

Environmental Impact and Health Risk Assessment of VOCs in Typical Industries in Jiaozuo City

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Abstract: To investigate the emission characteristics and environmental impacts of volatile organic compounds (VOCs) from typical industries in Jiaozuo City, samples were collected from seven categories of industrial enterprises. The results revealed that plastic products and packaging and printing industries exhibited similar VOC emission profiles, dominated by oxygenated VOCs (OVOCs) with contribution rates exceeding 90.00%. Industrial coating emissions were primarily composed of aromatic hydrocarbons (74.60%), followed by OVOCs (21.27%). The food manufacturing industry emitted VOCs dominated by OVOCs (41.93%), halogenated hydrocarbons (28.57%), and alkanes (17.55%), while the chemical industry showed significant contributions from OVOCs (39.40%) and alkanes (33.33%). The pharmaceutical industry was characterized by alkanes (79.55%), and shoe manufacturing emissions were dominated by OVOCs (60.94%) and aromatic hydrocarbons (29.92%). Calculations of ozone formation potential (OFP) and secondary organic aerosol production potential (SOAP) identified key contributing species: OVOCs and aromatic hydrocarbons were major contributors to OFP from organized VOC emissions, while aromatic hydrocarbons dominated SOA formation. Comprehensive analysis highlighted packaging and printing, industrial coating, and shoe manufacturing as priority control sectors for Jiaozuo City, with industrial coating requiring the most urgent intervention. Health risk assessments indicated no carcinogenic risks across industries, but non-carcinogenic risks were identified for industrial coating and packaging and printing, primarily associated with elevated hazard indices (HI) from m/p-xylene and o-xylene.

Keywords: Typical industries; VOCs; OFP; SOAP; Health risk assessment.

1. Introduction

According to the national ambient air quality status released by the Ministry of Ecology and Environment in 2022, China's ambient air quality has significantly improved. However, fine particulate matter (PM_{2.5}) and ozone (O₃) pollution remain severe, particularly in the Beijing-Tianjin-Hebei region and its surrounding areas, where their concentrations (44 μg/m³ and 179 μg/m³, respectively) exceed the national averages (29 μg/m³ and 145 μg/m³) [1]. Consequently, integrated air pollution prevention and control targeting PM_{2.5} and O₃ has become a critical objective for the "2+26" cities [2-3]. As volatile organic compounds (VOCs) serve as key precursors of secondary organic aerosols (SOA) and O₃, and SOA constitutes a major component of PM_{2.5}, enhanced regulation of VOCs is pivotal for mitigating both pollutants [4-5]. Atmospheric VOCs originate from natural and anthropogenic sources. Although natural emissions represent a significant contribution, anthropogenic sources dominate in densely populated and industrialized urban areas [6]. Notably, industrial emissions have emerged as a primary source of atmospheric VOCs in many cities [7-9].

Due to significant variations in raw materials, production processes, and emission control technologies, in-depth studies on VOC compositional characteristics across industries are critical to elucidating the formation mechanisms of O₃ pollution and secondary organic aerosols (SOA) in PM_{2.5}. Consequently, many cities and regions in China have investigated source profiles of industrial VOC emissions. Zhou et al. [10] established source profiles for automotive manufacturing, furniture manufacturing, petrochemicals, electronics production, and shoe manufacturing in Chengdu, analyzed VOC emission characteristics across production stages, and identified

priority components for control. Li et al. [11] developed VOC source profiles for automotive manufacturing and packaging and printing industries in Changsha under different pollution control facilities, analyzed component-specific emission patterns, and calculated ozone formation potential (OFP) to identify key reactive species. Zhong et al. [12] constructed source profiles for automotive manufacturing, shipbuilding, wood coating, metal surface coating, and petrochemical industries in the Pearl River Delta region to quantify VOC emission concentrations and assess their atmospheric reactivity. Zhang et al. [13] developed source profiles encompassing 104 VOC species across 14 industries in Zhengzhou, including packaging and printing, automotive manufacturing, and chemical production. Given the diversity of industrial sectors and complexity of production processes, industrial VOC sources and emission characteristics exhibit high heterogeneity. Distinct VOC compositional profiles across industries lead to varying contributions to SOA and O₃ formation. Therefore, establishing localized industrial VOC source profiles and analyzing industry-specific contributions to SOA and O₃ generation are essential for accurate source identification, pollution quantification, and refined urban air quality management [14].

