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Research Article

Changes in Indoor Air Quality in Public Facilities before and after the Enactment of Taiwan's Indoor Air Quality Management Act

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South Korea was the first to administer the Indoor Air Quality Control Act in 1996, followed by Taiwan's implementation in 2012. This study investigated indoor air quality (IAQ) in public facilities before and after the enactment of Taiwan's Indoor Air Quality Management (IAQM) Act in 2012 to assess the effectiveness of the Act. The study also calculates health risks for employers, and consumers/visitors separately. The mean concentration of carbon dioxide (CO_2) after the IAQM Act's enactment was higher than before, except for government offices. The lowest attainment rates for CO_2, below 80%, were 73% in hospitals and 78% in libraries. As for formaldehyde, average concentrations were higher after the IAQM Act's implementation, except for the exhibition room and library. Notably, improvements in particulate matter with a diameter less than 2.5 μm ($PM_{2.5}$) levels were evident in hospitals and libraries compared to other environments (attainment rates increased from 85% to 100% and 89% to 94%, respectively). However, in schools, preschools, and public transport spaces, unattainment rates worsened. Regarding cancer risk from formaldehyde exposure in the public, the 95% of upper risk limits ranged from 3.44×10^{-5} in the public transport system to 8.80×10^{-4} in preschools. Our findings highlight the necessity of integrating more measurement data after IAQM Act implementation and formulating management strategies based on risk assessments for future investigations.

1. Introduction

Three decades ago, discussions about indoor environmental quality primarily revolved around pollutants related to smoking [1, 2]. Since then, indoor air quality (IAQ) has gained substantial attention in public health. The World Health Organization (WHO) reported that indoor air pollution was responsible for an estimated 3.2 million deaths per year, including 237,000 deaths of children under the age of 5 in 2020 [3]. In terms of socioeconomic costs, premature deaths, and the loss of quality of life accounted for approximately 90% of the total cost in France, specifically, particles were the leading contributor at 75%, followed by radon [4]. Among diseases associated with IAQ, respiratory infections, allergies, asthma, and sick building syndrome incurred significant costs [5, 6]. Previous studies have also focused on investigating IAQ in various indoor environments, such as primary schools, along with associated health risks [7–11].

Table 1: Exposure scenarios for the general public and staff workers.

Location	Hours (day)	Days (week)	Weeks (month)	Months (year)	Exposure frequency[#1] (EF, day/year)	Exposure duration (ED, year)	Averaging time[#2] (AT, day)
General public							
School	6	4	4	9	36.00	10	29141.6
Library	6	3	2	3	4.50	12	29141.6
Preschool	8	5	4	9	60.00	5	29141.6
Hospital	4	The average frequency of outpatient visits was 15.22/ person/year in 2014			2.54	79.84	29141.6
Social welfare institution	2	1	4	12	4.00	79.84	29141.6
Government office	0.5	1	1	12	0.25	79.84	29141.6
Public transport system	0.5	6	4	12	6.00	79.84	29141.6
Exhibition room	4	10 days/year			1.67	79.84	29141.6
Department store/shopping center	3	1	4	12	6.00	79.84	29141.6
Staff workers							
School	8	5	4	12	80.00	35	29141.6
Library	8	5	4	12	80.00	35	29141.6
Preschool	8	5	4	12	80.00	35	29141.6
Hospital	8	5	4	12	80.00	35	29141.6
Social welfare institution	8	5	4	12	80.00	35	29141.6
Government office	8	5	4	12	80.00	35	29141.6
Public transport system	8	5	4	12	80.00	35	29141.6
Exhibition room	8	5	4	12	80.00	35	29141.6
Department store/shopping center	8	5	4	12	80.00	35	29141.6

[#1]Exposure frequency (day/year) = (h/day) × (day/week) × (week/month) × (month/year) × (day/24h). [#2]Averaging time (day) = 79.84 years × 365 days/year = 29141.6 days.

Studies have also explored IAQ in shopping districts [12], cooking areas [13], hairdressing/beauty salons [14, 15], workrooms with 3D printers [16], and nursing homes [17].

Numerous studies have reported on the exposure risk of indoor contaminants, including formaldehyde in primary school buildings [11], residential homes [18], and bathing and beauty places [19], as well as the evaluation of benzene [20] and polycyclic aromatic hydrocarbons [13]. Among all indoor contaminants, formaldehyde stands out as one of the most harmful. Indeed, formaldehyde pollution and ventilation frequency have been identified as risk factors for respiratory system disorders in both adults and children [21]. Additionally, each 10 μg/m^3 increase in formaldehyde exposure has shown a significant association with a 10% increase in the risk of asthma in children [22]. In the United States (U.S.), approximately 0.7% of 17,867 homes had estimated acute formaldehyde concentrations > 100 μg/m^3 immediately after the installation of Chinese-manufactured laminate flooring [18]. In Spain, air formaldehyde levels found in homes ranged from 9.65 to 47.7 μg/m^3, and outdoor levels ranged from 0.96 to 3.37 μg/m^3. Indoor air levels in workplaces varied from 5.86 to 40.4 μg/m^3 [23]. A study in Romania reported that indoor formaldehyde levels during a school week varied between 15.5 and 66.2 μg/m^3 [9]. This study also reported that the adjusted odds ratios for allergy-like, asthma-like, and flu-like symptoms were 3.23 (95% confidence interval (CI) 1.31–8.00), 2.69 (95% CI 1.04–6.97), and 2.39 (95% CI 1.04–5.50), respectively, when comparing children exposed to higher formaldehyde levels (>35 μg/m^3) during a school week with those exposed to lower formaldehyde levels [9]. In China, the average formaldehyde concentration was 0.57 mg/m^3 in a total of 564 different public places, including hotels and social interaction areas, bathing and beauty establishments, cultural and entertainment venues, and shopping areas. This level is 5.7 times higher than the acceptable concentration level regulated in China (0.1 mg/m^3) [19].

Previous studies have further demonstrated that formaldehyde and volatile organic compounds (VOCs) can be emitted from building materials [24]. In Japan, toluene, formaldehyde, and acetaldehyde were the predominant indoor VOCs in 5,017 randomly selected households [25]. In northwestern China, indoor VOCs and carbonyls primarily originated from furniture and building materials, paints and adhesives, household products, smoking, and cooking, as determined through source apportionment with a receptor model [26]. In Beijing, 85% of indoor formaldehyde concentrations in 410 dwellings and 67% in 451 offices exceeded the acute reference exposure level (REL) recommended by the Office of Environmental Health Hazard Assessment (OEHHA) in California, and the concentrations of all tested buildings were above the chronic REL recommended by OEHHA [20]. Additionally, 12% of indoor benzene concentrations in dwellings and 32% in offices exceeded the

