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Original Paper

Assessment of VOC mitigation from equipment leaks in petroleum refining in Guangdong, China: Insights from a long-term leak detection and repair (LDAR) implementation

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ABSTRACT

Fugitive volatile organic compound (VOC) emissions from equipment leaks in the petroleum refining industry threaten ambient air quality and human health. The impact of a long-term leak detection and repair (LDAR) on mitigating these emissions has not been adequately elucidated. Herein, we explored the VOC emission characteristics and mitigation from a petroleum refinery in a long-term LDAR implementation, established emission factors at production unit-level and enterprise-level, and assessed the VOC mitigation, ozone formation potential (OFP) and secondary organic aerosol formation potential (SOAP) from equipment leaks of petroleum refining in Guangdong, China. The results indicated that the long-term implementation of LDAR at the enterprise-level petroleum refining facility resulted in an approximately 40.5% reduction in overall VOC emissions. Kerosene hydrotreating unit (KHU), catalytic reforming unit (CRU), delayed coking unit (DCU), aromatics recovery complex (ARC), and hydrocracking unit (HCU) were the top five units for emission reduction, while valves and connectors were the top two sealing points. The implementation of LDAR across all petroleum refineries in Guangdong Province achieved annual VOC emission reductions ranging from 129.0 to 160.5 tons between 2018 and 2022, with corresponding reductions in OFP and SOAP of approximately 68.2%. Alkenes/alkynes were the primary contributors to OFP, whereas aromatics dominated SOAP. Three recommendations were proposed for the optimization of future LDAR implementation policies: to emphasize the quality control and assurance of LDAR detection data; to establish a refined LDAR work plan that integrates production units and sealing points; and to conduct LDAR work on a regular and continuous basis.

1. Introduction

As the leading global producer and consumer of energy resources, China occupies a pivotal position within the petroleum products sector (BP Energy Economics, 2025; Masnadi et al., 2018; Xu et al., 2018). Following its surpassing of the United States in 2021, China has maintained its position as the world's foremost in refining capacity for three consecutive years, representing approximately 18% of the global total (Liu et al., 2022; Xu, 2024). However, the petroleum refining process yields substantial emissions of volatile organic compounds (VOCs) stemming from equipment leaks, tank breathing, wastewater treatment, and fuel loading (Feng et al., 2020; Lv et al., 2021a, 2021b; Mo et al., 2015; Sun et al., 2023; Wei et al., 2014; Zhang et al., 2017, 2018). Especially concerning are the fugitive VOC emissions from equipment leaks, which can account for 40% to 50% of the total VOC emissions

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in the petroleum refining industry (Simayi et al., 2021; Yen and Horng, 2009). These VOC emissions not only lead to material losses but also have substantial adverse impacts on the atmospheric environment and human health (Cao et al., 2024; Zhou et al., 2023). Therefore, the effective control of VOCs from equipment leaks is of great significance for the scientific and precise reduction of VOC emissions in the petroleum refining industry, thereby improving air quality and human health.

Equipment leaks occur when VOCs are randomly emitted from the sealing points of production equipment like valves, pumps, flanges, and joints due to looseness, deformation, corrosion, or sealant failure. These leaks are characterized by numerous emission points, widespread distribution, dispersion, irregularity, and significant temporal and spatial fluctuations (Li, 2024). Leak detection and repair (LDAR) is an effective strategy for the unorganized control of VOC emissions from equipment leaks and serves as a crucial method for achieving precise VOC management (Zhang et al., 2021a, 2021b). The LDAR program quantitatively detects the leak concentration of the sealing points from production units to identify the leak points and repair them in a timely manner to reduce VOC emissions (Zhang, 2016). In the 1980s, the United States pioneered LDAR and systematically established LDAR technologies and regulatory frameworks (USEPA, 1992, 1995, 2007, 2017). In 1990, the U.S. Clean Air Act Amendments (CAAA) required petrochemical and chemical enterprises to implement LDAR. Over the subsequent 15 years, VOC emissions for petrochemical and chemical industries in the U.S. were reduced by 63% and 56%, respectively (USEPA, 2007). Based on the relevant experiences of the U.S., the European Union recommended that member state refineries implement LDAR in 1999. By 2014, LDAR was recognized as the Best Available Technique (BAT) for controlling the unorganized emissions of VOCs from oil and gas processing equipment (Barthe et al., 2015). LDAR initiatives in China commenced relatively late. Their development has been guided by a series of policies and standards issued since the Twelfth Five-Year Plan (MEEPRC, 2013; 2015a; 2015b, 2017, 2020, 2021). The methodological foundation was established by technical guidelines like HJ 733-2014 and subsequently refined in HJ 1230-2021. This regulatory evolution culminated in the promulgation of the compulsory *Emission Standard of Pollutants for Petroleum Refining Industry (GB 31570-2015)*, which mandated LDAR implementation for all existing refineries by July 1, 2017.

Given the significance of LDAR in regulating uncontrolled VOC emissions, extensive research has been undertaken on LDAR implementation processes, technical standards, quality assessments, and innovative technologies since the 1980s (Chris et al., 2010; Ehrhardt et al., 2017; Hinnrichs, 1999; Furry et al., 2007; Fox et al., 2021; Wang et al., 2024). In recent years, Chinese researchers have also increasingly focused on their research in this field (Bu et al., 2023; Dai et al., 2025; Liu et al., 2017; Zhang et al., 2017; 2021, 2022; Zhang et al., 2022; Zheng et al., 2018). However, the majority of research primarily focuses on the historical development, technical specifications, and assessments of LDAR in China, whereas studies examining VOC emission characteristics and the effectiveness of emission reduction from LDAR are comparatively scarce. Zhang et al. (2022) conducted a study on VOC emission characteristics before and after LDAR based on a survey of a typical petrochemical enterprise. However, LDAR is a continuously systematic project, and this study represents only the results of the initial round of LDAR implementation with a brief tracking period. Consequently, it cannot comprehensively reflect the VOC emission and reduction of continuous LDAR implementation. Although Zhang (2023) systematically analyzed the VOC leakage characteristics and control effects of six typical petrochemical enterprises, their assessment of emission reductions lacked process-level or finer-grained detail, focusing solely on the overall enterprise level. Similarly, Dai et al. (2025) studied five typical petrochemical companies to compare VOC leakage characteristics from equipment and pipelines across different processing scales and routes, proposing targeted measures to reduce fugitive VOC emissions. However, their study provided limited discussion on the mitigation effectiveness and characteristics of specific units and components. The lack of long-term, process-level assessment of LDAR mitigation effects hampers the development of targeted measures for enhancing its efficacy and enabling refined control. Moreover, the absence of local VOC emission factors for equipment leaks in China has led many petrochemical enterprises to rely on early average emission factors from the United States for evaluating VOC emissions and reductions. This discrepancy often results in significant disparities between estimated and actual emissions (Ding et al., 2014; Liu et al., 2020; Wu et al., 2017).

This study focuses on a typical petroleum refining enterprise in Guangdong, China. By continuously tracking a long-term LDAR implementation, the VOC emission characteristics and mitigation of equipment leaks across different LDAR implementation periods were investigated. Key contributing units and sealing points responsible for equipment leak VOC emissions were identified. Drawing upon a substantial dataset obtained through flame ionization detector (FID) detection during LDAR implementation, production unit-level and enterprise-level emission factors of VOCs before and after LDAR were established. Finally, VOC mitigation, potential impact on ozone and secondary organic aerosol formation of LDAR implementation from petroleum refining in Guangdong, China was assessed. This study uniquely examines multi-cycle LDAR performance and quantifies VOC mitigation and secondary pollution benefits (OFP/SOAP) using real FID field data. The findings are intended to advance LDAR practices and support the refined management of VOC leaks in China's petrochemical sector.

