



Real-world emission factors and inhalation health risks of PM-bound metals from workboats using ultra-low sulfur marine fuel

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ABSTRACT

The use of ultra-low sulfur fuels has become an important policy implemented by international ports to reduce ship-related pollution. However, their emission factors and associated health risks have rarely been evaluated. This study presents on-board measurements of gaseous, particulate, and metal emissions from three workboats operating on ultra-low sulfur marine fuels under berthing conditions in Kaohsiung Port. Fuel-based emission factors were derived, and potential non-cancer and cancer risks associated with inhalation exposure were quantified to assess implications for port-area air quality and public health. NO_x concentrations ranged from 167.41 ± 5.72 to 660.00 ± 27.60 ppm, with NO as the dominant species, while SO₂ (0.13 ± 0.02–6.70 ± 0.69 ppm) and CO (103.08 ± 17.28–344.39 ± 116.40 ppm) reflected variations in fuel sulfur content and combustion efficiency. PM₁₀ concentrations (2.06 ± 1.10–7.17 ± 0.80 mg/m³) were dominated by submicron particles (<1.0 μm). Major metals included Fe, Na, Zn, Ca, and Cr, primarily from fuel and lubricants. Fuel-based emission factors were 6.86–26.33 g/kg-fuel for NO_x, 0.20–1.86 g/kg-fuel for SO₂, 3.87–12.77 g/kg-fuel for CO, 3141.53–3166.62 g/kg-fuel for CO₂, and 0.72–5.11 g/kg-fuel for TSP. Health risk assessment revealed that Cr dominated both carcinogenic and non-carcinogenic risks. The total CR of individual vessels exceeding 1.00 × 10⁻⁶, which is generally considered the lower end of acceptable risk (typical range 1.00 × 10⁻⁶ to 1.00 × 10⁻⁴). These results indicate that although sulfur emissions are significantly reduced, potential carcinogenic risks may persist from ship emissions.

1. Introduction

Ports are critical nodes of global trade but also major hotspots of air pollution due to intensive vessel traffic, frequent maneuvering, auxiliary engine operation, and prolonged berthing. Emissions from ships, including sulfur oxides (SO_x), nitrogen oxides (NO_x), particulate matter (PM), black carbon (BC), volatile organic compounds (VOCs), and carbon dioxide (CO₂), have been widely reported to degrade air quality in port-adjacent regions and contribute to both local health impacts and global climate forcing (Han et al., 2023; Wu et al., 2021; Zhang et al., 2024). Elevated concentrations of NO_x, SO₂, and PM in harbor areas

are commonly associated with heavy fuel oil combustion, bunkering activities, and auxiliary engine use during berthing (Jang et al., 2023; Ledoux et al., 2018; Sinha et al., 2003; Tseng et al., 2021). Globally, international shipping accounted for approximately 20% of anthropogenic NO_x emissions and 12% of SO₂ emissions in 2017, with nearly 70% of ship-related emissions occurring within 400 km of coastlines, resulting in substantial public health burdens (McDuffie et al., 2020). In Europe, maritime transport contributed 24% of total NO_x, 24% of SO_x, and 9% of PM_{2.5} emissions in 2018, affecting nearly 40% of residents living within 50 km of the coastline (Yu et al., 2025). Episodic port congestion can further exacerbate these impacts, as demonstrated

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during the COVID-19 supply chain disruption in Los Angeles, where ship emissions increased NO₂ by up to 28% and raised PM_{2.5} concentrations by as much as 4.5 µg/m in nearby communities (Skipper et al., 2024).

Inhalation is the dominant exposure pathway to ship-related air pollutants, and fine particulate matter (PM_{2.5}) has been recognized since the early 21st century as a critical threat to human health (He et al., 2017). Epidemiological and toxicological studies have linked shipping emissions to premature mortality, aggravated asthma, cardiovascular stress, and other adverse outcomes, particularly in densely populated coastal regions (Broome et al., 2016; Mueller et al., 2023; Pillariseti et al., 2019; Sun et al., 2025). NO_x and SO_x emissions are of particular concern because they promote the formation of acidic secondary PM_{2.5}, intensifying respiratory and cardiovascular diseases among port residents (Viana et al., 2020). Moreover, PM_{2.5} generated from marine fuel combustion exhibits enhanced biotoxicity compared with other urban sources (Bendl et al., 2024; Wu et al., 2018). Long-term exposure to elevated PM_{2.5} levels can induce oxidative stress, inflammation, and DNA damage, ultimately contributing to disease progression (Luo et al., 2023). The presence of toxic heavy metals further amplifies health risks (Chen et al., 2024). For instance, arsenic increases cardiovascular risks (Qi et al., 2024), while metals such as Cr, Co, Pb, Cd, and Ni are toxic even at trace levels, bioaccumulate in the human body, and cause chronic health effects, including neurotoxicity, carcinogenesis, and systemic poisoning (Fang et al., 2013; Wang et al., 2022).

Kaohsiung Port is the largest harbor in Taiwan, covering 17,736 ha and accommodating up to 152 vessels simultaneously across 145 terminals and 19 mooring buoys (Taiwan International Ports Corporation, 2025). Although shore power facilities have been installed at selected terminals, limited adoption has resulted in continued reliance on auxiliary engines during berthing, making ship emissions a persistent and significant source of urban air pollution. Consequently, shipborne emissions persist as a major local pollution source, contributing significantly to urban air quality degradation and associated public health risks. Previous studies have shown that vessel main and auxiliary engines contribute measurably to PM_{2.5} concentrations in surrounding metropolitan areas, with local meteorology such as sea breezes facilitating pollutant transport inland (Tseng et al., 2024).

On-board measurements are increasingly recognized as the most reliable approach for quantifying real-world vessel emissions. Zhang et al. (2016) characterized gaseous and particulate pollutants from Chinese coastal vessels (Zhang et al., 2016), while Zhang et al. (2024) demonstrated that vessels using low-sulfur fuel emitted 48% more VOCs than those burning heavy fuel oil, increasing ozone and secondary organic aerosol formation (Zhang et al., 2024). Emission inventories based on conventional assumptions may substantially underestimate actual emissions, as shown for Qingdao Port (Yang et al., 2023). The chemical complexity of vessel exhaust has also been investigated, including the presence of toxic transition and alkaline earth metals in ultrafine particles (Moldanová et al., 2009) and strong dependencies on fuel type and engine load (Sinha et al., 2003). More recent work has examined exhaust aerosol properties across emission control systems (Kuittinen et al., 2024) and evaluated carcinogenic and non-carcinogenic risks of PM-bound metals from different vessel types (Wen et al., 2018). Our previous study quantified fishing boat emissions across Taiwan based on actual measurements (Chien et al., 2025). In recent years, ultra-low sulfur marine fuel policies have been implemented in international ports to mitigate environmental pollution. Nevertheless, empirical data on emission factors and associated health risks under these fuel regimes remain limited.