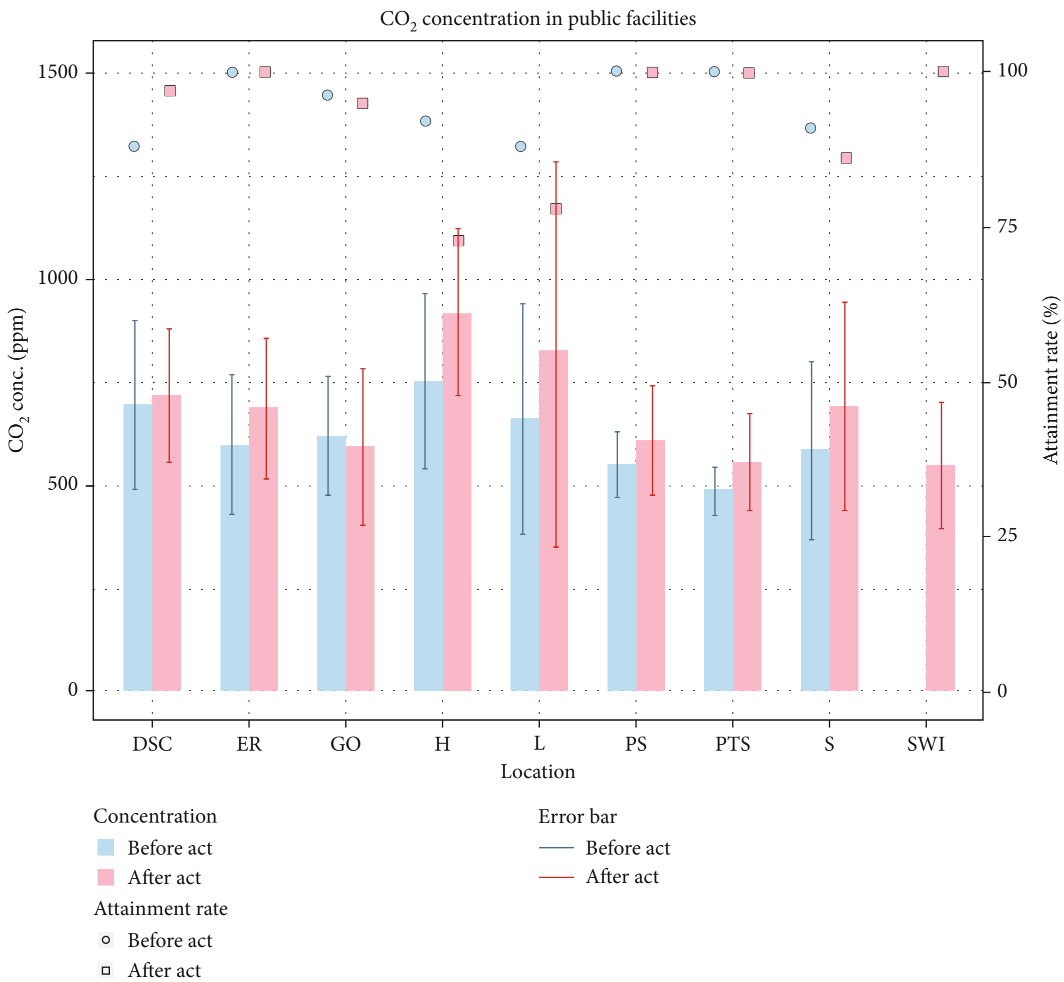

FIGURE 1: Concentrations of carbon dioxide (CO_2) in indoor environments and the corresponding attainment rates. H: hospital; L: library; S: school; ER: exhibition room; GO: government office; PS: preschool; DSC: department store/shopping center; PTS: public transport system; SWI: social welfare institution.

reference concentration recommended by the U.S. Environmental Protection Agency (US EPA) [20].

In 2010, the WHO had established IAQ guidelines for short- and long-term exposures to formaldehyde at 0.1 mg/m^3 (0.08 ppm) for all 30-minute periods throughout a person's lifetime [27]. Furthermore, to protect the health of building users, the European Union implemented Construction Products Regulation, with a particular focus on emissions of VOCs from construction products [28]. The Chinese government has also introduced a series of standards to regulate formaldehyde exposures, but concentrations in homes, office buildings, workshops, and public places frequently exceed the national standards [29]. Moreover, South Korea became the first government to enact an independent act—the Underground Air Quality Management Act—in 1996 [30], followed by Taiwan as the second to legally oversee IAQ indicators in public facilities since 2012 (Taiwan EPA). The Indoor Air Quality Management (IAQM) Act in Taiwan establishes standards for indoor environmental concentrations of carbon dioxide (CO_2, 8 h average ≤ 1000 ppm), carbon monoxide (CO, 8 h average ≤ 9 ppm), ozone (O_3, 8 h average ≤ 0.06 ppm), formaldehyde (1 h average ≤ 0.08 ppm), total volatile organic compounds (TVOCs, 1 h average ≤ 0.56 ppm), particulate matter with a diameter less than 2.5 μm ($PM_{2.5}$, 24 h average ≤ 35 μg/m^3), particulate matter with a diameter less than 10 μm (PM_{10}, 24 h average ≤ 75 μg/m^3), total bacteria (maximum ≤ 1500 colony forming unit (CFU)/m^3), and total fungi (maximum ≤ 1000 CFU/m^3, but indoor/outdoor ratio ≤ 1.3 falling outside of this constraint). This study is aimed at investigating IAQ in public facilities before and after the enactment of Taiwan's IAQM Act in 2012 to assess the effectiveness of its implementation. Additionally, this study is the first to estimate the exposure risk of the public (consumers/visitors) or the staff workers separately before and after the enactment of Taiwan's IAQM Act.

2. Materials and Methods

2.1. Data Sources. This study initially obtained official reports from both central and local government sectors responsible for environmental protection in Taiwan. These reports were sourced from The Environmental Project's Achievements Reports Query System (https://epq.epa.gov.tw/). A total of 91 project reports from 2002 to 2014 were