2. Methods and data

2.1. Basic information and LDAR tracking phases

The petroleum refining enterprise under investigation is situated in Guangdong, China. Its primary output consists of petrochemicals including gasoline, diesel, aviation fuel, and liquefied natural gas. The enterprise has established 16 production units, encompassing crude distillation unit (CDU), catalytic cracking unit (CCU), hydrocracking unit (HCU), kerosene hydrotreating unit (KHU), diesel hydrotreating unit (DHU), catalytic reforming unit (CRU), and delayed coking unit (DCU), among others (Table 1). The petroleum refining enterprise initiated its initial LDAR activities on all sealing points of production units in Q4 2020, subsequently maintaining ongoing efforts tailored to equipment and pipeline component types. In this context, A-class sealing points, including pumps, valves, open valves, compressors, pressure relief devices, and sampling connection systems, are subjected to LDAR procedures on a quarterly basis. Conversely, B-class sealing points, such as flanges, connectors, and other sealing devices, undergo LDAR semiannually.

As illustrated in Fig. 1, the LDAR program comprises three phases: project establishment, leak detection, and leak repair. The initial phase, project establishment, involves the identification, screening, coding, and archiving of all VOC (volatile organic compounds)-containing units and equipment component sealing points throughout the facility (GB 31570-2015). The second phase, leak detection, utilizes flame ionization detectors or optical instruments to inspect each equipment component in the above

Table 1
Basic information of typical petroleum refining enterprise.

No.	Production units	Number of equipment component sealing points
1	Aromatics recovery complex (ARC)	1.0×10^5
2	Aromatics recovery unit (ARU)	4.0×10^3
3	Catalytic cracking unit (CCU)	2.0×10^4
4	Crude distillation unit (CDU)	1.4×10^4
5	Catalytic reforming unit (CRU)	4.4×10^4
6	Delayed coking unit (DCU)	5.0×10^4
7	Diesel hydrotreating unit (DHU)	2.9×10^4
8	Hydrocracking unit (HCU)	5.7×10^4
9	Hydrogen plant (HP)	8.6×10^2
10	Iube base oil (IBO)	8.7×10^3
11	Kerosene hydrotreating unit (KHU)	4.8×10^4
12	Methyl tertiary buty1 ether (MTBE)	4.5×10^3
13	Propene recovery unit (PRU)	4.4×10^3
14	Sweetening complex unit (SCU)	5.3×10^3
15	Sulfur recovery unit (SRC)	3.3×10^2
16	Sour water stripper (SWS)	3.0×10^2

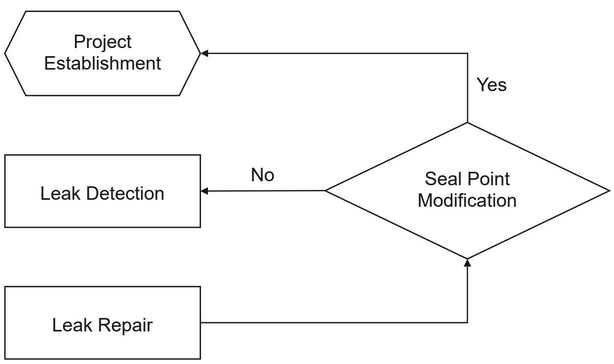

Fig. 1. LDAR implementation flowchart.

project as per the archive, confirming and marking the leaking sealing points. The final phase involves repairing the identified leaks and conducting subsequent retests to ensure successful remediation.

The case-study enterprise initiated its LDAR program in the fourth quarter (Q4) of 2020 for the first time. From Q4 2020 until a subsequent shutdown in the second quarter (Q2) of 2022, the enterprise consistently conducted LDAR activities on a quarterly basis for A-class components and a semiannual basis for B-class components. This period (Q4 2020–Q2 2022) constitutes the 7-quarter study period, for which the LDAR data is complete and uninterrupted. Within this framework, each quarterly LDAR implementation for A-class sealing points is defined as a sub-cycle. We assume that LDAR tasks for B-class points progressed at a constant rate, with half of the tasks completed midway through their semiannual cycle, as detailed in Table 2. This approach allows for the exploration of VOC emission and reduction characteristics across defined LDAR implementation periods.

The petroleum refining enterprise initiated LDAR implementation for the first time in 2020, subsequently conducting LDAR activities for respective sealing point types (A-class and B-class) on a quarterly and semiannual basis. In 2022, due to temporary shutdowns, LDAR implementation was limited to the second quarter. This study comprehensively tracks all LDAR activities carried out by the subject enterprise from 2020 to 2022. LDAR implementation for A-class sealing points is defined as a sub-cycle unit (one quarter). We assume that B-class sealing point LDAR projects are completed at a constant rate within the rap-up period, and half of the LDAR project tasks are completed exactly halfway through the implementation period, as depicted in Table 2. This approach allows exploration of VOC emission and reductions characteristics from equipment leaks during various LDAR implementation periods.

2.2. Detection of VOC equipment leakage from petroleum refining

Using a portable detector equipped with FID detector (Thermo Scientific TVA2020C), VOC equipment leakages from petroleum refining were detected. The FID used has a response time of less than 3.5 s and a detection range of 0–50,000 μmol/mol. The FID was calibrated daily according to the following procedure prior to leak detection: (1) Warm-up: The instrument was turned on and allowed to warm up for at least 30 min. During this period, it was kept in detection mode with the sampling probe and all connections properly secured. (2) Zero calibration: After warm-up, zero-air was introduced. The instrument reading was required to be within ±10 μmol/mol. If the deviation exceeded this limit, the zero point was adjusted accordingly. (3) Span calibration: Following zero calibration, the detector was calibrated using two certified methane-in-air standard gasses with concentrations of 500–550 μmol/mol and 10,000–11,000 μmol/mol. The recorded values for both standards were required to be within ±10% of their certified concentrations.

During detection, the sampling probe is placed at relevant positions of equipment or devices where leakage may occur and moved around the perimeter at a speed of less than 10 cm/s, while

Table 2
Tracking period of LDAR program in the petroleum refining enterprise.

Year	2020	2021				2022	
LDAR sub-cycle	The first cycle	The second cycle	The third cycle	The fourth cycle	The fifth cycle	The sixth cycle	The seventh cycle
Sealing point type	A1	A2	A3	A4	A5	A6	A7
	B1	B2-½	B2-1	B3-½	B3-1	B4-½	B4-1

A: Pumps, valves, open valves, compressors, pressure relief devices, and sampling connection systems.
B: Flanges, connectors, and other sealing devices.

monitoring the instrument readings. If an increase in readings is observed, the movement speed of the sampling probe is slowed until the maximum reading is obtained, and it is held at that spot for approximately twice the instrument's response time to record the maximum reading. For static seals (such as valves, flanges, connectors, open valves, open pipelines, depressurization equipment, etc.), the sampling probe is placed closely against the edge of the seal point while ensuring the safety of the detection personnel and preventing the instrument from inhaling oil, dirt, or liquids; for dynamic seals (such as pumps, compressors, mixers, etc.), the sampling probe is positioned no more than 1 cm from the shaft seal. All monitoring was conducted under steady-state operating conditions.