Jiaozuo City, a typical industrial hub in Henan Province and one of the "2+26" cities in the Beijing-Tianjin-Hebei air pollution transmission corridor, faces significant air quality challenges due to its topographical features and industrial structure. Severe PM_{2.5} pollution occurs in autumn and winter, while O₃ dominates in summer. Previous studies on VOCs in Jiaozuo have focused on emission inventory development and source apportionment [15-16], yet research on localized industrial source profiles remains limited, with insufficient attention to environmental impacts and health risk assessments. This study addresses these gaps by conducting

on-site sampling to characterize VOC emissions from typical industries, analyzing their OFP and secondary organic aerosol production potential (SOAP), and performing health risk evaluations. The findings provide critical data to identify priority control industries and key species, offering actionable insights for multi-pollutant prevention and control strategies in Jiaozuo and similar industrial cities.

2. Materials and Methods

2.1. Industry Selection

This study selected 15 industrial enterprises from seven

sectors—plastic products, industrial coating, food manufacturing, packaging and printing, chemical industry, pharmaceutical industry, and shoe manufacturing—based on local priority industry categories, enterprise scale, and VOC emission levels. Sampling campaigns were conducted from August to September 2023. Detailed information of the sampled enterprises is provided in Table 1, and their geographical distribution is illustrated in Figure 1.

Table 1. Enterprise Sampling Information

Industry	Enterprise ID	Enterprise Characteristics	Number of Samples
Plastic Products	1	Plastic Bottle Caps	3
	2	Foam Plastic	3
	3	Plastic Tableware and Composite Packaging Film	3
Industrial Coating	4	Oil-based Coatings	3
	5	Paints/Coatings	3
	6	Paints/Coatings	3
Food Manufacturing	7	Paints/Coatings	3
	8	Ethanol Production	3
Packaging And Printing	9	Water-based Inks	3
	10	Water-based Inks	3
	11	Water-based Inks	3
Chemical Industry	12	Chemical Raw Materials	3
	13	Chemical Raw Materials	3
Pharmaceuticals	14	Traditional Chinese Medicine Production	3
Shoe Manufacturing	15	Footwear Production	3