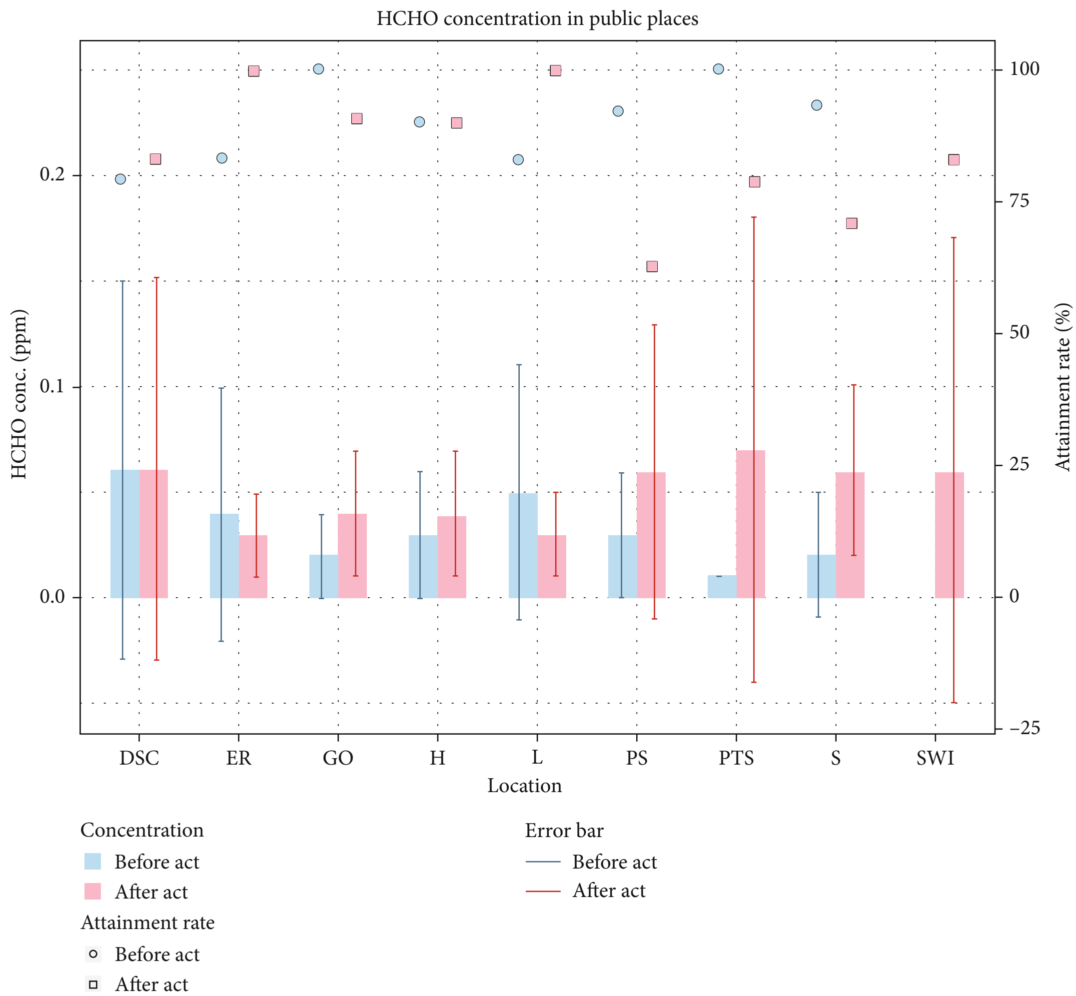

Figure 2: Concentrations of formaldehyde (HCHO) in indoor environments and the corresponding attainment rates. H: hospital; L: library; S: school; ER: exhibition room; GO: government office; PS: preschool; DSC: department store/shopping center; PTS: public transport system; SWI: social welfare institution.

included for data extraction. Among these, 66 were published before 2012, while the remaining 25 were published thereafter. Subsequently, the research team extracted indoor monitoring data measured using the standard environment methods promulgated by the Taiwan EPA. The final compiled dataset contained monitoring data from 502 public facilities for indoor air pollutants regulated by the Taiwan EPA. This included measurements for CO_2, CO, O_3, formaldehyde, TVOCs, $PM_{2.5}$, PM_{10}, total bacteria, and total fungi, as well as indoor environmental quality indicators such as temperature and relative humidity (RH). The data were categorized into nine types of public facilities, including schools, libraries, preschools, hospitals, social welfare institutions, government offices, public transport systems, exhibition rooms, and department stores/shopping centers for further investigation.

2.2. Measurement Methods. Since 2002, the Taiwan EPA has sponsored numerous projects aimed at measuring IAQ in various indoor settings. The fundamental requirement was that all sampling and laboratory experiments adhere to the standard operating procedure outlined in ISO 17025. Following the enactment of Taiwan's IAQM Act in 2012, the Taiwan EPA expanded its criteria for certifying laboratories beyond ISO 17025. Laboratories were additionally evaluated based on the accuracy and quality control of each indoor sampling and analysis methodology. In the study, monitoring data were collected using standard methods established by the Taiwan EPA. Specifically, CO_2 and CO measurements were conducted using nondispersive infrared analyzers (Taiwan EPA, NIEA A448, and NIEA A421, respectively) with response time less than 2 minutes and accuracy at least 1 ppm; O_3 concentrations were measured using the ultraviolet (UV) absorption method at a wavelength of 254 nm (NIEA A420) with the measured standard error within 0.005 ppm or variety less than 3%; formaldehyde concentrations were analyzed by high-performance liquid chromatography using the absorption solution of 2,4-dinitrophenylhydrazine (DNPH) and perchloric acid (NIEA A705); TVOCs were sampled via canister and analyzed by gas chromatography with mass spectrometry (NIEA A715); $PM_{2.5}$/PM_{10} measurements were conducted

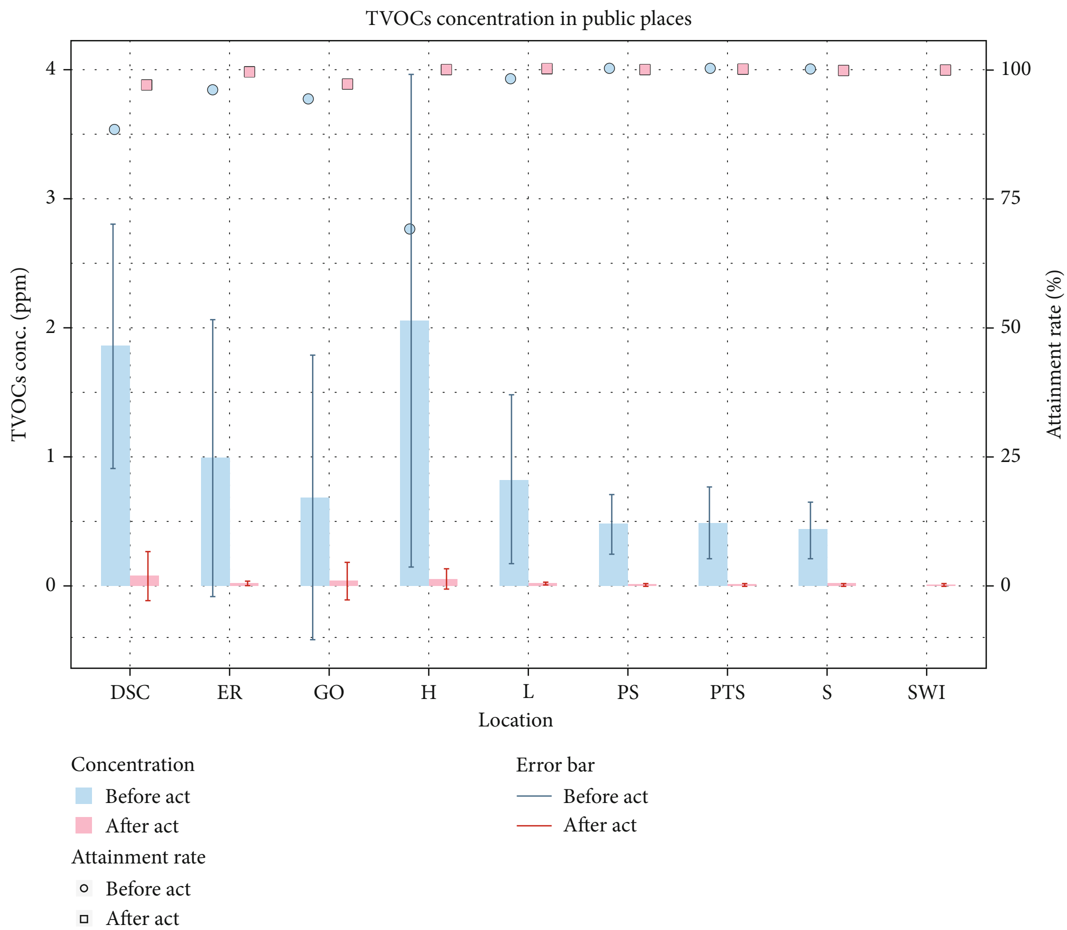

FIGURE 3: Concentrations of total volatile organic compounds (TVOCs) in indoor environments and the corresponding attainment rates. H: hospital; L: library; S: school; ER: exhibition room; GO: government office; PS: preschool; DSC: department store/shopping center; PTS: public transport system; SWI: social welfare institution.

using the beta-ray attenuation method (NIEA A206) or the inertial mass method (NIEA A207); bacteria and fungi levels were sampled using impactors with different agar plates followed by incubation for colony forming unit calculation (NIEA E301 and NIEA E401, respectively).