In this study, portable emission measurement systems were deployed to characterize real-world emissions from three workboats (one research vessel and two tugboats) operating on ultra-low sulfur marine fuel under berthing conditions in Kaohsiung Port. The objectives were to (i) quantify gaseous and particulate emissions under these specific operating conditions; (ii) characterize PM metal composition; and (iii) assess carcinogenic and non-carcinogenic health risks associated with PM-

bound metals within this study context.

2. Experimental methods

2.1. Test vessels and operating mode

Port workboats using ultra-low sulfur marine fuels (S<0.10%) with extended berthing durations and relatively stable emission characteristics were selected to obtain representative emission data for auxiliary engine (AE) operation during berthing. The tested vessels included one research vessel and two tugboats, which are commonly operated in Kaohsiung Port. Their technical specifications and berthing operating conditions are summarized in Table 1. Detailed information is shown in Supplementary Material (S2.1).

2.2. Fuel parameters of test vessels

The physical and chemical properties of the ultra-low sulfur marine fuels (marine gas oil, MGO) used by the tested vessels are summarized in Table S1. All vessels operated on ultra-low sulfur MGO with a density below 0.850 kg/L and a sulfur content of less than 0.10%, indicating compliance with the International Maritime Organization (IMO) emission control area (ECA) sulfur limit for marine fuels (IMO, 2020). Moreover, a 1 L MGO sample was collected for metal analysis of carbon (C), hydrogen (H), oxygen (O), nitrogen (N), and sulfur (S). The analysis indicated that the MGO contained 86.60% C, 13.37% H, and 0.04% S by mass, while O and N were not detected. In addition, 1 L of MGO and lubricating oil samples were collected from the tested vessels and analyzed for metal composition by a certified laboratory. Detailed information is provided in the Supplementary Material (S2.2).

2.3. Online measurement instruments and sample analysis

Gaseous compounds (including NO, NO_x, SO₂, CO, CO₂, and O₂) were measured using a Belltone BE-500 S/Pro analyzer (Belltone, Taiwan). Particulate matter (PM₁, PM_{2.5}, PM₄, and PM₁₀) was characterized using a Palas Fidas Frog analyzer (Palas, Germany), equipped with a Palas VKL dilution system (with a dilution ratio of 1:163). Exhaust opacity was continuously monitored using a Belltone OPA-550 analyzer (Belltone, Taiwan). The average background concentrations for PM are presented in Table S2, while the specific measurement ranges and technical specifications for PM and gaseous species are summarized in Table S3.

TSP and PM_{2.5} samples were collected on Teflon filters at a constant flow rate for subsequent metals analysis. Specifically, TSP samples were collected using a Gil Plus sampler (Sensidyne, USA) operated at a constant flow rate of 3 L/min with a two-stage filter cassette (SKC, USA). PM_{2.5} samples were collected using a Leland Legacy sampler (SKC, USA) operated at a constant flow rate of 9 L/min, equipped with a five-stage size-selective sampler (SKC, USA).

Table 1
Technical parameters and operational conditions of the tested vessels.

Item	Vessel A	Vessel B	Vessel C
Year Built	2019	2002	1976
Gross Tonnage	811	1864	1741
Vessel Type	Research vessel	Tugboat	Tugboat
Length, Overall (m)	45.0	64.3	64.7
Breadth, Moulded (m)	11.2	15.0	13.0
Draft, Moulded (m)	3.5	5.7	5.2
Max. Speed (knots)	14	15	14
Generator Rated Power (kW)	600 * 4 units	210 * 2 units	210 * 2 units
Berthing Load (%)	23	35	35
Exhaust Temperature (°C)	270	320	300
Operating Mode	Berthing	Berthing	Berthing
Sampling Target	AE	A.E.	A.E.
Fuel Type	MGO	MGO	MGO

Metal concentrations were determined using inductively coupled plasma mass spectrometry (ICP-MS, Agilent 7900, USA). Calibration was performed using multi-element standard solutions (AccuStandard, USA). QA/QC procedures included assessment of relative percent difference (RPD), control sample recovery, spike recovery, and drift in continuing calibration verification (CCV). Specifically, the RPD for duplicate analyses was within 5%, while recoveries for control samples and spike samples ranged from 80% to 120%. The CCV drift was maintained within 10% throughout the analytical process. Calibration curves for all target metals exhibited excellent linearity, with correlation coefficients (R) and coefficients of determination (R^2) both greater than 0.995. Quantification detection limits (QDLs) for individual metals were also reported. Detailed QA/QA data are summarized in Table S4. Additional technical details are provided in the Supplementary Material (S2.3).

2.4. Data analysis

2.4.1. Fuel-based emission factor

Emission factors (EFs) were calculated using the carbon balance method following the approach proposed by Zhang et al. (2024). Detailed information is shown in Supplementary Material (S2.4.1).

2.4.2. Gaussian plume model

The Gaussian Plume Model was applied to simulate the dispersion of exhaust plumes emitted from marine vessels during berthing. Pollutant concentrations were calculated using the following formula:

$$C(x, y, z, H) = \frac{Q}{2\pi\sigma_y\sigma_zU} \times \exp\left[-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right] \times \left\{ \exp\left[-\frac{1}{2}\left(\frac{z-H}{\sigma_z}\right)^2\right] + \exp\left[-\frac{1}{2}\left(\frac{z+H}{\sigma_z}\right)^2\right] \right\} \quad (1)$$

where C is the pollutant concentration ($\mu\text{g}/\text{m}^3$) at coordinate (x, y, z) ; σ_y and σ_z are the Pasquill-Gifford diffusion coefficients in horizontal and vertical directions (m), respectively, which depend on atmospheric stability class; U is the ambient wind speed (m/s); Q is the emission rate ($\mu\text{g}/\text{s}$); H is the stack effective height (m).

