reactivity accounted for the major fraction of ∑VOCs. The ROFP contributions for acrylic resin, plastic tape, metal manufacturing (integrated iron & steel, aluminum and steel foundries) and printing (plastic coating and stencil printing) emissions were mainly from aromatic VOCs. However, oxygenated VOCs was the major contributing group to the ROFP for other manufacturing sectors (i.e., organic solvent, polyester resin, no-ferrous metal and PU leather). Li et al. [19] also reported a similar VOC emission pattern for iron & steel and printing sectors. It should be noted that the ozone formation potential depends on the speciated VOC emission factors and their MIR values. Thus, VOCs with high emission factors may not always be the major contributors to ozone formation.

*3.4. Relative carcinogenic risk*

The RCR of each of the emission sources investigated in this study have been presented in Fig. S2. The RCR of emissions from the integrated iron & steel sector was the highest among all tested emission sources with the risk value of $40.6 \times 10^{-8}$ (mg $m^{-3})^{-1}$, followed by steel foundry ($4.0 \times 10^{-8}$ (mg $m^{-3})^{-1}$) and non-ferrous metal industry ($9.2 \times 10^{-9}$ (mg $m^{-3})^{-1}$). 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 $1.2 \times 10^{-10}$ – $9.1 \times 10^{-9}$ (mg $m^{-3})^{-1}$. The RCRs were not calculated for polyester resin and metal product & 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 & steel manufacturing sector and steel foundry because those sources emitted 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 [21,29]. Several previous studies have assessed cancer risks for the inhalation exposure to VOCs in industrial areas, but most of them focus on the ambient VOCs [35–37].

*3.5. 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 & 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 & 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 the consideration for the identification of potentially important VOC emission sources.

[Add Figure 4]

## 4. Conclusions

In this study, 13 types of stationery emission sources were investigated for the emission factors of speciated VOCs and associated ROFPs and RCRs. ROFPs and RCRs were used for the identification of potentially important VOC emission sectors. The results showed that the maximum ∑VOCs emission factors were observed for stencil printing (423 mg-VOC $kg^{-1}$) among all tested emission sources. Alkanes formed the dominant VOC group in the steel foundry (41.6% of ∑VOCs emission factors), aluminum foundry (25.1% of ∑VOCs emission factors) and synthetic resin (25.0% of ∑VOCs emission factors). However, in the chemical sector (synthetic and polyester resin), oxygenated VOCs such as acetone (55.7% of ∑VOCs emission factors) and ethyl acetate (79.7% of ∑VOCs emission factors) were the major contributors to total VOCs. However, *m,p,o*-xylene, ethylbenzene, and toluene formed > 95% of ∑VOCs emission factors in the emissions from acrylic resin manufacturing. Analysis of ROFP showed that metal product & machinery sector, acrylic resin manufacturing and stencil printing were potentially important emission sources in terms of OFP. However, in term of the NRCR, integrated iron & steel sector was the potentially important source with the highest NRCR index.

## Competing interests

The authors declare that they have no competing interests

## Availability of data and materials

All data generated or analyzed during this study are appear in the submitted article.

## Authors' contributions

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

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## References

[1] Hui L, Liu X, Tan Q, Feng M, An J, Qu Y, et al. Characteristics, source apportionment and contribution of VOCs to ozone formation in Wuhan, Central China. Atmos Environ 2018;192:55–71.

[2] Wei Y, Gu J, Wang H, Yao T, Wu Z. Uncovering the culprits of air pollution: Evidence from China's economic sectors and regional heterogeneities. J Clean Prod 2018;171:1481–1493.

[3] 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 2020; 92: 245-255.

[4] Deng C, Jin Y, Zhang M, Liu X, Yu Z. 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;18:3025–3034.

[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;19:1555–1565.

[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;18:3056–3067.

[9] Wu W, Zhao B, Wang S, Hao J. Ozone and secondary organic aerosol formation potential from anthropogenic volatile organic compounds emissions in China. J Environ Sci 2017;53:224–237.