In addition, before 2012, indoor samplings were randomly conducted, but indoor facilities had the liberty to refuse cooperation with Taiwan EPA requests, as there were no regulatory measures compelling their compliance. The indoor concentrations of contaminants collected before 2012 underscored the significance of identifying inadequate IAQ in certain environments. Consequently, since 2012, Taiwan EPA gradually regulated the priority of major hospitals, public administrative facilities, libraries, and other such indoor facilities under the IAQM Act. Furthermore, the IAQM Act mandated that public indoor environments, as outlined in this manuscript, undergo periodic IAQ assessments, with measurements to be conducted once every two years following the official measurement protocol.

The outcomes of these official measurements serve the purpose of conformity the IAQM Act standards, serving as a means to verify the adherence to IAQ norms within these public facilities. The sampling modules are strategically positioned within these establishments during their operational hours. Specific guidelines govern the placement of sampling equipment in adherence to protocol. Firstly, the sampling module must not be situated beneath the openings of ventilation systems and should be positioned at a distance from doors and windows. Secondly, it is imperative to avoid proximity to elevators or stairs, as these areas are not primary occupancy zones.

2.3. Data Analysis. By compiling previously published data on IAQ from various government sectors, this study assessed the levels and risks of indoor pollutants in various types of public facilities. To maintain the integrity of data processing, all originally extracted records were organized and stored in Excel 2003 files, subjected to double-entry verification. The SigmaPlot (version 10.0) was used for generating plots, and all statistical analyses were conducted using SAS (version 9.0), with a significance level set at 0.05.

Furthermore, formaldehyde levels in various public locations before and after the enactment of the IAQM Act were employed to estimate the health risks related to formaldehyde exposures for public and staff workers. The potential rise in cancer risk associated with inhalation of formaldehyde

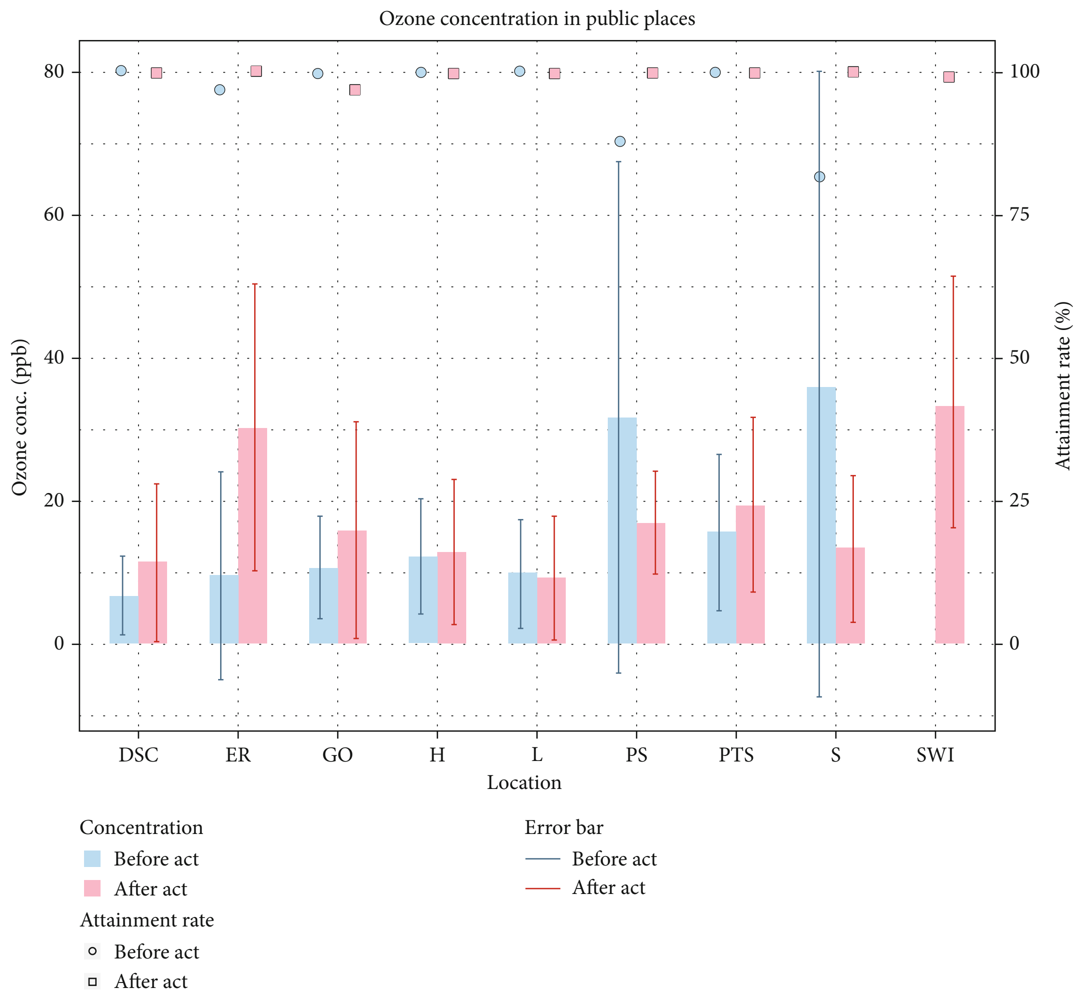

Figure 4: Concentrations of ozone in indoor environments and the corresponding attainment rates. H: hospital; L: library; S: school; ER: exhibition room; GO: government office; PS: preschool; DSC: department store/shopping center; PTS: public transport system; SWI: social welfare institution.

was calculated using Equation (1), with a unit risk (UR) value of 1.3×10^{-5} per $\mu g/m^3$ as provided by the US EPA, which is considered with lifetime exposure [18]:

$$\text{Cancer risk} = \text{indoor formaldehyde concentration}\left(\mu g/m^3\right) * \text{UR}\left(\left(\mu g/m^3\right)^{-1}\right). \quad (1)$$

To characterize cancer risks for different target populations, two exposure scenarios were developed for the public and the staff workers within nine public facilities individually (Table 1). The Monte Carlo simulation was adopted for the parameter characterization during risk estimating (@Risk 7.5.1, Palisade Corporation).