In this study, σ_y and σ_z were calculated using the parameterizations $\sigma_y = 0.22x/(1 + 0.0001x)^{0.5}$ and $\sigma_z = 0.20x$, where x represents the downwind distance (35 m). These formulations were adopted from Liu and Wang (2022), which provide dispersion coefficients under different atmospheric stability conditions (Liu and Wang, 2022). They are widely used and provide a conservative estimate for dispersion modeling. Additionally, since the exhaust stacks of the tested vessels are horizontally bent, plume rise was not explicitly considered.

Five metals (Cr, Ni, Pb, Co, and Cd) with high environmental toxicity were selected for dispersion modeling. Specifically, Cr, Ni, and Cd were prioritized as they are classified as Group 1 carcinogens by the International Agency for Research on Cancer (IARC), representing the highest level of cancer risk, while Pb and Co (Group 2) were included due to their significant non-cancer health implications. Their respective emission rates are summarized in Table S5. The parameters for ambient wind speed, solar radiation, and atmospheric stability class are summarized in Table S6. Detailed information is shown in Supplementary Material (S2.4.2).

For a conservative risk assessment, all measured Cr were assumed to be Cr(VI), the primary carcinogenic driver. This assessment focuses exclusively on the inhalation pathway, the dominant exposure route for airborne trace metals from ship emissions. This study aimed to evaluate the potential inhalation health risks associated with exhaust emissions from workboats operating on ultra-low sulfur fuel under berthing conditions in Kaohsiung Port. Since the maximum ground-level concentration represents a worst-case exposure scenario, the metal inhalation risk assessment was conducted at the location of the maximum ground-level concentration to provide an upper-bound estimate of potential health

risks within the scope of this study.

2.4.3. Average daily dose

Based on the ground-level concentrations estimated using the Gaussian Plume Model, the lifetime average daily dose via inhalation (LADD) was calculated as:

$$\text{LADD} = \frac{C \times \text{IR} \times \text{CF} \times \text{ED} \times \text{EF}}{\text{AT} \times \text{BW}} \quad (2)$$

where LADD ($\text{mg}/\text{kg}\cdot\text{day}$) represents the average daily inhalation dose over a lifetime. C denotes the modeled ground-level concentration (mg/m^3), assuming continuous exposure at this concentration. The inhalation rate (IR) was set to $20 \text{ m}^3/\text{day}$, following the U.S. Environmental Protection Agency (USEPA) reference value (USEPA, 1991). The conversion factor (CF) was taken as 1, as all conversions took place prior to calculations. The exposure duration (ED) was set at 81 years, corresponding to the average life expectancy in Taiwan (Taiwan Clinical Trials, 2024). Because port residents and workers are assumed to experience chronic exposure, the exposure frequency (EF) was assumed to be 365 d/yr. The averaging time (AT) was calculated as 81 years $\times$ 365 d/yr. Body weight (BW) was set to 70 kg, representing the average adult body weight in Taiwan.

2.4.4. Non-cancer risk assessment

Non-cancer risk associated with inhalation exposure to heavy metals was determined by hazard quotient (HQ), calculated as:

$$\text{HQ} = \frac{\text{LADD}}{\text{RfD}} \quad (3)$$

where HQ represents the non-cancer risk from inhalation exposure to a specific heavy metal, RfD is the inhalation reference dose ($\text{mg}/\text{kg}\cdot\text{day}$). Reference dose values for the analyzed metals are summarized in Table S7. The RfD values were obtained from the USEPA IRIS database (USEPA, 2026). For Pb, RfD values are not available in the IRIS database; therefore, values from Zhang and Aikawa (2023) were referenced (Zhang and Aikawa, 2023).

2.4.5. Cancer risk assessment

The cancer risk (CR) associated with inhalation exposure to individual heavy metals was estimated as:

$$\text{CR} = \text{LADD} \times \text{SFI} \quad (4)$$

where CR is the lifetime excess cancer risk due to inhalation exposure; SFI is the inhalation cancer slope factor ($\text{mg}/\text{kg}\cdot\text{day}$) of each metal (refer to Table S7). SFI values for specific metals were primarily based on the values reported by Wen et al. (2018) (Wen et al., 2018).

3. Results and discussion

3.1. Gaseous emissions under steady-state load conditions

Fig. 1 presents the average concentrations of conventional gaseous substances (NO , NO_x , SO_2 , CO , and O_2) measured online from the tested vessels under steady-state berthing conditions. Among the three vessels, vessel C exhibited the highest NO_x concentration, followed by vessels B and A, with NO_x levels ranging from 167.41 ± 5.72 to 660.00 ± 27.60 ppm. NO_x formation is governed by multiple factors, including intake air temperature, humidity, pressure, air-fuel ratio, injection timing, and combustion chamber design, with cylinder temperature playing a dominant role in thermal NO formation (Zhang et al., 2018). Although vessel A is equipped with the highest-rated auxiliary engine power, its relatively lower NO_x emissions can be attributed to a newer engine and a lower operational load ($\sim 23\%$) during berthing. Additionally, the measured NO/NO_x ratios were close to unity for all vessels, indicating that NO was the dominant nitrogen oxide species under these operating