[10] Tajuelo M, Rodríguez A, Baeza-Romero MT, Aranda A, Díaz-de-Mera Y, Rodríguez D. Secondary organic aerosol formation from α-methylstyrene atmospheric degradation: Role of NOx level, relative humidity and inorganic seed aerosol. Atmospheric Res 2019;230:104631.

[11] Montero-Montoya R, López-Vargas R, Arellano-Aguilar O. Volatile organic compounds in air: sources, distribution, exposure and associated illnesses in children. Ann Glob Health 2018;84:225.

[12] 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;19:375–382.

[13] IARC, 2019. List of Classifications – IARC Monographs on the Identification of Carcinogenic Hazards to Humans n.d. https://monographs.iarc.fr/list-of-classifications/ (accessed November 26, 2019).

[14] Mo Z, Shao M, Lu S, Niu H, Zhou M, Sun J. Characterization of non-methane hydrocarbons and their sources in an industrialized coastal city, Yangtze River Delta, China. Sci Total Environ 2017;593:641–653.

[15] Wiltse J, Dellarco VL. US Environmental Protection Agency guidelines for carcinogen risk assessment: past and future. Mutat Res Genet Toxicol 1996;365:3–15.

[16] 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. The Lancet 2014;383:785–795.

[17] Yuan B, Shao M, Lu S, Wang B. Source profiles of volatile organic compounds associated with solvent use in Beijing, China. Atmos Environ 2010;44:1919–1926.

[18] Zhao Y, Mao P, Zhou Y, Yang Y, Zhang J, Wang S, et al. Improved provincial emission inventory and speciation profiles of anthropogenic non-methane volatile organic compounds: a case study for Jiangsu, China. Atmospheric Chem Phys 2017;17:7733–7756.

[19] Li G, Wei W, Shao X, Nie L, Wang H, 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 2018;67:78–88.

[20] Wang H, Qiao Y, Chen C, Lu J, Dai HX, Qiao L-P, et al. Source profiles and chemical reactivity of volatile organic compounds from solvent use in Shanghai, China. Aerosol Air Qual Res 2014;14:301–310.

[21] 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;157:569–578.

[22] 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. Atmospheric Pollut Res 2019.

[23] Geng C, Yang W, Sun X, Wang X, Bai Z, Zhang X. Emission factors, ozone and secondary organic aerosol formation potential of volatile organic compounds emitted from industrial biomass boilers. J Environ Sci 2019;83:64–72.

[24] Zheng J, Shao M, Che W, Zhang L, Zhong L, Zhang Y, et al. Speciated VOC emission inventory and spatial patterns of ozone formation potential in the Pearl River Delta, China. Environ Sci Technol 2009;43:8580–8586.

[25] Carter WP. Updated maximum incremental reactivity scale and hydrocarbon bin reactivities for regulatory applications. Calif Air Resour Board Contract 2009:07–339.

[26] 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;19:2477–2489.

[27] Kiurski JS, Marić BB, Aksentijević SM, Oros IB, Kecić VS. Occupational hazards in printing industry. Int J Environ Sci Technol 2016;13:955–972.

[28] 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 Res 2016;23:3799–3808.

[29] Zheng J, Yu Y, Mo Z, Zhang Z, Wang X, Yin S, 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;456:127–136.

[30] Bailey MA, Costin R. Unsaturated polyester resin compositions comprising metallic monomers, 2002; US6472069B1.

[31] Tsubaki H, Inokuchi S, Hirose I, Kosaka T. Double-sided pressure-sensitive adhesive tape for fixing decorative panel, 2011; US20110244230A1.

[32] Chang CT, Lin KL. Assessment of the strategies for reducing VOCs emission from polyurea-formaldehyde resin synthetic fiber leather industry in Taiwan. Resour Conserv Recycl 2006;46:321–334.

[33] Wang B, Feng Z, Zhou Y, Liu H. VOC components in the air caused by the local polyurethane synthetic leather industries in the Pearl River Delta region. China Environ Sci 2009;29:914–918.

[34] Liu B, Liang D, Yang J, Dai Q, Bi X, Feng Y, et al. Characterization and source apportionment of volatile organic compounds based on 1-year of observational data in Tianjin, China. Environ Pollut 2016;218:757–769.

[35] 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;172:133–148.

[36] 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.

[37] 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.