3. Results

The concentrations of pollutants within indoor environments and the attainment rates of the IAQ standards established by the Taiwan EPA are shown in Figures 1–8. Since the indoor CO measurements were consistently well below the IAQ standard of 9 ppm, data for this parameter are not included in the figures. In summary, before the enactment of the IAQM Act, only indoor $PM_{2.5}$ (Figure 7) and PM_{10} (Figure 8) levels did not show statistically significant variations across indoor facilities. However, postenactment, except for formaldehyde (Figure 2) and particulate matters ($PM_{2.5}$ and PM_{10}), the remaining criteria for indoor air pollutants showed different concentrations among various indoor facilities, with statistical significance.

Regarding CO_2 (Figure 1), the mean levels after the IAQM Act enactment were generally higher than those observed prior, except in the case of government offices. The attainment rates for CO_2 after the enactment, falling below 80%, were 73% in hospitals and 78% in libraries. Concerning formaldehyde, the average indoor concentrations were higher after the enactment compared to pre-enactment levels, except for exhibition rooms and libraries. The three lowest attainment rates after enactment were identified in preschools (63%), schools (71%), and public

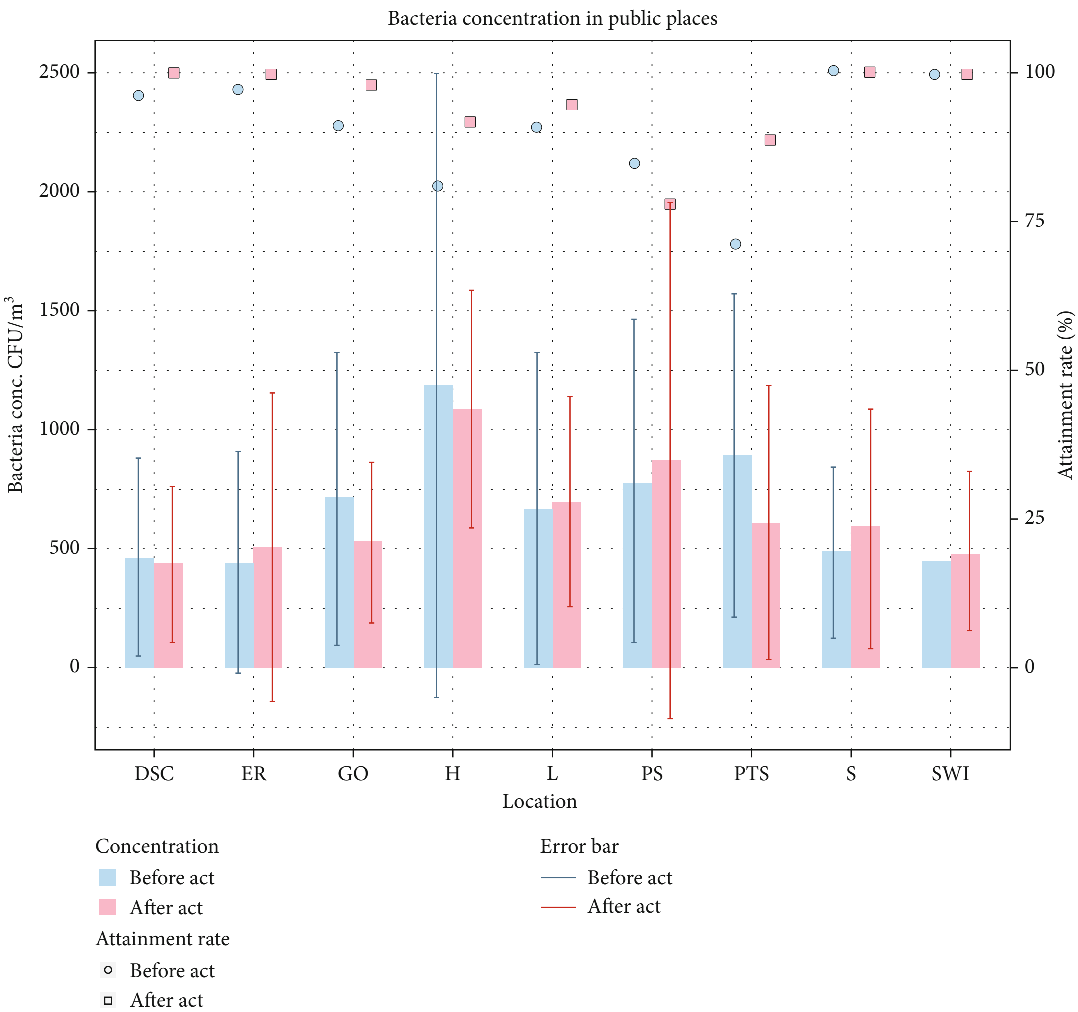

FIGURE 5: Concentrations of total bacteria in indoor environments and the corresponding attainment rates. H: hospital; L: library; S: school; ER: exhibition room; GO: government office; PS: preschool; DSC: department store/shopping center; PTS: public transport system; SWI: social welfare institution.

transport systems (79%). As for TVOCs in Figure 3, while mean concentrations in department stores/shopping centers, exhibition rooms, libraries, hospitals, and government offices exceeded the IAQ standard of 0.56 ppm prior to enactment, all mean indoor measurements were well below the standard after the enactment. Regarding O_3 (Figure 4), the attainment rates before enactment were 88% and 82% in preschools and schools, respectively, both of which achieved a 100% attainment rate after enactment.

For indoor biological contaminants, the most significant improvement after enactment was observed in the public transport system for both bacteria (Figure 5) and fungi (Figure 6), with attainment rates increasing from 71% to 89% and from 64% to 87%, respectively. In preschools, 22% of measured bacterium levels still did not meet the IAQ standard of 1500 CFU/m^3 after enactment. Furthermore, concerning indoor $PM_{2.5}$ concentrations in hospitals and libraries, notable improvements were observed compared to other indoor environments, with attainment rates increasing from 85% to 100% for hospitals and from 89% to 94% for libraries. However, in preschools and public transport spaces, attainment rates decreased to 83% and 80%, respectively, after enactment. Similar trends in attainment rates were also identified for indoor PM_{10} concentrations.

Regarding cancer risk from exposure to indoor formaldehyde for the public, before the enactment, the 95th percentile upper limits of risk ranged from 2.99×10^{-6} in the public transport system to 5.25×10^{-4} in libraries; after the enactment, the 95th percentile upper limits of risk ranged from 3.44×10^{-5} in government offices to 8.80×10^{-4} in preschools (Table 2). For staff workers, before the enactment, the 95th percentile upper limits of risk ranged from 4.79×10^{-5} in the public transport system to 1.17×10^{-3} in department stores/shopping centers; after the enactment, the 95th percentile upper limits of risk ranged from 3.76×10^{-4} in libraries to 1.53×10^{-3} in the public transport system (Table 3).