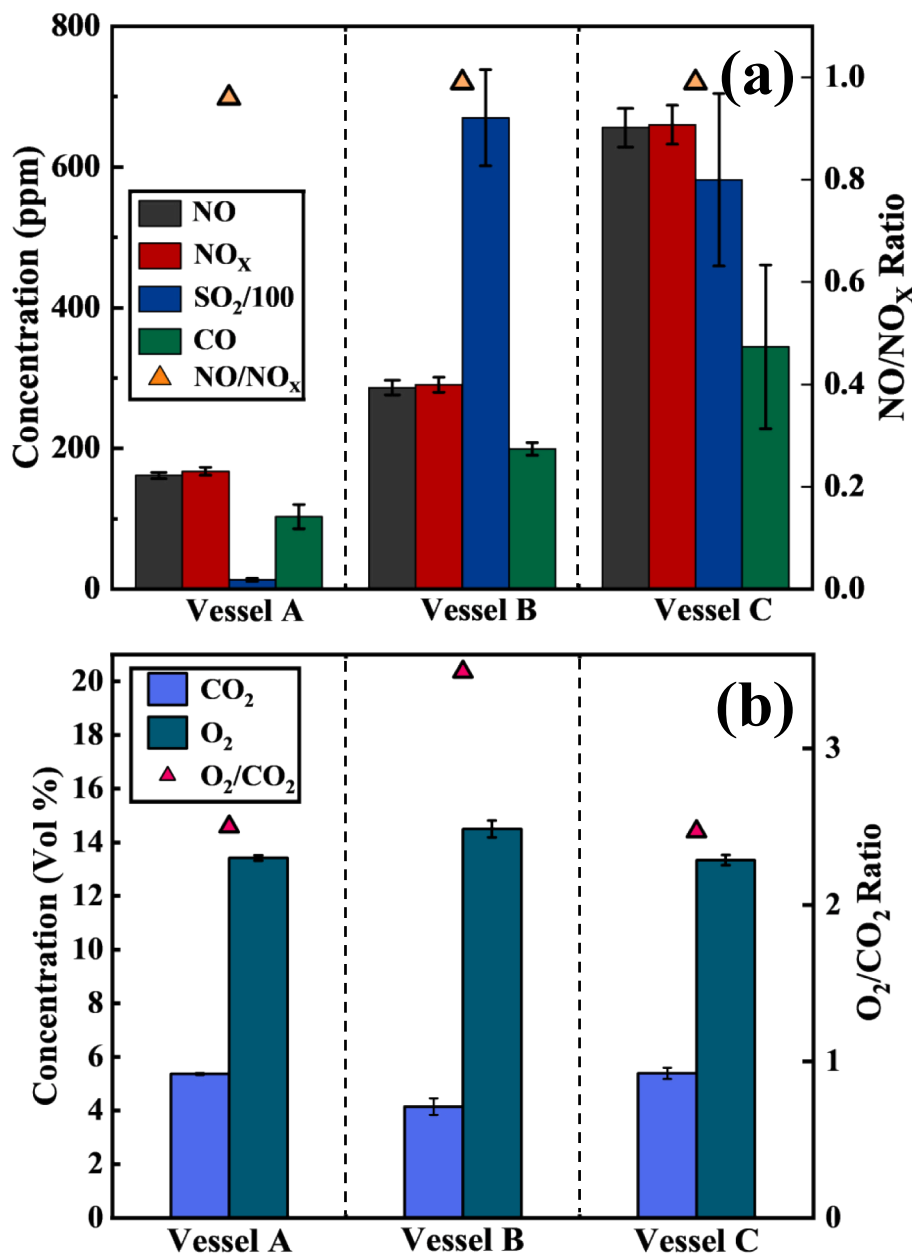


Fig. 1. Gaseous emissions concentration from AE of the tested vessels during berthing: (a) NO, NO_x, SO₂, and CO; (b) CO₂ and O₂.

conditions.

The average SO₂ concentrations were lowest for vessel A (0.13 ± 0.02 ppm), followed by vessel C (5.82 ± 1.23 ppm) and vessel B (6.70 ± 0.69 ppm). These differences primarily reflect variations in sulfur input to the engine system. Previous studies have shown that over 90% of the sulfur in marine fuels is converted to SO₂ during combustion (Zhao et al., 2020). Furthermore, SO₂ emissions may also arise from lubricating oil consumption, which is particularly relevant for older engines with higher oil usage rates (Juwono et al., 2013). As a result, SO₂ emissions are influenced by both fuel properties and engine condition.

The average CO concentrations among the tested vessels ranged from 103.08 ± 17.28 to 344.39 ± 116.40 ppm. CO is a product of incomplete combustion and is strongly affected by local oxygen availability, combustion temperature, and residence time (Yang et al., 2023). During berthing, auxiliary engines typically operate at low loads, resulting in lower in-cylinder temperature and less fuel-air mixing. These conditions promote oxygen-deficient zones and incomplete oxidation, favoring CO formation over complete conversion to CO₂. Therefore, CO

concentrations would decrease during cruising operations, when higher loads and improved engine combustion efficiency enhance fuel oxidation.

Fig. 1(b) shows that the average CO₂ emission concentrations ranged from $4.15 \pm 0.31\%$ to $5.39 \pm 0.21\%$. The relatively narrow variation (1.24%) among vessels reflects the use of the same fuel type and similar low-load operating conditions during berthing. Additionally, the relationship between O₂ and CO₂ concentrations provides insight into combustion performance (Andersson and Johnsson, 2007). Efficient combustion consumes oxygen and produces CO₂, with minimal CO formation (Fan et al., 2023). Consistent with this principle, Vessel C exhibited a lower O₂/CO₂ ratio than Vessel B, corresponding to higher CO and CO₂ concentrations and enhanced thermal NO_x formation. Overall, the results indicate that newer vessels tend to emit lower concentrations of conventional gaseous pollutants such as NO_x, SO₂, and CO, likely due to improved engine technology and combustion efficiency.

3.2. Particulate emissions under steady-state load conditions

In addition to gaseous carbon-containing products formed during combustion, a fraction of the fuel-bound carbon is converted into suspended particulate matter, particularly under conditions of incomplete combustion (Sippula et al., 2014). Carbonaceous material typically accounts for approximately 50% of the total particulate mass, with the remainder composed of metals, water-soluble ions, ash, and other inorganic and organic constituents (Huang et al., 2018). Fig. 2 presents the average concentrations of PM₁₀ (including PM_{0.18-1.0}, PM_{1.0-2.5}, PM_{2.5-4.0}, and PM_{4.0-10.0}) and the corresponding maximum opacity values. The measured PM₁₀ concentrations ranged from 2.06 ± 1.10 to 7.17 ± 0.80 mg/m³, with the majority of particulate mass dominated by accumulation-mode particles smaller than 1.0 μ m. This size distribution is characteristic of combustion-generated aerosols and is consistent with a previous study (Chu-Van et al., 2018). Such inhalable particles are of particular concern due to their enhanced ability to penetrate deep into the respiratory system, thereby posing significant risks to human health. Nevertheless, during exhaust dilution and cooling processes, diesel particles may undergo dynamic transformations, including nucleation of new particles through condensation of organic compounds or coagulation and adsorption onto existing particles, resulting in an increase in particle size (Heywood, 2018; Zhang and Balasubramanian, 2016).

Among the tested vessels, vessel B exhibited the highest average PM emission concentrations, followed by vessel C and vessel A. Although all vessels operated on the same fuel type, the observed variability may partially be attributed to differences in fuel sulfur content. Under high-temperature and oxygen-rich conditions, SO₂ can be oxidized to SO₃, which subsequently reacts with water vapor to form sulfate aerosols, thereby increasing PM concentrations (Zhao et al., 2010). Notably, the vessel with the highest PM emissions also exhibited relatively higher exhaust opacity in this study (refer to Fig. 2). Overall, these findings indicate that particulate emissions from vessels are strongly governed by fuel characteristics (e.g., sulfur content) and engine combustion efficiency.