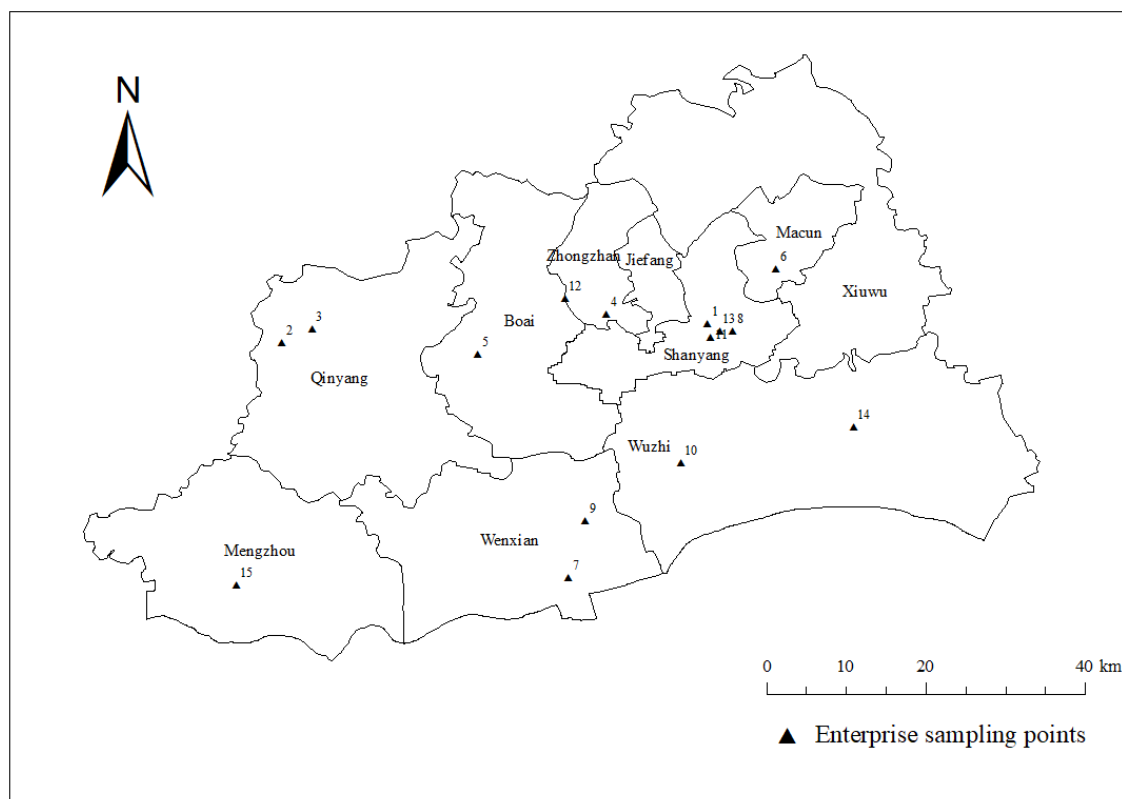


Figure 1. Geographical distribution of enterprise sampling points

2.2. Sampling Methods

VOCs samples were collected in accordance with *HJ 759-*

2015 (Determination of volatile organic compounds in ambient air using canister sampling and gas chromatography-mass spectrometry) ^[17] and *HJT 397-2007* (Technical

specifications for stationary source emission monitoring)^[18]. Sampling was conducted at organized emission outlets downstream of exhaust treatment facilities across 15 industrial enterprises during normal production operations with functional pollution control systems. A 3.2 L Summa canister (Entech Instruments, USA) was connected to a passivated copper tube and an anhydrous sodium sulfate tube, with a silanized filter head installed at the inlet and positioned centrally within the sampling port. Three replicate samples were collected from each facility, with arithmetic means calculated for data analysis.

2.3. Analytical Methods

Samples in Summa canisters were analyzed following *US EPA Method TO-15*. A three-stage cryogenic pre-concentration system (Entech 7100A) coupled with a GC-MS/FID detector (Agilent 8890-5977B GC-MSD) was employed for VOC quantification. Briefly, samples were injected into an automated pre-concentrator for initial treatment, where VOCs were trapped and concentrated. Enriched VOCs were then rapidly volatilized and transferred to the GC-MS/FID system for separation and detection. Calibration standards included photochemical assessment monitoring station (PAMS) mixtures and TO-15-certified gas standards (Spectra Gases, USA). Internal standards (bromochloromethane, 1,4-difluorobenzene, chlorobenzene-d5, and 1-bromo-4-fluorobenzene) were used for quality control.

2.4. Quality Assurance and Quality Control

Prior to sampling, Summa canisters were purged with high-purity N₂ (>99.999%) at least five times, and 20% of the canisters were randomly selected for blank testing. Target compound concentrations in blanks were required to remain below method detection limits (MDLs). During analysis, blank tests and standard curve calibrations were performed every 24 hours. Blank samples were required to exhibit target compound concentrations below MDLs, while relative deviations between measured and certified values for standard samples were mandated to be <10%.

2.5. OFP

This study employed the Maximum Incremental Reactivity (MIR) method to estimate the ozone formation potential (OFP) of VOCs emitted from typical industries in Jiaozuo City based on species-specific MIR coefficients. This approach quantifies the maximum contribution of individual VOC components to ozone (O₃) production in the atmosphere, thereby identifying key sources and species driving ozone formation. Source reactivity (SR) was applied to assess the ozone-forming potential per unit mass of VOCs emitted from each pollution source, independent of emission intensity, making it particularly suitable for regional ozone formation assessments^[19]. Furthermore, SR (O₃) was utilized to characterize the incremental OFP per unit VOC emitted, enabling the evaluation of OFP impacts across industries. The calculation formulas are defined as follows (Equations 1 and 2):

$$OFP_i = [VOCs]_i \times MIR_i \quad (1)$$

$$SR(O_3) = \sum_i^n Y_i \times MIR_i \quad (2)$$

In the equations, OFP represents the maximum ozone formation potential of a species (unit: mg·m⁻³); VOCs denotes the mass concentration of VOC components (unit: mg·m⁻³); MIR_i is the maximum incremental reactivity of species *i*, adopted from the coefficients established by Carter et al.^[20, 21]; SR(O₃) refers to the ozone formation coefficient of VOCs (unit: mg·mg⁻¹); and Y_i is the mass fraction of species *i* in the total VOC mass.

2.6. SOAP

This study adopted the toluene-weighted mass contribution method to estimate the SOAP values of other VOC species. This method quantifies the contribution of atmospheric VOCs to SOA formation. Additionally, SR(SOA) was employed to characterize the incremental SOA formation per unit mass of emitted VOCs, enabling the assessment of SOA impacts from VOCs across typical industries. The calculation formulas are defined as follows (Equations 3 and 4):

$$SOAP_i = [VOCs]_i \times \frac{SOAP_i}{100} \times FAC \quad (3)$$

$$SR(SOA) = \sum_i^n Y_i \times \frac{SOAP_i}{100} \times FAC \quad (4)$$

In the equations, SOAP denotes the secondary organic aerosol formation potential of a species (unit: mg·m⁻³); VOCs represents the mass concentration of VOC components (unit: mg·m⁻³); SOAP_i is the SOAP value of VOC component *i*, adopted from the coefficients reported by Derwent et al.^[22]; FAC (aerosol fraction coefficient of toluene) is assigned a value of 5.4%; SR(SOA) refers to the secondary organic aerosol coefficient of VOCs (unit: mg·mg⁻¹); and Y_i is the mass fraction of species *i* in the total VOC mass.