4. Discussion

4.1. The Effectiveness of Implementing IAQM Act. Among indoor contaminants, formaldehyde and VOCs have

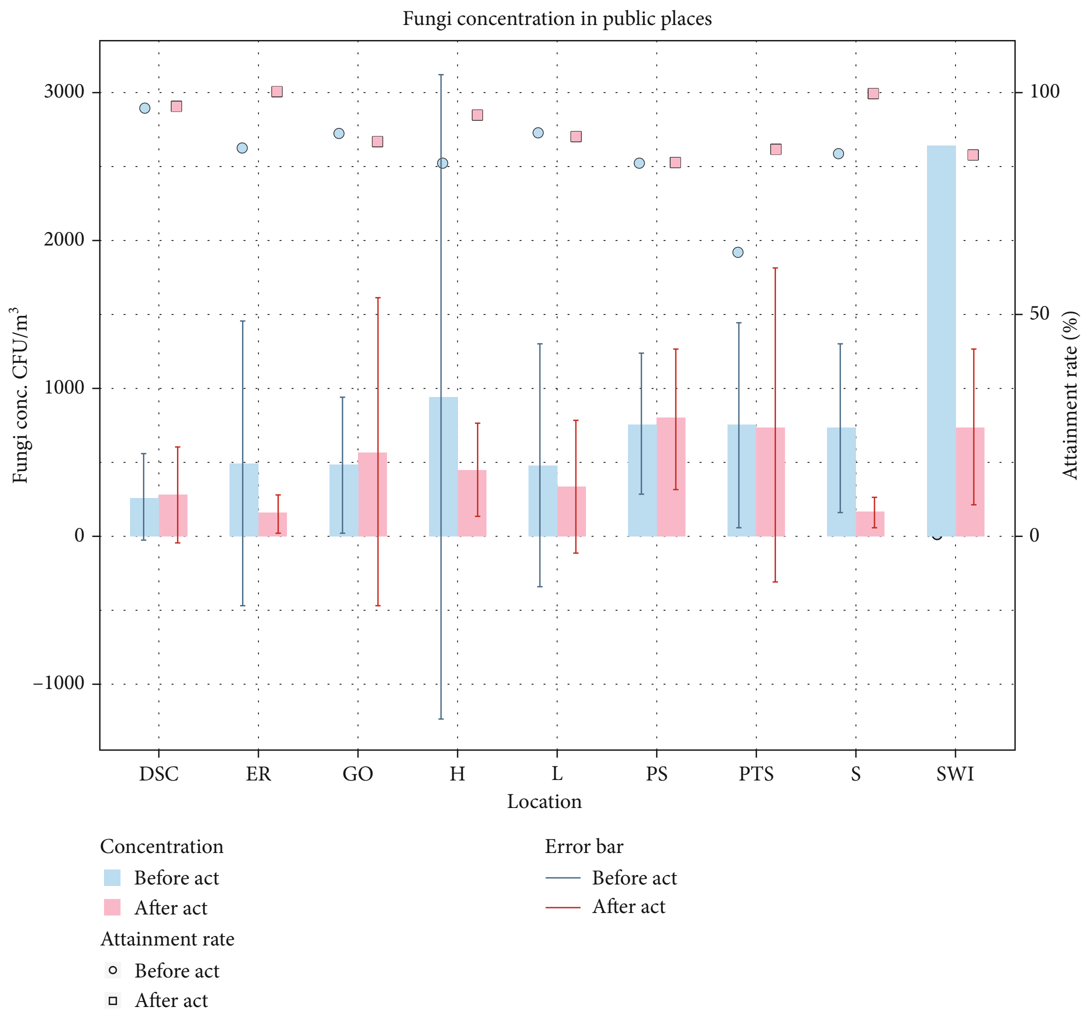

Figure 6: Concentrations of total fungi in indoor environments and the corresponding attainment rates. H: hospital; L: library; S: school; ER: exhibition room; GO: government office; PS: preschool; DSC: department store/shopping center; PTS: public transport system; SWI: social welfare institution.

undeniably attracted the most significant attention due to their emission from building materials and high toxicity [12, 18, 24, 31–33]. While the formaldehyde issue has shown significant improvement in exhibition rooms and libraries following the enactment of the law, relatively low attainment rates still persist in preschools (63%) and schools (71%). In addition to students' activities [34], the disparity might be attributed, in part, to the fact that preschools and schools were not subjected to regulation under the IAQM Act, unlike exhibition rooms and libraries.

Before the enactment, statistically significant differences in CO_2 levels were observed among the indoor environments. CO_2 accumulation is a result of human respiratory actions, smoking, and other combustion activities, particularly in indoor environments with high occupancy density and poor ventilation. Indoor CO_2 levels can play a critical role in evaluating IAQ and are strongly correlated with bacteria measurements, for instance [8]. To further improve indoor CO_2 reduction after the law enactment, it is essential to focus on limiting the number of occupants and increasing ventilation rates in places such as hospitals (with an attainment rate of 73%) and libraries (78%).

Additionally, a previous report revealed that bacterial cell envelope components act as inflammatory agents, causing respiratory symptoms, and that the total bacterial load is the most accurate indicator for assessing the biotoxicity of indoor air [8]. In this study, 22% of the preschool measurements did not meet the IAQ standard for total bacteria after the law enactment. Consequently, strategies for biological pathogen control and proper management are needed in indoor environments occupied by susceptible populations.

According to the analysis of pollutant trends spanning from 1995 to 2020 in Taiwan, a decreasing trend has been observed not only for O_3 but also for $PM_{2.5}$, PM_{10}, sulfur dioxide (SO_2), and nitrogen oxides [35, 36]. The enhancement of outdoor $PM_{2.5}$ and PM_{10} levels may influence indoor environments, particularly those reliant on natural ventilation. Nevertheless, few instances were noted in current indoor environments. The notable improvement in $PM_{2.5}$ and PM_{10} levels was primarily observed in hospitals