3.3. Metal composition analysis

3.3.1. Metal content in marine gas oil and lubricating oil samples

Table S8 presents the concentrations of metals detected in MGO samples, which were classified into three groups based on their abundance: major metals (Zn, Na, Ca, Fe, Al, Cu, Cr, K, and Mg), sub-major metals (Pt, Sr, Mn, Mo, Ni, Pb, and Ba), and minor metals (Rb, Ti, Co, Pd, As, Sn, Ag, Rh, Ga, Cd, In, V, Se, Li, and Be). Among the major metals, Zn, Na, and Ca exhibited the highest concentrations, ranging

from 9.8 to 70 mg/kg, indicating significant enrichment in the fuel. These were followed by Fe, Al, Cu, Cr, K, and Mg, with concentrations between 0.08 and 10.0 mg/kg. These metals have been frequently reported as enriched constituents in marine fuels, especially Zn, Na, and Ca (Corbin et al., 2018; Coufalík et al., 2019). The sub-major metals were generally detected at concentrations between 0.01 and 1.0 mg/kg, while the minor metals were present at levels below 0.1 mg/kg. Notably, V and Ni, which are often regarded as tracers of vessel emissions (Popovicheva et al., 2009; Zhang et al., 2014). In this study, Ni was detected at concentrations ranging from 0.03 to 0.31 mg/kg, whereas V was only detected in the MGO sample from vessel C at 0.004 mg/kg and was not detected in the other samples. This observation is consistent with the higher degree of refinement of MGO relative to traditional heavy fuel oil (HFO), which typically contains substantially higher V concentrations (Agrawal et al., 2009; Viana et al., 2014). Overall, these findings indicate that the fuel used by the tested vessels in this study was of comparatively high quality.

According to Table S9, the metal composition of lubricating oil samples was dominated by Zn and Ca, with concentrations ranging from 91.50 to 1299.55 mg/kg and 44.37 to 455.83 mg/kg, respectively. Together, these two metals accounted for approximately 49.6% to 92.8% of the total metal content in the lubricant oil. Consistent with previous studies, Zn and Ca have been identified as key tracer metals for lubricant-derived emissions, reflecting the complex metal composition of lubricants (Carbone et al., 2019; Saraji-Bozorgzad et al., 2025). In addition, Mg (35.16–86.60 mg/kg), Na (3.23–41.03 mg/kg), K (1.00–31.88 mg/kg), Fe (4.51–9.86 mg/kg), and Al (1.49–6.26 mg/kg) collectively contributed an additional 6.5% to 48.3% of the total metal concentration. Other metals, including Pt, Sr, Mn, Mo, Ni, Pb, Ba, Rb, Ti, Co, Pd, As, Sn, Ag, Rh, Ga, Cd, In, V, Se, Li, and Be, were each present at concentrations contributing less than 1% of the total metal content. It is noteworthy that a small fraction of lubricating oil is typically consumed during engine operation and combustion (Zhao et al., 2020), and previous studies have demonstrated that lubricants can significantly influence the elemental composition of particulate emissions (Alanen et al., 2020).

3.3.2. Metal composition in PM_{2.5} and TSP samples

Fig. 3 illustrates the concentrations of 19 metals detected in PM_{2.5} and TSP samples. These metals were broadly classified into major and sub-major groups based on their concentrations. The metal composition of exhaust particulate matter was consistent with that of the fuel, suggesting that the detected metals were primarily present in oxidized forms produced during combustion processes (Corbin et al., 2018). Among the measured metals, Fe and Na exhibited the highest concentrations, ranging from 797.05 to 6048.67 μ g/m³ and 245.13 to 3577.08 μ g/m³, respectively, indicating that they were the most abundant metals in the exhaust. These were followed by Zn (37.70 to 381.55 μ g/m³), Ca (66.70 to 982.60 μ g/m³), Al (59.06 to 756.62 μ g/m³), Cu (3.96 to 42.75 μ g/m³), and Cr (9.23 to 177.60 μ g/m³). Zn and Ca are well-established tracer metals of lubricating oil and may therefore partially originate from lubricant combustion (Carbone et al., 2019; Moldanová et al., 2013). The sub-major metals, primarily Mn, Ni, Sr, Pb, Ba, and Ag, were detected at concentrations below 100 μ g/m³. Overall, the metal profiles were consistent with those detected in the MGO and lubricating oil, suggesting that fuel combustion is the dominant source, with additional contributions from lubricating oil combustion. Consistent with these findings, several port-area air quality studies have identified Fe, Na, Ca, Al, Zn, Cr, and Ni as commonly occurring metals in ambient particulate matter (Le Berre et al., 2025; Siudek, 2024; Tseng et al., 2025; Yuan et al., 2024), further supporting the findings of the present results. Notably, V was not detected in the PM samples, whereas Ni was present. This observation suggests that the V/Ni ratio could be influenced by differences in fuel composition. A similar trend has been reported by Le Berre et al. (Le Berre et al., 2025). While the V/Ni ratio in port areas typically ranged from 2 to 3, recent studies indicated that it

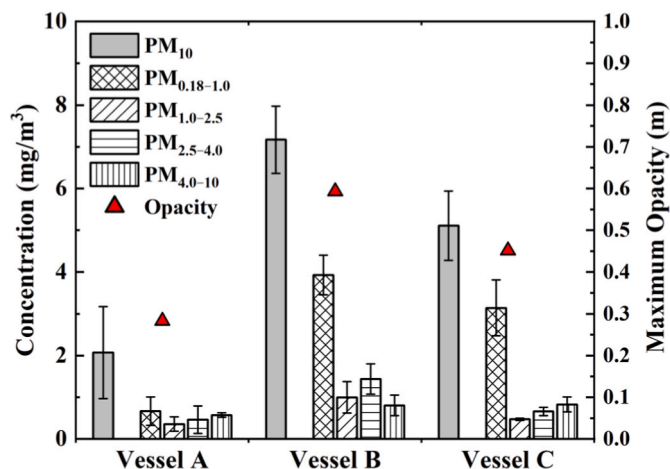


Fig. 2. PM emissions concentration and opacity from AE of the tested vessels during berthing.