2.7. Health Risk Assessment

Health risks of pollutants were evaluated according to the U.S. EPA methodology, encompassing carcinogenic risk assessment and non-carcinogenic risk assessment. For non-carcinogenic risks, the hazard index (HI) was calculated as the primary metric (Equation 5). Carcinogenic risks were characterized by the lifetime carcinogenic risk (LCR), as defined in Equation 6.

$$HI = \frac{(C_i \times ET \times EF \times ED)}{365 \times AT_{nca} \times 24} \times \frac{1}{RfC} \quad (5)$$

$$LCR = \frac{(C_i \times ET \times EF \times ED)}{365 \times AT_{ca} \times 24} \times IUR \quad (6)$$

In the equations, C_i: Concentration of VOC component *i* (unit: mg/m³); ET: Exposure time (8 h/day); EF: Exposure frequency (250 days/year); ED: Exposure duration (20 years); AT_{nca}: Averaging time for non-carcinogenic risk (25 years); RfC: Reference concentration for non-carcinogenic effects (unit: mg·kg⁻¹·day⁻¹); AT_{ca}: Averaging time for carcinogenic risk (70 years); IUR: Inhalation unit risk factor (unit: kg·day·mg⁻¹). The RfC and IUR values for VOC species were obtained from the U.S. EPA Integrated Risk Information System (IRIS)^[23, 24]. Parameters for assessing carcinogenic and non-carcinogenic risks to workers were

referenced from Jia et al. [25].

3. Results and Discussion

3.1. VOC Emission Concentrations and Composition Profiles

A total of 116 VOC species were analyzed, 29 alkanes, 11 alkenes, 1 alkyne, 17 aromatic hydrocarbons, 35 halogenated hydrocarbons, 22 oxygenated volatile organic compounds (OVOCs), and carbon disulfide. The emission concentrations and compositional profiles of VOCs from typical industries are summarized in Figure 2.

The packaging and printing industry exhibited the highest VOC emission concentration (148.62 mg/m³), followed by plastic products (10.04 mg/m³), industrial coating (20.73 mg/m³), and pharmaceutical industry (12.52 mg/m³). In contrast, food manufacturing, chemical industry, and shoe manufacturing showed lower emission concentrations. Notably, the chemical industry, characterized by large-scale production facilities and standardized VOC collection/treatment systems, demonstrated the lowest concentration (1.49 mg/m³). The VOC concentrations for food manufacturing and shoe manufacturing were 5.12 mg/m³ and 3.61 mg/m³, respectively.

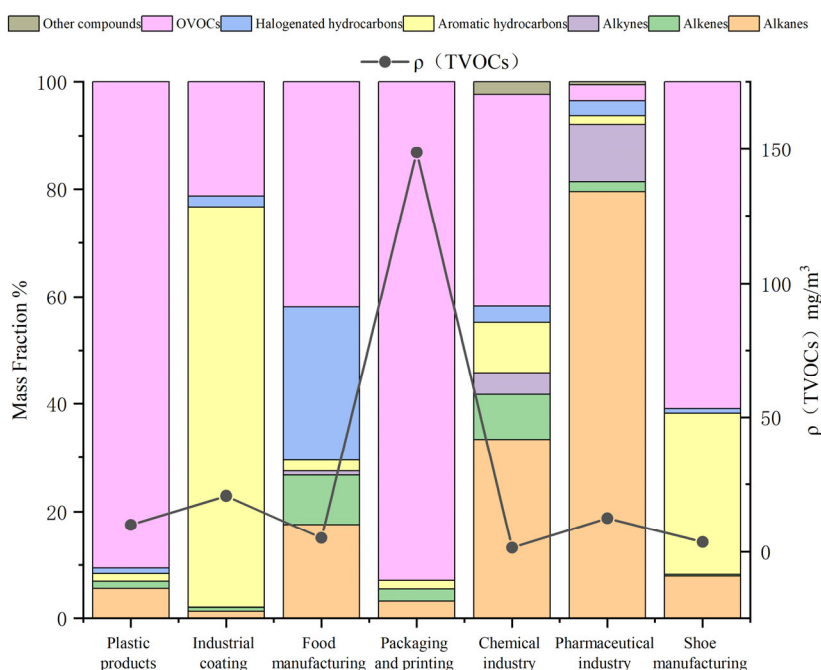


Figure 2. VOC Emission Concentrations and Composition Profiles of Typical Industries