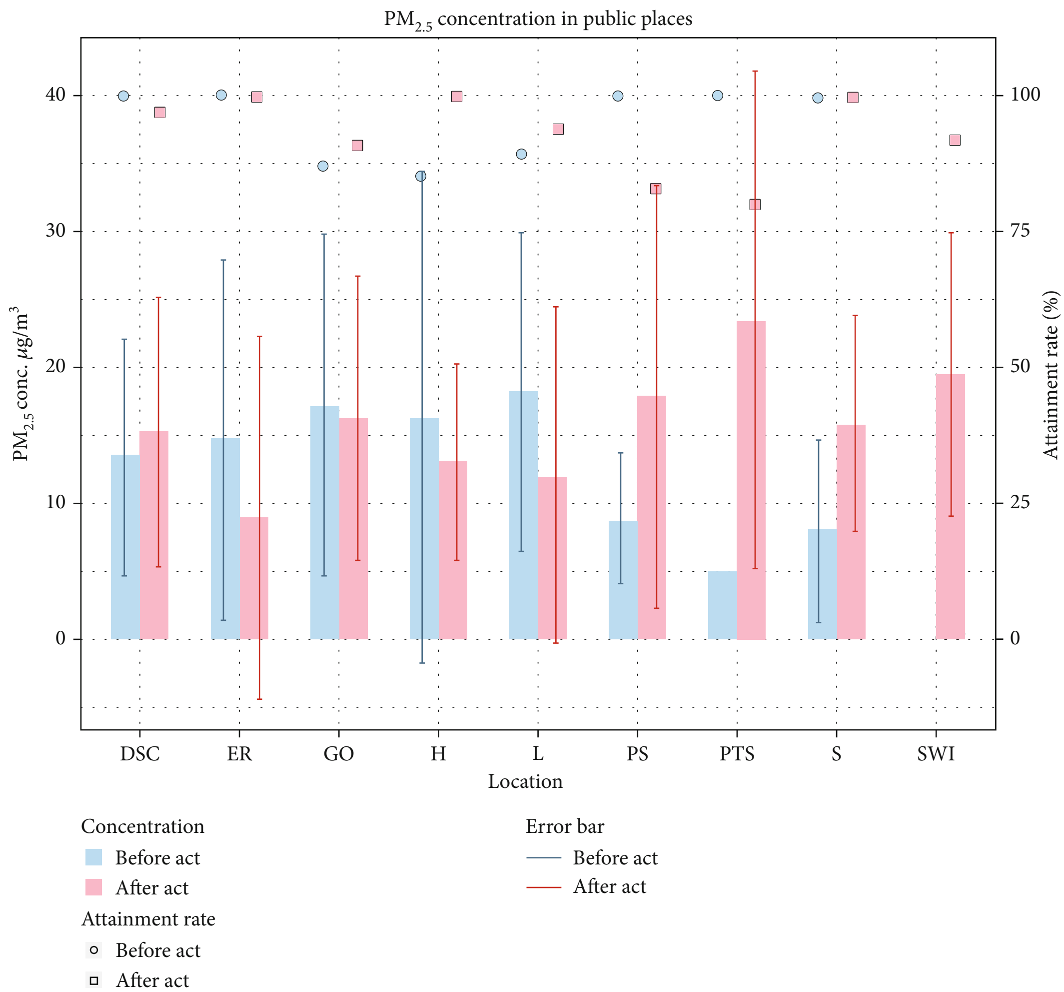

Figure 7: Concentrations of particulate matter with a diameter less than 2.5 μm ($PM_{2.5}$) in indoor environments and the corresponding attainment rates. H: hospital; L: library; S: school; ER: exhibition room; GO: government office; PS: preschool; DSC: department store/shopping center; PTS: public transport system; SWI: social welfare institution.

and libraries following the enactment of relevant measures, contrasting with other indoor environments. However, the attainment rates of particulate matters worsened in preschools and the public transport system, partly due to outdoor particulate pollution. These findings suggest that despite improvements in outdoor environments, the implementation of the IAQM Act remains necessary for enhancing IAQ, particularly for achieving high-efficiency improvements in IAQ in hospitals and libraries.

Finally, during the coronavirus pandemic, ambient levels of CO, O_3, SO_2, nitrogen dioxide (NO_2), PM_{10}, and $PM_{2.5}$ showed significant associations with SARS-CoV-2 mortality and morbidity worldwide. These findings further emphasized the significance of indoor and outdoor air quality in relation to infectious droplet dispersion during and after epidemic outbreaks [37]. Overall, the information presented in this study could be valuable for policy authorities and decision-makers when discussing potential enhancements to the IAQM Act.

4.2. Inhalation Cancer Risk. Formaldehyde, despite its economic significance, has been classified as a human carcinogen, linked to the development of nasopharyngeal cancer and potentially leukemia. In the U.S., exposure data were collected from 899 homes where acute formaldehyde concentrations exceeded higher than 100 $\mu g/m^3$ after the installation of Chinese-manufactured laminate flooring. The 50th and 95th percentile values of the expected lifetime cancer risk for residents in these homes were estimated to be 0.33×10^{-6} and 1.2×10^{-6}, respectively [18]. Similarly, in Spain, the mean carcinogenic risks associated with formaldehyde exposure in homes and workplaces were notably high ($>10^{-4}$) [23]. A study of five central European countries revealed that formaldehyde exposure in sixty-four primary school buildings led to median excess lifetime cancer risks exceeding the acceptable threshold of 1×10^{-6} [11]. In a heavily polluted city in northwestern China during wintertime, cancer risks attributed to formaldehyde (5.73×10^{-5}), 1,3-butadiene (2.07×10^{-5}), and 1,2-dichloroethane (1.44×10^{-5}) were all higher than the acceptable level of 1×10^{-6} [26]. In newly remodeled buildings in Beijing, China, the median cancer risks from indoor exposure to formaldehyde and benzene were 1.15×10^{-3} and 1.06×10^{-4}, respectively [20].

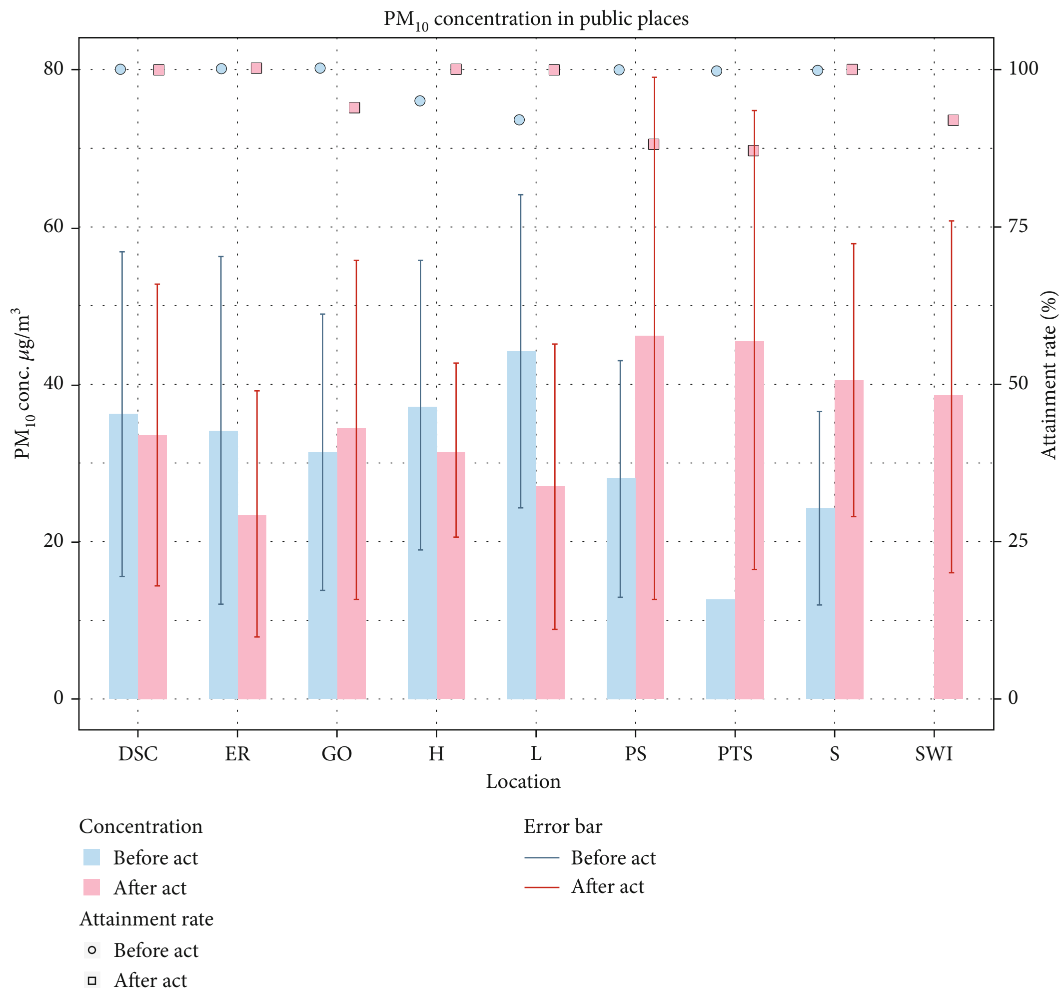

FIGURE 8: Concentrations of particulate matter with a diameter less than 10 μm (PM_{10}) in indoor environments and the corresponding attainment rates. H: hospital; L: library; S: school; ER: exhibition room; GO: government office; PS: preschool; DSC: department store/shopping center; PTS: public transport system; SWI: social welfare institution.