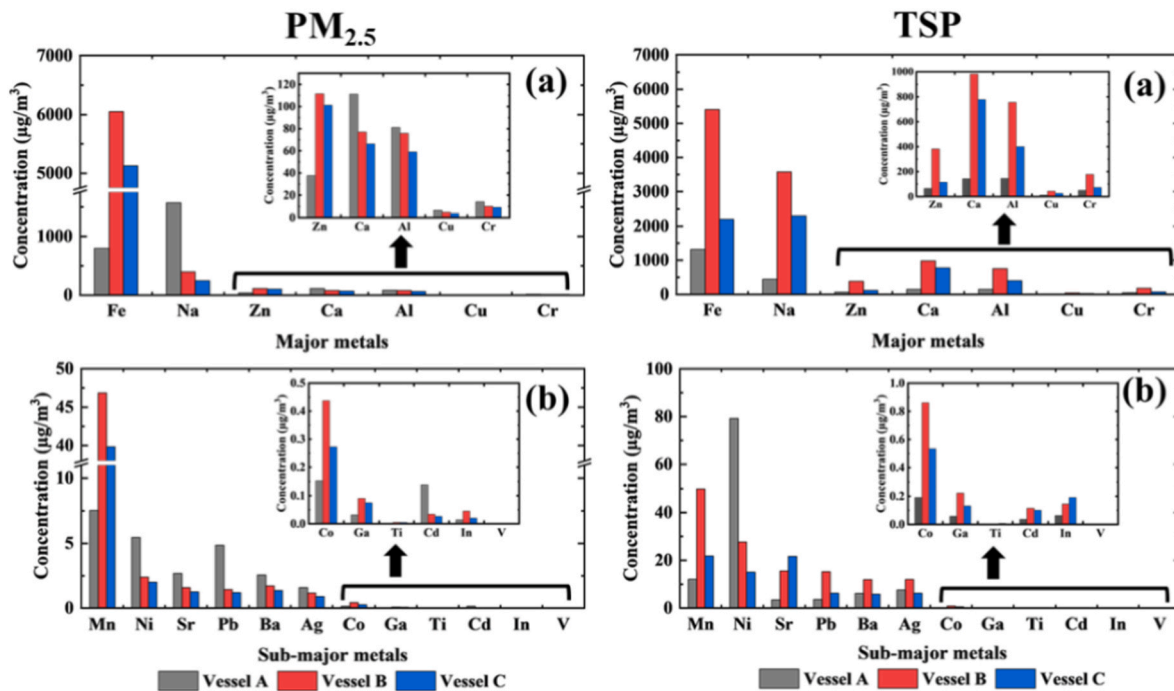


Fig. 3. Metal concentrations in PM_{2.5} and TSP from the tested vessels: (a) major metals; (b) sub-major metals.

has decreased to below 2 in recent years (Fossum et al., 2024; Yu et al., 2021).

3.4. Emission factors based on fuel consumption

In recent years, several studies have investigated vessel emissions using a variety of measurement and estimation approaches. In this study, data collected from on-board measurements were used to estimate fuel-based EFs for workboats using ultra-low sulfur fuel. The results were compared with values reported in previous studies and summarized in Table 2 and Fig. S6.

The EFs for NO, NO₂, and NO_x from the AE of workboats ranged from 6.49 to 26.08 g/kg-fuel, 0.24 to 0.37 g/kg-fuel, and 6.86 to 26.33 g/kg-fuel, respectively, indicating that NO was the dominant contributor to total NO_x emissions. Overall, the NO_x EFs observed in this study are comparable to those reported by Zhang et al. (2024) and Ziegler and Hansson (2003) for auxiliary and diesel engines (Zhang et al., 2024; Ziegler and Hansson, 2003), and are significantly lower than the values reported for main engines in previous studies. This finding aligns with the results of Chu-Van et al. (2018), who reported that the combustion characteristics of main and auxiliary engines differ substantially, with main engines generally operating at higher temperatures, thereby producing elevated NO_x emissions (Chu-Van et al., 2018).

The SO₂ EFs for workboats exhibited relatively limited variability, ranging from 0.20 to 1.86 g/kg-fuel, with an average of 1.09 g/kg-fuel. This variability is primarily attributed to differences in the sulfur content of the fuels used. The average SO₂ EFs reported in this study is comparable to values previously reported for vessels operating on diesel fuel and is substantially lower than those associated with residual fuels such as low-sulfur fuel (LSF) and heavy fuel oil (HFO). This finding is consistent with expectations given the lower sulfur content of MGO. Moreover, sulfur emissions from international shipping have declined markedly following the enforcement of the International Maritime Organization's (IMO) 2020 global sulfur cap regulations (Vedachalam et al., 2022; Yuan et al., 2022).

The CO EFs measured for workboats in this study ranged from 3.87 to 12.77 g/kg-fuel, with an average of 8.74 g/kg-fuel, consistent with values previously reported for marine main and auxiliary engines and

primarily reflecting differences in combustion efficiency (Cooper, 2003). In contrast, significantly higher CO EFs have been reported for fishing vessels, likely due to the lower combustion efficiency of high-speed diesel (HSD) engines commonly used in that sector (Chien et al., 2025; Zhang et al., 2018). Similarly, elevated CO emissions observed for engineering vessels have been attributed to lower engine power and suboptimal operating conditions (Zhang et al., 2016). The relatively stable emissions observed during berthing in this study suggest that, under steady-state conditions, combustion performance remains comparatively consistent in the absence of transient load fluctuations.

CO₂ EFs for workboats ranged from 3141.53 to 3166.62 g/kg-fuel, with an average of 3150.51 g/kg-fuel. The CO₂ EFs are primarily governed by fuel carbon content and combustion efficiency (Yang et al., 2023). The limited variability observed here reflects the use of MGO under stable operating conditions during berthing (Yang et al., 2022). Compared with vessels operating on residual fuels such as HFO or LSF, workboats using MGO generally exhibit lower CO₂ EFs due to the lower carbon intensity of distillate fuels. Conversely, CO₂ EFs reported for fishing vessels are often lower, consistent with their smaller engine sizes and reduced fuel consumption rates (Xu et al., 2017; Zhang et al., 2018).

The PM_{2.5} and TSP EFs from the AE of workboats were found to range from 0.69 to 4.08 g/kg-fuel and 0.72 to 5.11 g/kg-fuel, respectively. Vessel B shows the highest TSP EFs, consistent with measured PM concentrations. These values are comparable to those reported for marine diesel engines, whereas fishing boats generally exhibit higher PM EFs, likely due to lower combustion efficiency. In summary, fuel quality and combustion efficiency jointly govern particulate mass emissions and composition (Kuittinen et al., 2024).