A comprehensive QA protocol was implemented to ensure data integrity: (1) Environmental conditions: Field measurements were conducted only within the instrument's specified operational environmental conditions. Outdoor detection was suspended during rain, snow, or high winds (ground-level wind speed >8 m/s). (2) Background measurement: The ambient background concentration was measured at least once per day for each process unit in an open area. (3) Drift verification: At the end of each day, the same calibration gas used in the morning was introduced without any instrument adjustment. If the absolute value of the reading drift exceeded 10%, the instrument was recalibrated, and controlled sealing points measured that day were re-inspected.

2.3. Estimation of VOC emissions from equipment leaks

VOC emissions from equipment leaks were estimated using established USEPA correlation equations, with the leak concentration data obtained by FID serving as the primary input.

$$E_{i,j,n} = \left(e_{\mathrm{TOC},i,j,n} \times \frac{\mathrm{WF}_{\mathrm{VOC},i,j,n}}{\mathrm{WF}_{\mathrm{TOC},i,j,n}} \times t_{i,j,n} \right) \tag{1}$$

where i represents the production unit; j represents the sealing point; n represents the sub-cycle of LDAR implementation; E represents the VOC emissions from equipment leaks, kg; e_{TOC} represents the TOC emission rate, kg·h^{-1}, $\mathrm{WF}_{\mathrm{VOC}}$ represents the average mass fraction of VOCs in the material during the operating period; $\mathrm{WF}_{\mathrm{TOC}}$ represents the average mass fraction of TOC in the material during the operating period, and if the average mass fraction of VOCs in the material is not provided, it is assumed to be 1. t represents the operating time within one sub-cycle of LDAR implementation, h.

e_{TOC} was calculated using measured data obtained from FID leak detection. The calculation method references empirical formulas published by the USEPA (USEPA, 1995). The specific calculation formula is as follows:

Table 3
Leak rate for equipment components in oil refining industries.

Seal point type	$e_{0,i}$ kg·h^{-1}	$e_{p,i}$ kg·h^{-1}	$e_{f,i}$ kg·h^{-1}
Pump	2.4E-05	0.074	5.03E-05 × SV$^{0.610}$
Valve	7.8E-06	0.064	2.29E-06 × SV$^{0.746}$
Connector	7.5E-06	0.028	1.53E-06 × SV$^{0.735}$
Flange	3.1E-07	0.085	4.61E-06 × SV$^{0.703}$
Open valve or open pipeline	2.0E-06	0.030	2.20E-06 × SV$^{0.704}$
Others	4.0E-06	0.073	1.36E-05 × SV$^{0.589}$

$$e_{\mathrm{TOC},i,j,n} = \begin{cases} e_{0,i,j,n} & (0 \le \mathrm{SV} < 1) \\ e_{p,i,j,n} & (\mathrm{SV} \ge 50000) \\ e_{f,i,j,n} & (1 \le \mathrm{SV} \le 50000) \end{cases} \tag{2}$$

where SV represents the equipment leak detection value, ppmv, e_0 represents the default zero emission rate, kg·h^{-1}, e_p represents the specified emission rate, kg·h^{-1}, and e_f represents the emission rate calculated by the relevant equation, kg·h^{-1}. The equipment emission rate for petroleum refining equipment components are detailed in Table 3.

2.4. Emission factors of VOCs from equipment leaks

Equipment leak VOC emission factors were established for production unit-level and enterprise-level based on the number of sealing points and the capacity of raw material or product processing. The emission factors before LDAR implementation represent the VOC emission factors of the first detection and without repair, while the emission factors after stable LDAR implementation represent the average VOC emission factors after LDAR in each sub-cycle.

2.4.1. Emission factors based on the number of sealing points

The emission factors based on the number of sealing points refers to the VOC emissions from a single sealing point within a sub-cycle and can be calculated using the following formula:

$$\mathrm{EF}_{N,i,\mathrm{Before}} = \frac{E_{i,1,\mathrm{Before}}}{N_i} \tag{3}$$

$$\mathrm{EF}_{N,i,\mathrm{After}} = \frac{\sum_n E_{i,n}}{7 \times N_i} \tag{4}$$

where EF_N is the emission factor of VOCs from equipment leaks based on the number of sealing points, g/(pcs·quarter); where N represents the number of sealing points; "7″ represents the total sub-cycle of LDAR project implementation. "Before" and "After" represent the periods prior to and following the implementation of the LDAR project, respectively.

2.4.2. Emission factors based on raw material processing

For enterprises that have not yet been constructed or have not conducted sealing point quantity statistics, utilizing emission factors based on the number of sealing points proves challenging. Consequently, this study also establishes VOC emission factors from equipment leaks based on the raw material or product processing.

$$\mathrm{EF}_{P,i,\mathrm{Before}} = \frac{E_{i,1,\mathrm{Before}}}{A_i} \tag{5}$$

$$\mathrm{EF}_{P,i,\mathrm{After}} = \frac{\sum_n E_{i,n}}{7 \times A_i} \tag{6}$$

where EF_P represents the emission factor of VOCs from equipment leaks based on raw material or product processing, kg/(10,000 tons·quarter); A represents the raw material or product processing, 10,000 tons. It should be noted that the SCU is a combination of gas desulfurization units from various sources of different units, therefore, this device is not measured by the annual raw material processing. Additionally, the enterprise-level raw material processing was measured by the annual crude oil processing capacity.

2.5. Secondary pollution formation potential

2.5.1. Ozone formation potential (OFP)

Ozone formation potential (OFP) for equipment leaks of petroleum refining was compiled based on the speciated VOC emissions and MIR values. It was calculated as follows:

$$\mathrm{OFP_{EI}} = \sum \mathrm{SP}(k) \times \mathrm{MIR}(k) \quad (7)$$

$$\mathrm{OFP} = E \times \mathrm{OFP_{EI}} \quad (8)$$

where k is a specific VOC species; OFP is the total OFP emissions; $\mathrm{OFP_{EI}}$ is the OFP emissions intensity; E is the total VOC emissions; $\mathrm{SP}(k)$ is the weight percentage of species k, which were obtained from our previous study (Sun et al., 2023). and $\mathrm{MIR}(k)$ is the maximum incremental reactivity of species k. The updated MIR values reported by Venecek et al. (2018) were used in this study (Table S1).

2.5.2. Secondary organic aerosol formation potential (SOAP)

Secondary organic aerosol formation potential (SOAP) for equipment leaks of petroleum refining was compiled based on the speciated VOC emissions and SOA yields (Cai et al., 2019; Huang et al., 2022). It was calculated as follows:

$$\mathrm{SOAP_{EI}} = \sum \mathrm{SP}(k) \times Y(k) \quad (9)$$

$$\mathrm{SOAP} = E \times \mathrm{SOAP_{EI}} \quad (10)$$

where SOAP is the total SOAP emissions; $\mathrm{SOAP_{EI}}$ is the OFP emissions intensity; and Y_k is the SOA yield of species k, which were obtained from McDonald et al. (2018).

3. Results and discussions

3.1. Characteristics of equipment leak before LDAR

The characteristics of equipment leak before LDAR are shown in Figs. 2 and 3. Overall, the VOC emissions from equipment leakage in the petroleum refinery was 71.8 tons/year. According to the definition of the leakage threshold in the “Technical Specification for Implementation of Leak Detection and Repair (LDAR) in Guangdong Province” (DEEGP, 2016), the total leakage rate of the petroleum refinery was 0.67% (Fig. 2), which is consistent with the results of previous studies (0.48%~1.3%) (Chen et al., 2016; Ding et al., 2014; Zhang et al., 2022; Zhu et al., 2014). However, these very few leakage points contributed 54.9% of the total VOC emissions from equipment leaks. This indicates that the identification and repair of leak points are crucial for reducing VOC emissions from equipment leaks. The quantitative impact of LDAR on VOC emissions is analyzed in detail in Section 3.2.