3.2. Environmental Impact Analysis

3.2.1. Analysis of OFP from VOCs

The calculated ozone formation potential (OFP) values across industries ranged from 3.60 to 145.54 mg/m³ (Figure 3). The highest OFP was observed in the packaging and printing industry, driven by high concentrations of oxygenated VOCs (OVOCs), particularly ethyl acetate, which significantly enhanced its ozone-forming capability. The industrial coating sector exhibited the second-highest OFP, despite having VOC concentrations comparable to plastic products and pharmaceutical industries. This discrepancy is attributed to the dominance of aromatic hydrocarbons in industrial coating emissions, which possess higher maximum incremental reactivity (MIR) coefficients, leading to disproportionately elevated OFP even at similar concentrations. This highlights the critical role of reactivity in ozone formation.

OFP values for plastic products, food manufacturing, pharmaceutical, and shoe manufacturing industries were relatively moderate (7.81–12.89 mg/m³). For plastic products and shoe manufacturing, OVOCs were the primary OFP contributors (>60.00%). In contrast, alkenes dominated OFP in food manufacturing (67.66%), and alkanes contributed substantially to pharmaceutical emissions (79.55%). The chemical industry demonstrated the lowest OFP (1.49 mg/m³),

primarily due to its reduced emission levels, OVOCs and alkenes as key contributors. These findings underscore that OFP is predominantly governed by species-specific MIR values, with VOC concentrations playing a secondary role.

Source reactivity (SR(O₃)), which reflects ozone-forming capacity per unit of VOC emitted, further prioritized control targets. Industrial coating exhibited the highest SR(O₃) (5.30 mg·mg⁻¹), followed by chemical industry (3.28 mg·mg⁻¹) and shoe manufacturing (2.43 mg·mg⁻¹), while other sectors showed lower values (0.88–1.52 mg·mg⁻¹). Therefore, from an ozone control perspective, industrial coating, chemical industry, and shoe manufacturing should be prioritized for VOC regulation in Jiaozuo City.

3.2.2. Analysis of SOAP from VOCs

As shown in Figure 4, the secondary organic aerosol formation potential (SOAP) values across typical industries ranged from 0.01 to 0.76 mg/m³. The highest SOAP (0.76 mg/m³) was observed in the industrial coating sector, primarily due to the dominance of aromatic hydrocarbons with higher reactivity and elevated aerosol fraction coefficients (FAC). The packaging and printing industry exhibited the second-highest SOAP (0.15 mg/m³), attributable to its significantly higher VOC emission concentrations. Other industries showed relatively low and comparable SOAP values (0.01–0.06 mg/m³).

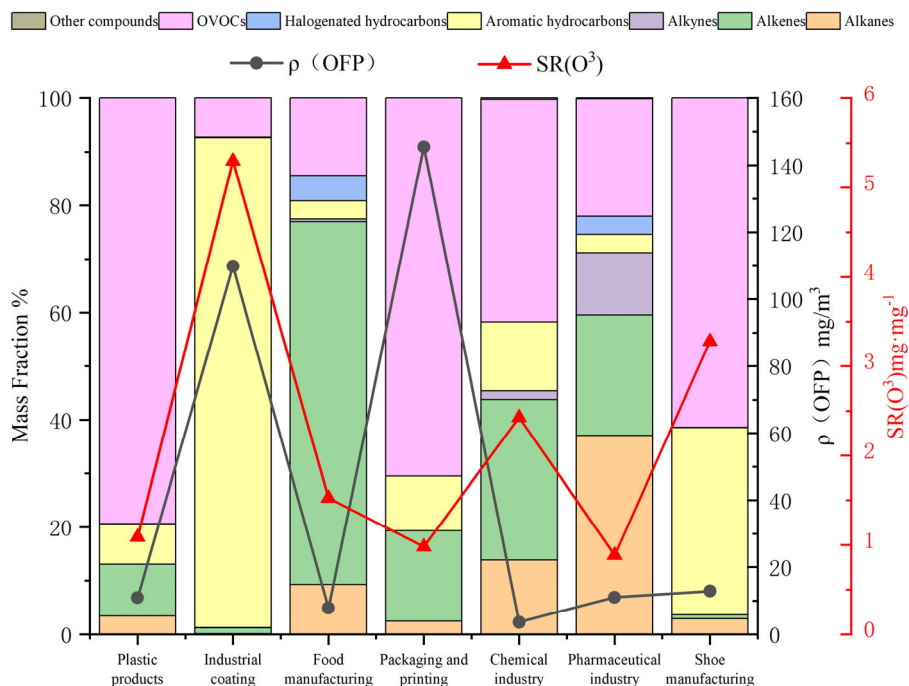


Figure 3. OFP Values, Composition Contributions, and SR Values of Typical Industries