3.5. Health risks assessment

Five heavy metals (Cr, Ni, Pb, Co, and Cd) in LADD, HQ, and CR in PM_{2.5} were evaluated due to their potential long-term health risks from inhalation exposure (IARC, 2026; Khoshakhlagh et al., 2024). The HQ and CR calculations in this study were based on class A LADD values, as the atmospheric stability class was determined to be mostly class A. In addition, the calculated LADD value is shown in Table S10.

Table 2
Fuel-based EFs from AE in this study and previous studies (g/kg-fuel).

Studies	Type	Operation and fuel	NO	NO ₂	NO _x	SO ₂	CO	CO ₂	THC	TSP	PM _{2.5}
This study	Vessel A	Berthing_ MGO (AE)	6.49	0.37	6.86	0.20	3.87	3166.62	—	0.72	0.69
	Vessel B		14.79	0.32	15.11	1.86	9.59	3141.53	—	5.11	4.08
	Vessel C		26.08	0.24	26.33	1.20	12.77	3143.39	—	3.24	1.33
Zhang et al. (2016)	Workboat (average)		15.79	0.31	16.10	1.09	8.74	3150.51	—	3.02	2.03
	Engineering vessel	Diesel (ME)	—	—	115.00	1.60	30.20	3071.00	23.70	9.40	—
	Research vessel	Diesel (ME)	—	—	35.70	0.92	9.20	3151.00	1.24	0.72	—
Zhang et al. (2024)	Coastal cargo ships	Diesel (AE)	27.9	1.89	29.79	—	3.51	3148.00	—	—	—
	Ocean-going vessels	Diesel (AE)	24.40–31.16	1.02–1.98	25.42–33.04	—	1.32–13.80	3108.00–3132.00	—	—	—
		HFO (AE)	20.8–33.83	0.40–3.62	22.3–37.11	—	1.86–3.33	3174.00–3185.00	—	—	—
Chien et al. (2025)	Fishing boat	ME	19.60 ± 1.70	3.76 ± 1.36	23.36 ± 3.06	0.53 ± 0.17	20.45 ± 6.19	3030.59 ± 57.96	—	—	—
Zhang et al. (2018)	Fishing boat	ME	44.30 ± 29.10	9.57 ± 4.00	54.20 ± 30.70	5.94 ± 6.38	50.70 ± 31.70	3074.00 ± 55.90	—	9.54 ± 2.27	—
Ziegler and Hansson (2003)	Medium-speed diesel engine	Trawling _ diesel	—	—	22.90–34.50	0.70	1.07–3.22	3170.00	0.92–2.36	—	—
Yang et al. (2023)	Medium-speed diesel engine	Gillnet fishing _ diesel	—	—	25.40–42.90	0.70	1.27–4.36	3170.00	1.08–3.35	—	—
	Cargo ship	LSF (ME)	—	—	53.10 ± 5.60	63.00 ± 5.60	10.80 ± 1.10	3086.32 ± 94.50	6.10 ± 0.40	8.90 ± 0.70	—
	Cargo ship	LSF (ME)	—	—	116.80 ± 10.10	24.50 ± 3.40	7.90 ± 0.70	3316.10 ± 103.60	3.80 ± 0.30	2.90 ± 0.40	—
Moldanová et al. (2009)	Tugboat	HFO (ME)	—	—	100.90 ± 9.80	18.30 ± 2.20	7.50 ± 0.50	3383.90 ± 64.50	2.80 ± 0.20	3.20 ± 0.30	—
	Fishing boat	ME	—	—	146.80 ± 12.70	82.20 ± 4.40	9.50 ± 1.00	2878.60 ± 86.40	4.70 ± 0.40	10.80 ± 0.80	—
	Cargo ship	HFO (ME)	—	—	31.60	2.60	2.17	3441.00	4.18	0.16	—
Sinha et al. (2003)	Cargo ship	Residual fuel (ME)	—	—	65.50 ± 3.30	52.20 ± 3.70	3.00 ± 0.20	3176.00 ± 95.00	3.00 ± 0.10	—	—
Kuittinen et al. (2024)	Modern cruise ship	Cruise _ HFO (ME)	—	—	51.49–58.44	17.30–17.95	1.18–2.09	3112.00–3135.00	—	—	—
		Berthing_ HFO (ME)	—	—	83.63–101.16	16.16–18.64	2.62–4.68	3094.00–3260.00	—	—	—
		Berthing_ MGO (ME)	—	—	77.53	1.63	1.69	3091.00	—	—	—

*ME, main engine; AE, auxiliary engine; HFO, heavy fuel oil; LSF, low sulfur fuel; MGO, marine gas oil.

Table 3 summarizes the estimated non-cancer and cancer risks of Cr, Ni, Pb, Co, and Cd, along with their maximum ground-level concentrations presented in Fig. S1–S5. Cr exhibited the highest ground-level concentration from a single vessel under stability class A, ranging from 1.5×10^{-3} to $3 \times 10^{-3} \mu\text{g}/\text{m}^3$ at around 35 m, and contributed most substantially to both non-cancer and cancer risks. In addition, the maximum ground-level concentrations of Co, Pb, Ni, and Cd ranged from 3.0×10^{-5} to 9.0×10^{-5} , 2.0×10^{-4} to 1.0×10^{-3} , 4.0×10^{-4} to 1.2×10^{-3} , and 5.0×10^{-6} to $3.0 \times 10^{-5} \mu\text{g}/\text{m}^3$, respectively. For individual metals, the HQ and CR values for Co, Pb, Ni, and Cd were below regulatory thresholds, indicating negligible health risk. In contrast, Cr exhibited substantially higher CR values (2.08×10^{-5} to 3.38×10^{-5}), suggesting it as the dominant contributor to cancer risk from vessel emissions. Although assuming all Cr as Cr(VI) may overestimate actual risk, this conservative, worst-case approach highlights a potential concern that warrants attention. This finding is consistent with Wen et al. (2018), who indicated Cr as the primary contributor to both cancer and non-cancer risks from fishing boats, cargo ships, and ferries (Wen et al., 2018). In this study, total CR values for individual vessels ranged from 2.11×10^{-5} to 3.42×10^{-5} under worst-case (maximum ground-level concentration) exposure conditions. The results indicate a potential cancer risk from inhalation of metal components in emissions from workboats under berthing conditions in Kaohsiung Port. Similar findings have been reported in previous studies. As summarized in Table 4, studies investigating metal-related health risks from ship emissions have reported CR values that may exceed commonly accepted risk thresholds under certain conditions (Betha and Balasubramanian, 2011; Dong et al., 2025; Kouras et al., 2025; Wu et al., 2020; Zhang et al., 2021). These studies further support the arguments of this research. Overall, the results suggest that, under the specific assumptions and conditions applied in this study, exposure to metals from vessel emissions, especially Cr, may pose a potential cancer risk.