The leakage rate and VOC contribution of leakage point in the petroleum refinery were discussed (Fig. 2). Considering the leakage characteristics of various production units (Fig. 2(a)), PRU, MTBE, ARU, and CRU exhibited the highest leakage rates, all exceeding 1%. HCU, SCU, and HP also had leakage rates higher than the enterprise's overall leakage rate, ranging from 0.70% to 0.76%. The remaining units had leakage rates below the total enterprise leakage rate (0.67%). The contribution of leak points to the total VOC emissions in distinct units from equipment leaks shows variation. Specifically, leak points of DCU, SCU, and MTBE contributed more than 90% to the total VOC emissions of the unit. Leak points from KHU, CCU, CDU, and PRU contributed more than the total contribution rate of the enterprise, with a range from 58.7% to 79.8%. The contribution of VOCs from the leak points of the remaining units ranged from 0% to 51.4%. From the perspective of sealing point types (Fig. 2(b)), Open pipeline, pump, valve, and flange have relatively large leakage rates, which were 3.2%, 2.2%, 1.5%, and 1.0%, respectively. The leakage rates of other sealing point types were smaller than the comprehensive leakage rate of the enterprise. Open pipeline and valve leakage points contributed significantly to the total VOC emissions from equipment leaks, accounting for 93.1% and 87.4%, respectively. The contributions of the leakage points of other sealing point types ranged from 0% to 50.6%.

The relationship between the VOC emissions and the number of sealing points and leakage points from equipment leaks in a petroleum refinery was also analyzed (Fig. 3). From the perspective of production unit types (Fig. 3(a)), the ARC, which contributes the most to VOC emissions from equipment leaks (21.1%), also has the highest number of sealing points and leakage points. Conversely, the KHU, which is second in VOC emission contribution (17.1%), ranks fourth and fifth in terms of the number of sealing points and leakage points, with proportions of 12.1% and 8.6%, respectively. This indicates that production units with a large number of sealing points do not necessarily have a high number of leakage points and VOC emissions. Similarly, units with numerous leakage points do not always contribute significantly to VOC emissions, which is closely tied to the emission rate of the leakage points (USEPA, 1995). Regarding sealing point types (Fig. 3(b)), connectors, valves, and flanges exhibited the highest contributions to VOC emissions, aligning with the findings of Zhang et al. (2022). The VOC emissions from these three types collectively accounted for approximately 96.0% of the total emissions. Among them, connectors had the highest VOC emissions contribution (42.0%) and

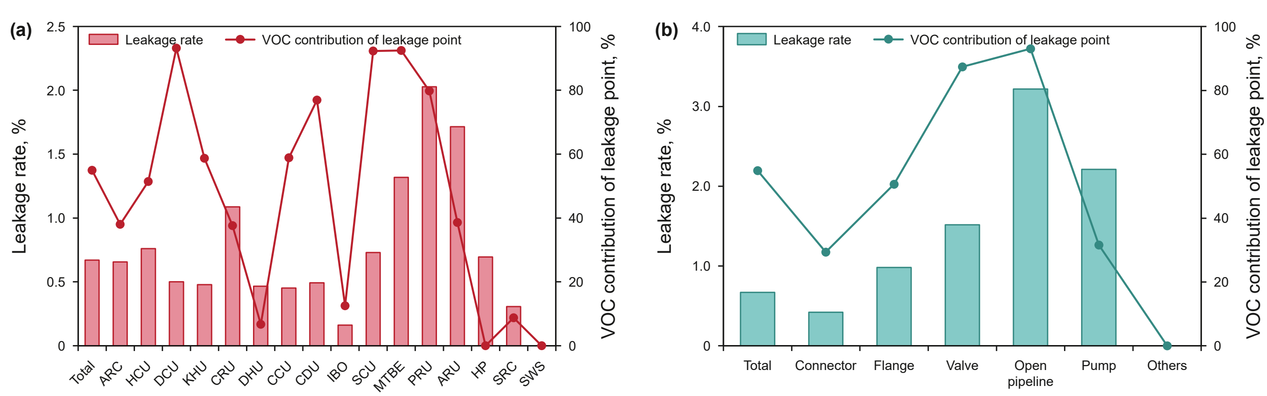

Fig. 2. Leakage rate and VOC contribution of leakage point before repair. (**a**) Different production devices; abbreviations for production devices are defined in Table 1; (**b**) different types of sealing points.

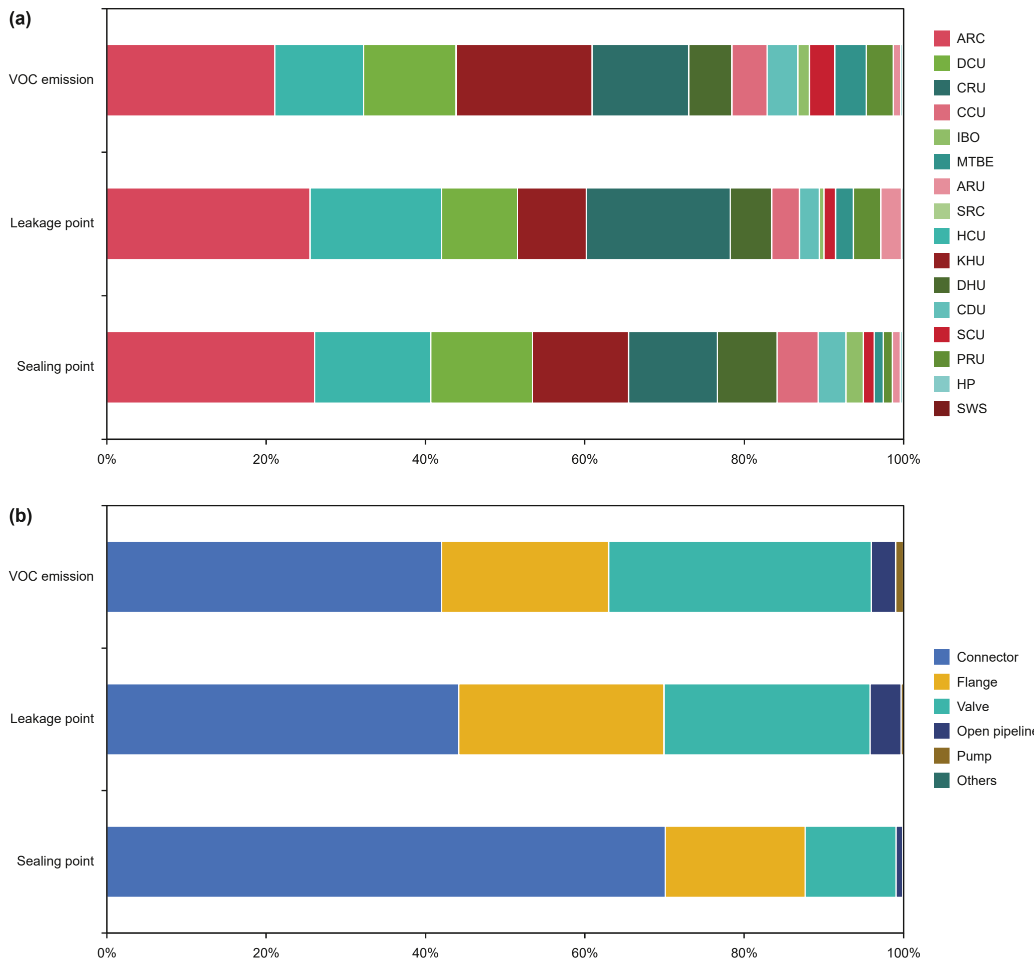

Fig. 3. Contribution of sealing points, leakage points, and VOC emissions from equipment leaks. (**a**) Contribution by production unit type; abbreviations for production device are defined in Table 1; (**b**) contribution by sealing point type.

the greatest number of sealing and leakage points. Conversely, although valves ranked second in VOC emissions contribution (33.0%), they ranked third in the number of sealing and leakage points, at 11.4% and 25.8%, respectively. These further underscores the critical role of the emission rate at sealing points in determining VOC emissions.