Aromatic hydrocarbons contributed most substantially to SOAP across all industries, exceeding 80.00% in all sectors except plastic products, where alkanes (39.81%) and aromatic hydrocarbons (54.92%) jointly dominated. These findings demonstrate that aromatic hydrocarbons play a critical role in SOA formation. Consequently, from a $PM_{2.5}$ control perspective, aromatic hydrocarbons should be prioritized for VOC regulation in Jiaozuo City.

Figure 4 further illustrates the SR(SOA) values, which

reflect SOA-forming efficiency per unit VOC emitted. The industrial coating sector exhibited the highest SR(SOA) ($0.037 \text{ mg}\cdot\text{mg}^{-1}$), followed by shoe manufacturing ($0.016 \text{ mg}\cdot\text{mg}^{-1}$) and chemical industry ($0.004 \text{ mg}\cdot\text{mg}^{-1}$). All other industries showed negligible SR(SOA) values ($<0.002 \text{ mg}\cdot\text{mg}^{-1}$). Thus, industrial coating and shoe manufacturing should be prioritized for targeted VOC control measures to mitigate $PM_{2.5}$ impacts.

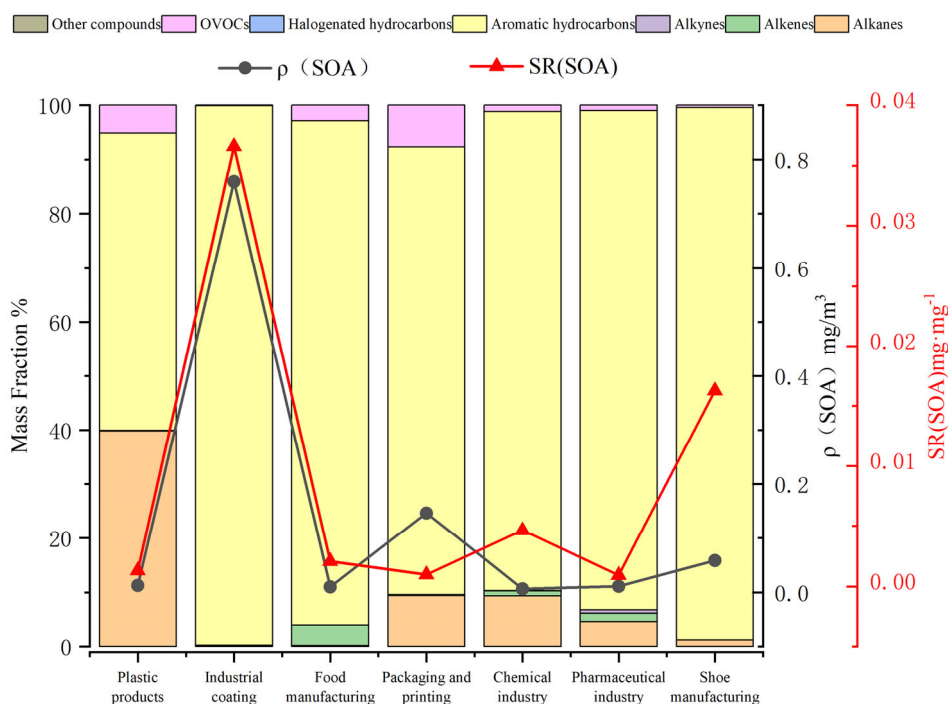


Figure 4. SOAP Values, Composition Contributions, and SR Values of Typical Industries