4. Conclusion

This study presents a comprehensive characterization of pollutant emissions, metal content, emission factors, and risk assessment from workboats operating on ultra-low sulfur fuel under steady-state load conditions. The results show that NO_x emissions were dominated by NO, and both concentrations and emission factors were notably lower than those typically reported for main engines, reflecting differences in combustion characteristics and operating loads. SO₂ emissions were low due to the use of ultra-low sulfur marine gas oil, while CO emissions increased under low-load conditions. CO₂ emission factors showed little variation among vessels, consistent with the use of the same fuel type and stable berthing conditions.

Particulate emissions were dominated by submicron particles (<1.0

Table 3
PM_{2.5} metal non-cancer risk (HQ) and cancer risk (CR) for vessels A, B, and C at atmospheric stability class A (calculated using concentration at downwind distance of 35 m).

Metal	Vessel A	Vessel B	Vessel C
Non-cancer risk (HQ)			
Cr	2.81×10^{-2}	2.66×10^{-2}	1.73×10^{-2}
Ni	1.00×10^{-5}	1.00×10^{-5}	1.00×10^{-5}
Pb	8.00×10^{-5}	3.00×10^{-5}	2.00×10^{-5}
Co	1.50×10^{-3}	5.71×10^{-3}	2.57×10^{-3}
Cd	1.00×10^{-5}	$<1.00 \times 10^{-5}$	$<1.00 \times 10^{-5}$
Total	2.97×10^{-2}	3.24×10^{-2}	1.99×10^{-2}
Cancer risk (CR)			
Cr	3.38×10^{-5}	3.20×10^{-5}	2.08×10^{-5}
Ni	2.59×10^{-7}	1.50×10^{-7}	9.06×10^{-8}
Pb	2.33×10^{-9}	9.13×10^{-10}	5.42×10^{-10}
Co	8.42×10^{-8}	3.20×10^{-7}	1.44×10^{-7}
Cd	4.96×10^{-8}	1.62×10^{-8}	9.02×10^{-9}
Total	3.42×10^{-5}	3.25×10^{-5}	2.11×10^{-5}

Table 4
HQ and CR of metals from ship and diesel engine emissions in this study and previous studies.

Study	Scenario	HQ	CR	Dominant metal
This study	Workboat emissions; health risk for adults; inhalation	<1	2.10 × 10 ⁻⁵ to 3.41 × 10 ⁻⁵	Cr, Ni, Cd, Pb, and Co
Dong et al. (2025)	Ship emissions; health risk for adults; inhalation	<1	2.00 × 10 ⁻⁶	Ni and V
Kouras et al. (2025)	Ship emissions; health risk for adults; inhalation	<1	3.60 ± 2.50 × 10 ⁻⁵	Cd, Cr, Ni, Co, Pb, and As
Wu et al. (2020)	Ship emissions; health risk for adults; inhalation	<1	2.85 × 10 ⁻⁵	As, Cd, Ni, V, Mn, Cr, Ba, and Pb
	Ship emissions; health risk for children; inhalation	<1	7.12 × 10 ⁻⁶	
Betha and Balasubramanian (2011)	Diesel engine emissions; biodiesel; ultra-low sulfur fuel; health risk for adults; ingestion	<1	12.30 × 10 ⁻⁶ to 16.60 × 10 ⁻⁶	As, Cd, Cr, Ni, Al, and Mn
	Diesel engine emissions; biodiesel; ultra-low sulfur fuel; health risk for children; ingestion	<1	28.60 × 10 ⁻⁶ to 38.80 × 10 ⁻⁶	
Zhang et al. (2021)	Coastal urban area; health risk for adults; inhalation	0.1	1.90 × 10 ⁻⁵	Pb, As, Cr, and Ni
	Coastal urban area; health risk for children; inhalation	0.1	4.80 × 10 ⁻⁶	

μm), and PM concentrations were strongly correlated with exhaust opacity. Fuel composition, particularly sulfur content, and combustion efficiency were key factors influencing PM levels. Metal analysis revealed that fuel and lubricating oils contained high levels of Zn, Na, and Ca, and that the metallic composition of exhaust particulates was largely consistent with these sources. The absence of V in PM samples, alongside detectable Ni, suggests that the traditional V/Ni ratio for ship emission tracing may change with fuel composition. Importantly, the health risk assessment demonstrates that exposure to metals from a single vessel could pose carcinogenic risks, with Cr(VI) identified as the primary contributor.

Overall, the findings highlight that fuel properties, lubricating oil composition, engine technology, and operating conditions significantly affect both gaseous and particulate emissions. In addition, the results suggest that emissions from workboats operating on ultra-low sulfur fuel under berthing conditions in Kaohsiung Port may still pose potential carcinogenic risks associated with metal exposure, although these findings are based on worst-case assumptions. These results provide useful reference data for emission characterization for similar vessel types operating under comparable conditions. However, parameters such as air–fuel ratio, combustion temperature, and fuel injection timing may limit the interpretation of certain emission trends. Future work that includes these variables under a broader range of operating conditions would further enhance understanding of marine engine emission mechanisms. Additionally, implementing shore power systems during vessel berthing and optimizing the quality of fuel and lubricating oil are recommended as effective strategies to further reduce emissions and associated health risks.

CRedit authorship contribution statement

Po-Yen Chien: Writing – original draft, Methodology, Investigation,

Data curation, Conceptualization. **Chia-Hsiang Lai:** Supervision, Resources. **Chia C. Wang:** Supervision, Resources. **Dhruv Vishal Patel:** Writing – original draft, Data curation. **Ajay Pillarisetti:** Supervision. **Wu-Xing Chen:** Supervision. **Chia-Hung Chen:** Investigation. **Yi-Ching Lin:** Investigation. **Tsai-Jung Yen:** Investigation. **Hsiang-Ying Wu:** Investigation. **Dong-Ni Wu:** Investigation. **I-Hsuan Wu:** Investigation. **Kun-Tu Lu:** Supervision, Methodology. **Yen-Ping Peng:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yen-Ping Peng reports financial support was provided by Ministry of Environment, Taiwan. If there are other authors, they 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

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Data availability

Data will be made available on request.

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