3.2. Characteristics under different LDAR implementation periods

Fig. 4 illustrates the characteristics of VOC emission rate under different LDAR implementation periods. In the initial period, the emission rate before repair was the highest (8.3 kg/h), significantly exceeding the emission rates before repair (3.8–6.8 kg/h) and after repair (3.2–5.1 kg/h) in subsequent periods. This highlights the crucial role of repair efforts of LDAR in mitigating VOC emissions from equipment leaks. Although VOC emission rates from equipment leaks have decreased after implementing LDAR, the continuous operation of production facilities and the aging of equipment and components lead to new leaks. Consequently, VOC emission rates detected in each implementation cycle often exceed rates observed after repairs in previous cycles. This underscores that LDAR work is not a one-time task but requires long-term, regular implementation as an ongoing effort to mitigate the impact of equipment and component aging on VOC emissions.

Fig. 4 also illustrates the contribution of different production unit and sealing point types to the VOC emission rate from equipment leaks across various LDAR implementation periods. The contributions from different production unit types and sealing point types have varied over these periods. Overall, ARC, HCU, DCU, KHU, and CRU were the five unit types contributing the most to the VOC emission rate, collectively accounting for 70.0% to 80.6% of the total emissions. Connectors, flanges, and valves consistently remained the sealing point types with the highest contribution, accounting for 92.7% to 98.2% of the total. These production unit and sealing point types are crucial targets for controlling emissions from equipment leaks in petroleum refining enterprises. It is recommended that in future LDAR implementations, more frequent or stringent detection measures be applied to these key units and sealing point types. Additionally, enhancing preventive maintenance practices can better control and reduce VOC emissions.

Fig. 5 presents the VOC emissions from equipment leaks in the petroleum refinery before and during different LDAR implementation periods. Prior to LDAR implementation, VOC emissions from equipment leaks were 17.9 tons per quarter. After stable LDAR implementation, the average VOC emissions decreased to 7.3 tons per quarter, demonstrating a significant reduction. However, despite the overall decrease, VOC emission levels across different periods post-LDAR implementation still exhibit fluctuations, revealing the nonlinear emission reduction characteristics of LDAR work over time. This suggests that there is some uncertainty in the effectiveness of LDAR work. This variability can be attributed to several factors: the inherent uncertainty in identifying leaks near

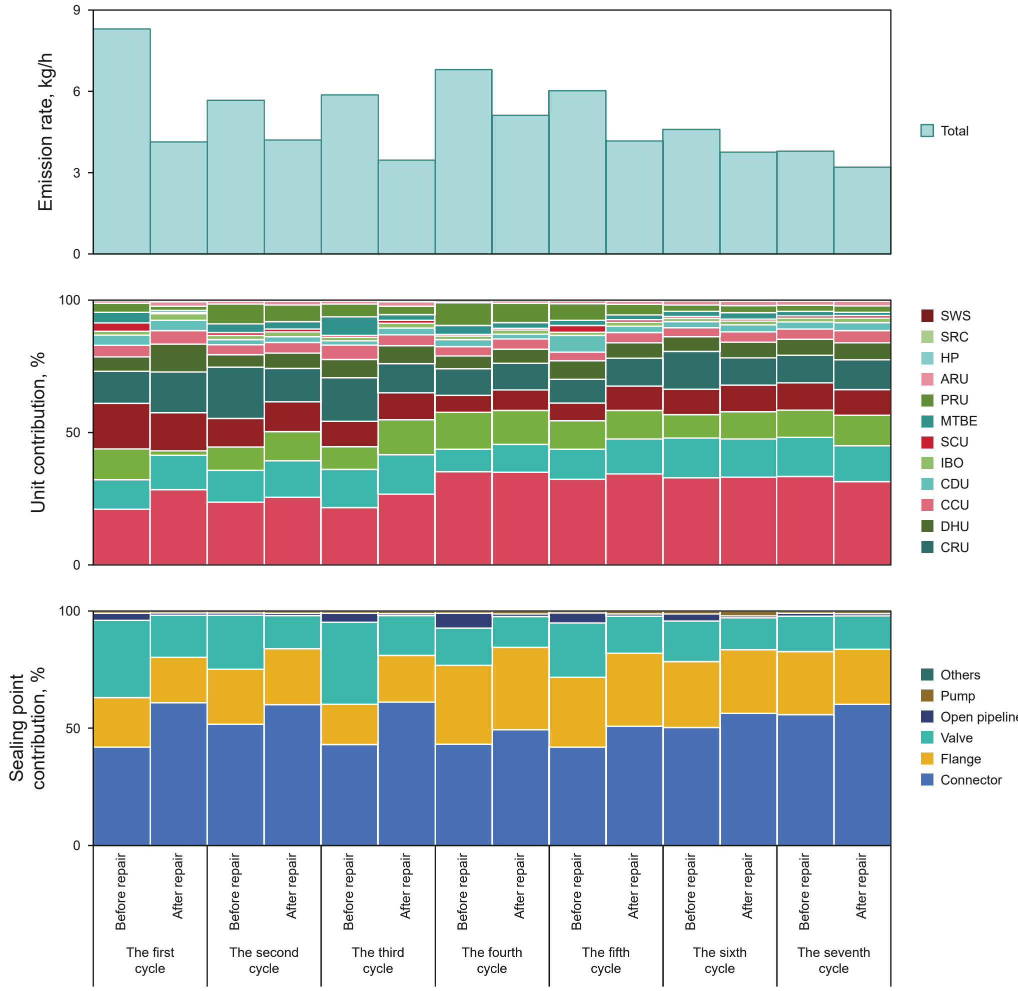

Fig. 4. Characteristics of VOC emission rate under different LDAR implementation periods; Abbreviations for production Unit are defined in Table 1.

concentration thresholds, the varying contribution to total emissions from the specific leaks repaired in each cycle, and delays in repairing leaks that require a unit shutdown for safe intervention. To reduce it, we recommend: (1) enhancing detection QA/QC for more consistent identification; (2) adopting a leak prioritization system to focus on high-impact leaks first; and (3) integrating repairable-but-not-immediately-fixable leaks into planned shutdown schedules. These strategies can make LDAR effectiveness more reliable. The primary unit types and sealing point types contributing to VOC emissions from equipment leaks were examined. Consistent with the observed VOC emission rates, the ARC, HCU, DCU, KHU, and CRU equipment types were identified as the predominant contributors, together accounting for 73.0% to 79.5% of the total emissions. Additionally, connectors, flanges, and valves consistently emerged as the sealing point types with the highest contributions, accounting for 94.8% to 98.1% of the total.