3.2.3. Comprehensive Analysis of VOC Environmental Impacts

As illustrated in Figure 5, the organized emission concentrations of VOCs, ozone formation potential (OFP), and secondary organic aerosol formation potential (SOA) across typical industries reveal distinct patterns. The packaging and printing industry exhibited the highest TVOC concentrations ($\rho(\text{TVOCs})$) and OFP values ($\rho(\text{OFP})$), with SOA ($\rho(\text{SOA})$) slightly lower than that of the industrial coating sector, primarily due to its exceptionally high emission concentrations driving elevated OFP and SOA despite lower source reactivity ($\text{SR}(\text{O}_3)$: $0.88\text{--}1.52\text{ mg}\cdot\text{mg}^{-1}$; $\text{SR}(\text{SOA})$: $<0.002\text{ mg}\cdot\text{mg}^{-1}$). In contrast, the industrial coating and shoe manufacturing sectors demonstrated disproportionately high OFP and SOA relative to their

moderate emission concentrations, attributed to their elevated $\text{SR}(\text{O}_3)$ (5.30 and $2.43\text{ mg}\cdot\text{mg}^{-1}$) and $\text{SR}(\text{SOA})$ (0.037 and $0.016\text{ mg}\cdot\text{mg}^{-1}$), reflecting dominance of high-MIR aromatic hydrocarbons and high-FAC toluene derivatives. Comprehensive analysis reveals that, from a $\text{PM}_{2.5}$ and O_3 co-control perspective, packaging and printing, industrial coating, and shoe manufacturing should be prioritized for emission control in Jiaozuo City, with industrial coating being the most critical target. Specific recommendations include: packaging and printing should enhance end-of-pipe treatment to reduce emission concentrations, while industrial coating and shoe manufacturing require source control via substitution of high-MIR/FAC raw materials (e.g., aromatic solvents) with low-reactivity alternatives (e.g., alkanes or water-based formulations), ensuring dual mitigation of ozone and particulate pollution.

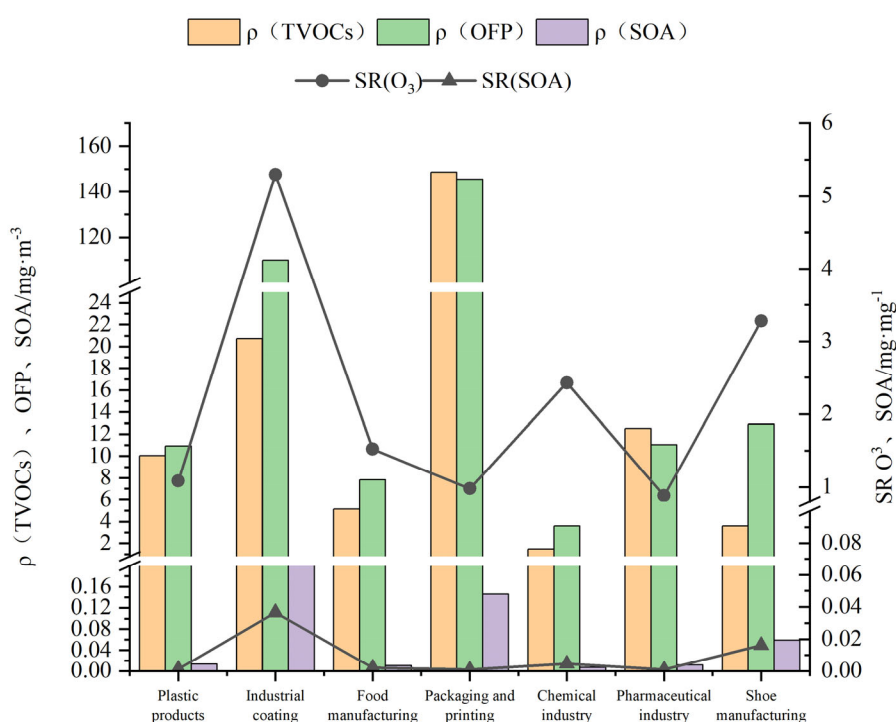


Figure 5. VOC Emission Concentrations, OFP, and SOA Generation in Typical Industries

3.2.4. Health Risk Assessment

According to the U.S. EPA risk assessment framework, a hazard index (HI) greater than 1 indicates potential non-carcinogenic risks^[34]. As shown in Figure 6(a), the HI values for VOCs across typical industries revealed elevated risks in industrial coating ($\text{HI} = 21.51$) and packaging and printing ($\text{HI} = 3.11$), both exceeding the threshold. Table 2 lists species contributing to $\text{HI} > 1$, primarily m/p-xylene and o-xylene. These compounds, widely used as solvents in paints and coatings due to their solubility and stability, exhibit dose- and

duration-dependent toxicity. Therefore, their application in these industries—particularly in industrial coating—should be strictly regulated. HI values for other species remained below 1, indicating negligible non-carcinogenic risks.

For carcinogenic risks, lifetime carcinogenic risk (LCR) was categorized into four tiers: identified risk ($>1\times 10^{-4}$), high probability risk ($1\times 10^{-5}\text{--}1\times 10^{-4}$), low probability risk ($1\times 10^{-6}\text{--}1\times 10^{-5}$), and negligible risk ($<1\times 10^{-6}$). As illustrated in Figure 6(b), all industries exhibited LCR values below 1×10^{-6} , indicating no significant carcinogenic risks to humans.

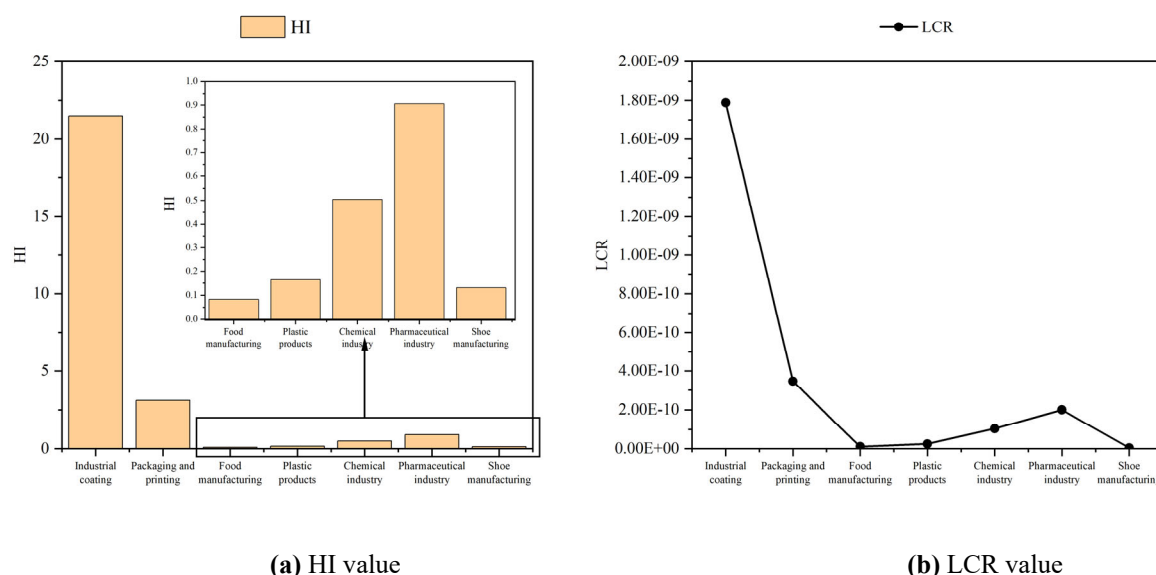


Figure 6. HI and LCR Values in Typical Industries

Table 2. Species with HI > 1 in Industrial Coating and Packaging and Printing Industries

Industry Category	Species with HI > 1
Industrial coating	m/p-Xylene (13.03);o-Xylene (7.59)
Packaging and printing	o-Xylene (1.56);m/p-Xylene (1.38)

4. Conclusions

(1) This study quantified VOC emission concentrations across seven industries—plastic products, industrial coating, food manufacturing, packaging and printing, chemical industry, pharmaceutical industry, and shoe manufacturing. The results revealed the following emission hierarchy: packaging and printing (148.62 mg/m³) > industrial coating (20.73 mg/m³) > pharmaceutical industry (12.52 mg/m³) > plastic products (10.04 mg/m³) > food manufacturing (5.12 mg/m³) > shoe manufacturing (3.61 mg/m³) > chemical industry (1.49 mg/m³). Overall, OVOCs, aromatic hydrocarbons, and alkanes were identified as the dominant VOC categories emitted from these industries in Jiaozuo City.

(2) Based on field-sampled VOC data, the impacts on O₃ and SOA formation were evaluated by OFP and SOAP. Analysis of OFP contributions revealed that OVOCs and aromatic hydrocarbons are key species driving O₃ generation in industrial VOC emissions. For SOA formation, aromatic hydrocarbons were identified as the predominant contributors.

(3) A comparative analysis of organized VOC emission concentrations, OFP, SOAP, and SR values across industries demonstrated that packaging and printing, industrial coating, and shoe manufacturing should be prioritized for coordinated PM_{2.5}-O₃ control in Jiaozuo City, with industrial coating requiring the most urgent intervention.

(4) Health risk assessments were conducted to evaluate potential hazards from VOC emissions. Non-carcinogenic risks (HI) exceeded thresholds for industrial coating and packaging and printing, primarily driven by m/p-xylene and o-xylene. LCR for all industries remained below regulatory limits, indicating no significant carcinogenic hazards.

5. CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

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