3.3. VOC mitigation from stable implementation of LDAR

Fig. 6 illustrates the VOC mitigation of equipment leaks in petroleum refineries achieved from LDAR programs. The stable implementation of LDAR at the enterprise-level petroleum refining facility led to an overall VOC emission reduction of approximately 29.1 tons/year, with an emission reduction rate of around 40.5%. This 40.5% VOC emission reduction rate observed after LDAR implementation is consistent with the findings reported in previous studies on the petroleum refining industry (30%–50%) (Ding et al., 2014; Sun et al., 2023; Xu, 2024). The VOC emission reductions by individual production units show that the stable implementation of LDAR programs led to varying degrees of VOC emission reductions from equipment leaks across the different production units, with reduction rates ranging from 9.2% to 76.5% (Fig. 6(a)). Specifically, the SCU, KHU, MTBE, and CDU units achieved the highest reduction rates, all exceeding 50%. These results indicate that the effectiveness of the LDAR program was influenced by the specific characteristics and emission sources within each production unit.

An analysis of the contributions of different production units to the total VOC emission reduction from equipment leaks reveals that the KHU, CRU, DCU, ARC, and HCU units were the top five contributors, accounting for a cumulative 70.3% of the total emission reduction. While the SCU exhibited the highest individual VOC emission reduction rate at 76.5%, its contribution to the total emission reduction was only 6.0%. In contrast, units like KHU, DCU, and CRU demonstrated both high reduction rates as well as substantial contributions to the overall emission reductions, making them the production units that achieved the greatest benefits from the LDAR program implementation. This finding highlights the importance of considering both the individual unit-level reduction rates as well as the relative contributions of each production unit when evaluating the overall effectiveness of LDAR implementation strategies. Such a comprehensive assessment can

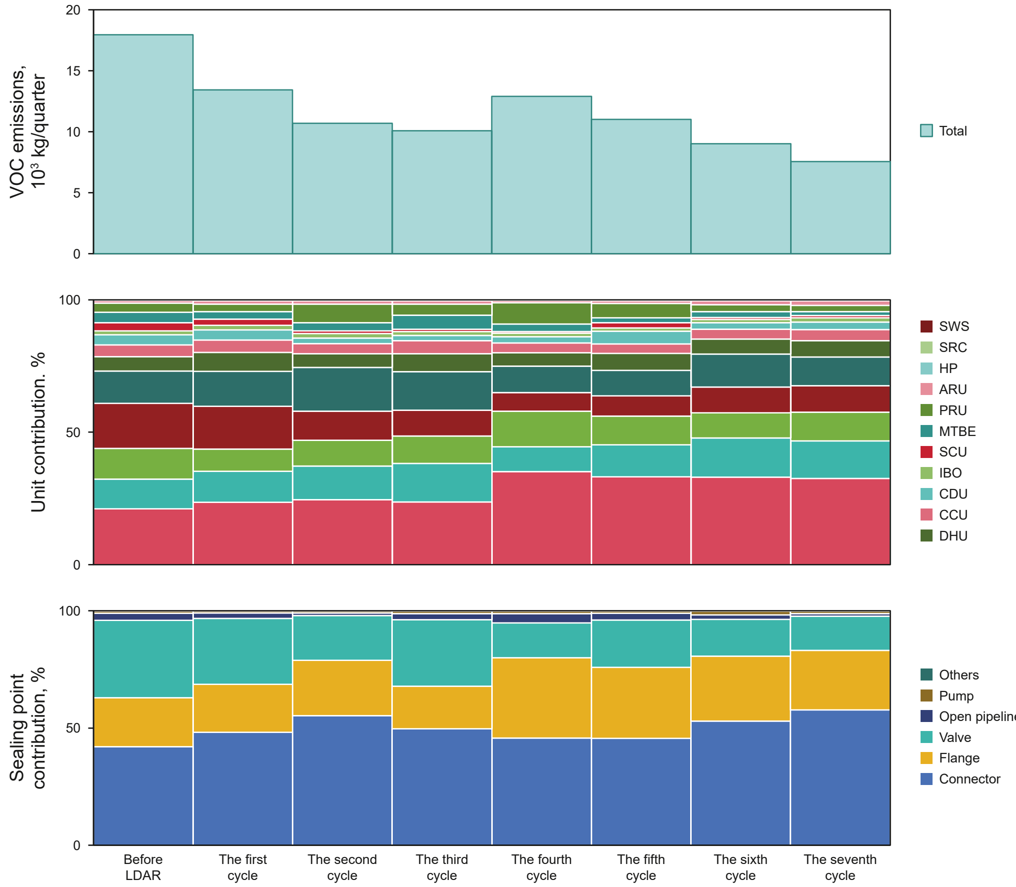

Fig. 5. Characteristics of VOC emissions before and during different periods of LDAR implementation; abbreviations for production devices are defined in Table 1.

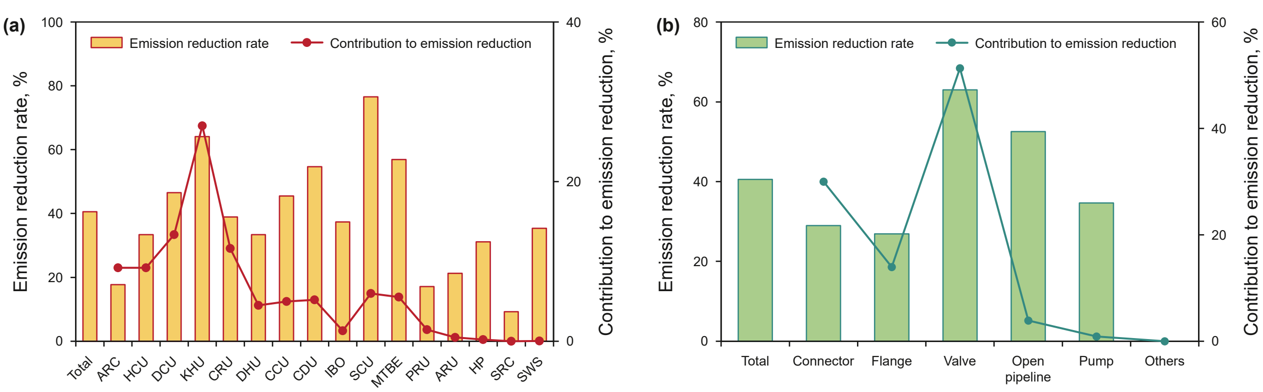

Fig. 6. VOC emission reduction from equipment leaks in petroleum refining before and after LDAR implementation. (**a**) Emission reduction by different production units; Abbreviations for production devices are defined in Table 1; (**b**) emission reduction by different types of sealing points.

help identify the critical emission sources and target the most impactful interventions to maximize the VOC emission reduction benefits.

The VOC mitigation achieved from equipment leaks was also analyzed according to the type of sealing point (Fig. 6(b)). The reduction rates varied significantly across the different sealed unit types, ranging from 0% to 63.0%. Notably, valves and open pipelines exhibited the highest reduction rates, both exceeding 50%. Further analysis of the contributions of each sealing point type to the total VOC emission reduction from equipment leaks revealed that valves and connectors were the top contributors, accounting for 51.3% and 30.0% of the total reduction, respectively. The substantial contributions of Valves and Connectors to the overall emission reduction underscore the importance of strategically targeting these critical equipment types during LDAR implementation to maximize the VOC mitigation benefits across the industrial facility.

Table 4
VOC emission factors of equipment leakage before and after LDAR implementation.

Units	EFs based on the number of sealing points, g/(pcs·quarter)		EFs based on raw material processing, kg/(10,000 tons ·quarter)	
	Before LDAR	After LDAR	Before LDAR	After LDAR
ARC	36.86	30.34 ± 7.46	47.22	38.86 ± 9.56
HCU	35.02	23.34 ± 2.89	5.01	3.34 ± 0.41
DCU	41.54	22.21 ± 6.06	4.96	2.65 ± 0.72
KHU	64.41	23.15 ± 10.32	8.51	3.06 ± 1.36
CRU	49.56	30.29 ± 8.23	10.85	6.63 ± 1.80
DHU	33.25	22.16 ± 5.53	4.89	3.26 ± 0.81
CCU	38.95	21.22 ± 5.27	6.63	3.61 ± 0.90
CDU	50.73	22.99 ± 10.61	0.58	0.26 ± 0.12
IBO	29.68	18.60 ± 5.09	6.43	4.03 ± 1.10
SCU	106.44	24.99 ± 17.19	/	/
MTBE	158.10	68.18 ± 31.84	117.86	50.83 ± 23.74
PRU	138.68	114.97 ± 67.57	20.52	17.01 ± 10.00
ARU	41.97	33.04 ± 4.17	4.78	3.76 ± 0.47
HP	51.99	35.79 ± 8.71	2.99	2.06 ± 0.50
SRC	20.81	18.89 ± 4.31	1.13	1.03 ± 0.23
SWS	21.61	13.96 ± 4.27	0.02	0.02 ± 0.01
Enterprise-level	45.63	27.14 ± 5.23	14.95	8.89 ± 1.71

3.4. VOC emission factors before and after LDAR implementation

Table 4 presents the VOC emission factors of equipment leakage at both the production unit and enterprise levels, before and after LDAR program implementation. Emission factors are reported in two contexts: (1) based on the number of sealing points, and (2) based on the raw material or product processing capacity. Following stable LDAR program implementation, VOC emission factors decreased at both enterprise and production unit levels compared to pre-implementation levels. Specifically, VOC emission factors decreased by approximately 40.5% at the enterprise level and by 9.2% to 76.5% at the production unit level. This significant variation in reduction rates across different units can be attributed to several factors. The primary reason is the difference in the pre-LDAR contribution of leak-related emissions. Units with a higher initial proportion of emissions from leaks, such as the DCU, SCU, and MTBE, demonstrated greater potential for reduction, resulting in higher percentage decreases. Furthermore, unit-specific conditions, such as a high propensity for new leaks (e.g., the high-pressure PRU) and variations in repair effectiveness, also modulated the final reduction rates observed. This underscores that a nuanced, unit-specific approach is essential for optimizing LDAR programs, moving beyond a one-size-fits-all strategy.

The VOC emission factors based on the number of sealing points showed that the enterprise-level VOC emission factor was 45.63 g/(pcs·quarter) before LDAR implementation, which decreased to 27.14 ± 5.23 g/(pcs·quarter) after LDAR implementation. Among individual production units, the MTBE, PRU, and SCU units had the highest VOC emission factors, exceeding 100 g/(pcs·quarter) before LDAR implementation. However, following stable LDAR implementation, the PRU (114.97 ± 67.57), MTBE (68.18 ± 31.84), and ARC (30.34 ± 7.46) units had the largest emission factors. Considering that LDAR efforts primarily target identifying and repairing leaking sealing points in production units, these findings suggest that the effectiveness of LDAR implementation in reducing VOC emissions can vary significantly among different production units. The varying degrees of emission reduction highlight that the efficacy of LDAR programs may hinge on the unique processed raw material and operational attributes of each production unit within the enterprise. This is well exemplified by the PRU (Pressurized Refining Unit), which exhibited the highest post-LDAR emission factor. The PRU's process, involving the high-purity separation of light hydrocarbons, requires operation at high pressures (e.g., 1.5–2.0 MPa in the depropanizer tower) to maintain these components in a liquid state. This combination of highly volatile materials and severe operating conditions creates an inherent propensity for leaks to develop continuously. Consequently, although each LDAR cycle effectively repairs existing leaks, new leaks frequently emerge, leading to a higher time-averaged emission factor over multiple cycles. This case underscores that unit-specific characteristics are a primary determinant of LDAR effectiveness. The VOC emission factors based on raw material or product processing amount indicated that the enterprise-level VOC emission factor was 14.95 kg/(10,000 tons·quarter) before LDAR implementation, which decreased to 8.89 ± 1.71 kg/(10,000 tons·quarter) after stable LDAR implementation. Among individual production units, the MTBE, ARC, and PRU units consistently had the highest VOC emission factors both before and after LDAR implementation.

Interestingly, despite the reduction in emission factors across all production units following LDAR implementation, the upper limits of emission factors for certain units, such as ARC, PRU, and SRC, may surpass those observed prior to LDAR implementation. This phenomenon is primarily attributed to two factors: First, the persistent effects of mechanical shock and material corrosion progressively degrade the sealing efficacy of equipment, might resulting in an increased number of leakage points identified during each inspection cycle. Second, the limitations of current maintenance techniques prevent the complete remediation of all leakage points during each maintenance cycle without a shutdown of the production unit. The emergence of these random leakage points and the inability to repair certain leakage points within a specific timeframe indicate that, for some units, the VOC emissions during certain periods post-LDAR implementation may exceed the levels recorded before the implementation of LDAR. Additionally, it should be noted that, considering the uncertainties associated with the application of different emission factors, it is recommended to prioritize the use of VOC emission factors based on the number of sealing points, rather than those based on raw material or product processing amounts, depending on the availability of actual activity data. Furthermore, when available, the production unit-level VOC emission factors should be prioritized over the enterprise-level VOC emission factors.

3.5. VOC mitigation, OFP and SOAP in petroleum refining for Guangdong

The quantification of province-wide LDAR effectiveness for Guangdong requires a clear definition of the implementation period. This study defines the baseline (pre-LDAR) and assessment (post-LDAR) periods based on key regulatory milestones: the

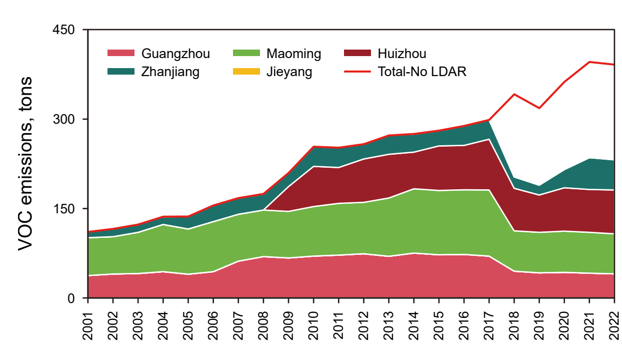

Fig. 7. VOC emission characteristics from equipment leaks of petroleum refining industry in Guangdong for the period of 2001–2022.

mandate from the national standard GB 31570-2015 (effective July 2017) (MEEPPRC, 2015) and the technical details from Guangdong's 2016 specifications (DEEGP, 2016). The period before 2018 is characterized as a preliminary phase with inconsistent implementation, while stable and effective VOC reduction began around 2018. Therefore, our estimation of VOC emissions from 2001 to 2022 (Fig. 7) uses this regulatory context to interpret the trends, combining crude oil processing data and our derived emission factors.

The VOC emissions from equipment leaks in the petroleum refining industry of Guangdong exhibited a trend of initial increase, followed by a decrease, and then a subsequent increase during the period from 2001 to 2022. The VOC emissions reached a maximum peak value of 298.7 tons in 2017. Since 2018, due to the stable implementation of LDAR programs, the VOC emissions from equipment leaks have rapidly decreased. After 2020, as the crude oil processing capacity increased, the VOC emissions from equipment leaks have begun to rise again, reaching 232.7 tons in 2022. In 2022, in terms of the city-level contributions to VOC emissions from equipment leaks in the petroleum refining industry, Huizhou, Maoming, and Zhanjiang were the top three contributing cities, accounting for 31.6%, 28.8%, and 21.8% of the total emissions, respectively. Compared to the scenario without LDAR implementation, the VOC emission reductions from equipment leaks in Guangdong's petroleum refining industry attributable to the LDAR implementation were 129.0 to 160.5 tons during the 2018–2022 period.

The OFP_{EI} and $SOAP_{EI}$ from equipment leaks in the petroleum refining industry were determined to be 3.87 $gO_3/gVOC$ and 0.01 gSOA/gVOC. The OFP_{EI} value is notably higher than the range observed in the other industries (0.11–2.91 $gO_3/gVOC$), as visually presented in the new Fig. 8. This difference underscores that per unit of VOC emitted, fugitive leaks from petroleum refining possess a significantly greater potential for ozone formation compared to many other anthropogenic sources. The primary reason is likely the distinct VOC speciation profile and their different photochemical reactivities. This analysis strongly emphasizes the unique and potent environmental impact of VOC leaks from refining equipment, thereby highlighting the critical importance of targeted LDAR programs not just for mass reduction but also for mitigating secondary pollution like ozone. The total OFP and SOAP from equipment leaks in the petroleum refining industry of Guangdong in 2022 were 901.0 and 2.1 tons. Compared to a scenario where LDAR was not implemented, LDAR implementation resulted in an approximate 68.2% reduction in OFP and SOAP. The largest chemical groups to OFP were alkenes/alkynes, accounting for 60.2%, followed by aromatics and alkanes, which contributed 21.3% and 14.8%, respectively. In contrast, aromatics were the primary contributors to SOAP, comprising 86.4% of the total SOAP emissions, followed by alkanes at 12.1%. Propylene, 1-butene, m-xylene, ethylene, and p-xylene were the top five species contributing to OFP, collectively accounting for 70.0% of the total emissions. In contrast, toluene, ethylbenzene, m-xylene, p-xylene, and styrene represented the leading five contributors to SOAP, together comprising 76.5% of the total SOAP. These species were the key VOCs targeted for equipment leak control in petroleum refining.

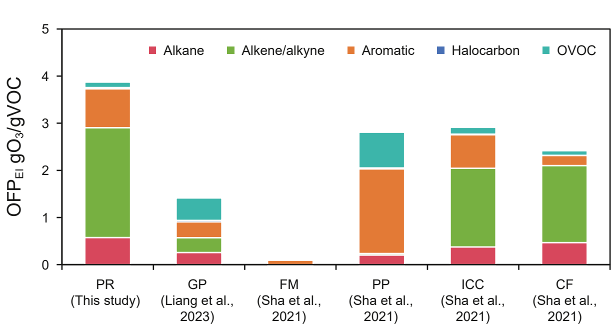

Fig. 8. Comparison of OFP_{EI} from equipment leaks in the petroleum refining industry with other industries: PR =Petroleum refining; GP = Gravure printing; FM=Furniture manufacturing; PP=Paint production; ICC=Industrial coal combustion; CF=Cooking fumes.

3.6. Policy implications

Based on the analysis of the VOC emission characteristics and emission reduction during the long-term implementation of LDAR in the oil refining enterprise, the following three recommendations are proposed for the optimization of future LDAR implementation policies:

Firstly, emphasize the quality control and assurance of LDAR detection data. Accurate and reliable detection data is essential for the effective implementation of LDAR and serves as a crucial basis for calculating the total amount of VOC emissions and managing pollutant discharge permits (Liu et al., 2017). Leak points are the primary targets for both VOC emissions (Fig. 2) and LDAR repairs. Special attention should be given to the data quality assessment of sealing points with detection concentrations approaching or exceeding the leakage threshold, and strict requirements should be imposed on the error range of spot checks for this data range.

Secondly, establish a refined LDAR work plan that integrates production units and sealing points. To achieve this, we propose a tiered approach based on our findings: (1) Differentiated monitoring frequencies for production units: Allow enterprises to apply for unit-specific frequencies based on historical leak data. For instance, units with high leak propensity (e.g., KHU) should be monitored more frequently, while low-risk units (e.g., IBO, SWS) could be monitored less often. (2) Priority-based inspection for sealing point types: Implement a risk-based strategy where components with higher leak rates (e.g., valves, open-ended lines, pumps) are inspected more frequently than those with lower rates (e.g., flanges, connectors), an approach consistent with the rationale behind existing standards (MEEPPRC, 2015). (3) Exemption list for low-risk streams: Establish a list to exempt sealing points containing materials with very low volatility (e.g., lubricating oils) from mandatory detection, thereby optimizing resource allocation without compromising environmental goals.

Thirdly, conduct LDAR work on a regular and continuous basis. Despite the repairs made each time, the continuous operation of production facilities and the aging of equipment and components can cause new leaks (Fig. 4). Failure to promptly address these leaks may negate the efficacy of prior LDAR efforts and result in an increased emission of VOCs. Hence, LDAR is not a one-time task but requires regular and sustained implementation to ensure the continuous reduction of VOC emissions.

4. Conclusions

Through the investigation of the continuous implementation of LDAR in a petroleum refining enterprise, this study explored variations in VOC emission characteristics from equipment leaks at different periods of implementation. The VOC mitigation from the enterprise equipment leaks with LDAR application were evaluated and VOC emission factors at production unit-level and enterprise-level were established. Finally, the VOC mitigation, OFP and SOAP of LDAR application from petroleum refining in Guangdong, China was assessed.

Specifically, the long-term implementation of LDAR at the enterprise-level petroleum refining resulted in an approximately 40.5% reduction in overall VOC emissions. KHU, CRU, DCU, ARC, and HCU were the top five units for emission reduction, accounting for a cumulative 70.3% of the total reduction. Valves and connectors were the top contributors, together accounting for 81.3% of the total reduction. The enterprise-level VOC emission factor based on the number of sealing points was 45.63 g/(pcs·quarter) before LDAR, which reduced to 27.14 ± 5.23 g/(pcs·quarter) following LDAR implementation. Meanwhile, the VOC emission factors based on raw material or product processing amount showed a reduction from 14.95 kg/(10,000 tons·quarter) before LDAR implementation to 8.89 ± 1.71 kg/(10,000 tons·quarter) after stable LDAR implementation. VOC mitigation from equipment leaks in Guangdong's petroleum refining industry attributable to the LDAR implementation were 129.0 to 160.5 tons during the 2018–2022 period. The long-term LDAR implementation also resulted in an approximate 68.2% reduction in OFP and SOAP. Alkenes/alkynes made the largest contribution to OFP, while aromatics comprised the most significant portions of SOAP. The following three suggestions were put forward for the optimization of future LDAR implementation policies: to strengthen quality control and assurance of LDAR detection data; to establish a well-defined LDAR work plan that integrates production units with sealing points; and to implement LDAR work on a regular and continuous basis.

The generalizability of the VOC emission factors and emission reduction benefits reported in this study must be qualified by two essential conditions: the stringent QA/QC procedures that safeguard data integrity (Section 2.2) and the sustainable, ongoing implementation of the LDAR work, which together ensure the validity and reliability of the outcomes.

CRediT authorship contribution statement

Xi-Bo Sun: Writing – original draft, Methodology, Investigation, Formal analysis. **Cheng-Hao Liao:** Investigation. **Zhi-Yang Liu:** Investigation. **Yong-Bo Zhang:** Supervision, Funding acquisition. **Xiao-Ming Liang:** Writing – review & editing, Supervision. **Li-Min Chen:** Supervision. **Dai-Qi Ye:** Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.petsci.2026.03.008.

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