TABLE 2: Inhalation cancer risk of formaldehyde exposure for the general public in different indoor environments.

Location	Inhalation unit risk adjusted $(\mu g/m^3)^{-1}$	Before Conc. $(\mu g/m^3)$	Before Inhalation cancer risk Average	Before Inhalation cancer risk 95% upper limit	After Conc. $(\mu g/m^3)$	After Inhalation cancer risk Average	After Inhalation cancer risk 95% upper limit
School	3.25×10^{-6}	23.9	7.75×10^{-5}	2.44×10^{-4}	74.7	2.43×10^{-4}	5.23×10^{-4}
Library	3.25×10^{-6}	58.9	1.91×10^{-4}	5.25×10^{-4}	45.2	1.47×10^{-4}	2.82×10^{-4}
Preschool	4.33×10^{-6}	32.7	1.42×10^{-4}	3.92×10^{-4}	65.3	2.83×10^{-4}	8.80×10^{-4}
Hospital	2.17×10^{-6}	33.3	7.22×10^{-5}	2.19×10^{-4}	50.9	1.10×10^{-4}	2.48×10^{-4}
Social welfare institution	1.08×10^{-6}	0.0	—	—	74.7	8.09×10^{-5}	3.37×10^{-4}
Government office	2.71×10^{-6}	16.8	4.56×10^{-6}	1.16×10^{-5}	44.5	1.21×10^{-5}	3.44×10^{-5}
Public transport system	2.71×10^{-7}	8.6	2.33×10^{-6}	2.99×10^{-6}	82.8	2.24×10^{-5}	9.55×10^{-5}
Exhibition room	2.17×10^{-6}	54.6	1.18×10^{-4}	4.47×10^{-4}	31.5	6.83×10^{-5}	2.23×10^{-4}
Department store/shopping center	1.63×10^{-6}	75.3	1.22×10^{-4}	4.40×10^{-4}	75.3	1.22×10^{-4}	4.40×10^{-4}

Table 3: Inhalation cancer risk of formaldehyde exposure for staff workers in different indoor environments.

Location	Inhalation unit risk adjusted $(\mu g/m^3)^{-1}$	Before Conc. $(\mu g/m^3)$	Before Inhalation cancer risk Average	Before Inhalation cancer risk 95% upper limit	After Conc. $(\mu g/m^3)$	After Inhalation cancer risk Average	After Inhalation cancer risk 95% upper limit
School	4.33×10^{-6}	23.9	1.03×10^{-4}	3.25×10^{-4}	74.7	3.24×10^{-4}	6.97×10^{-4}
Library	4.33×10^{-6}	58.9	2.55×10^{-4}	7.00×10^{-4}	45.2	1.96×10^{-4}	3.76×10^{-4}
Preschool	4.33×10^{-6}	32.7	1.42×10^{-4}	3.92×10^{-4}	65.3	2.83×10^{-4}	8.80×10^{-4}
Hospital	4.33×10^{-6}	33.3	1.44×10^{-4}	4.38×10^{-4}	50.9	2.21×10^{-4}	4.95×10^{-4}
Social welfare institution	4.33×10^{-6}	0.0	—	—	74.7	3.24×10^{-4}	1.35×10^{-3}
Government office	4.33×10^{-6}	16.8	7.29×10^{-5}	1.85×10^{-4}	44.5	1.93×10^{-4}	5.51×10^{-4}
Public transport system	4.33×10^{-6}	8.6	3.73×10^{-5}	4.79×10^{-5}	82.8	3.59×10^{-4}	1.53×10^{-3}
Exhibition room	4.33×10^{-6}	54.6	2.36×10^{-4}	8.93×10^{-4}	31.5	1.37×10^{-4}	4.46×10^{-4}
Department store/shopping center	4.33×10^{-6}	75.3	3.26×10^{-4}	1.17×10^{-3}	75.3	3.26×10^{-4}	1.17×10^{-3}

Moreover, Chinese cooking oil fumes, which contain benzene, formaldehyde, $PM_{2.5}$-bound polycyclic aromatic hydrocarbons, and $PM_{2.5}$-bound heavy metals, were found to increase incremental lifetime cancer risks of 9.28×10^{-7}, 2.45×10^{-5}, 1.68×10^{-5}, and 5.80×10^{-4}, respectively [13]. In a study conducted in China involving 564 different public places, the excess cancer risk (ECR) of formaldehyde for employees in four categories of public places (hotel and social interaction areas, bathing and beauty establishments, cultural and entertainment venues, and shopping areas) ranged from 4.70×10^{-5} to 1.57×10^{-4}, with the highest ECR observed in bathing and beauty places [19]. Additionally, the highest ECR for formaldehyde exposure was 3.0×10^{-3} in a shopping mall in China [38].

In addition to indoor contaminants, outdoor formaldehyde contributes to indoor concentrations by about 25% [39]. However, a recent study in South Korea indicated that the indoor 95th percentile ECR of formaldehyde is nearly equal to the threshold stated in the IAQ Control Act and is about 10 times higher than its outdoor ECR [12]. Therefore, selecting appropriate materials for IAQ control becomes a crucial issue [20, 33].

Until now, measuring information remains insufficient in Taiwan, and the results of ECR indicate an immediate need for developed strategies to address formaldehyde exposure. As indoor VOCs and formaldehyde concentrations vary with indoor temperature and RH [24], ensuring good indoor environmental quality should consider about housing, well-being [40, 41] and thermal comfort [42], as well as affordable and clean energy [43]. This should also include VOCs and inorganic gaseous pollutant concentrations, along with their outdoor counterparts, indoor and outdoor temperature and RH, the month of the year, duration of window opening, kerosene heater usage and operation hours, and building age [25, 39]. The IAQM Act is pertinent to a multifaceted political, social, and health challenge [44]. In response, Taiwan EPA has established a platform aimed at advancing IAQ, encompassing staff training, the maintenance of IAQ management certification, and the implementation of standardized IAQ monitoring at regular intervals, alongside self real-time monitoring. The sustained efficacy of IAQ management demands ongoing scrutiny in the future.

5. Conclusions

Overall, the key strengths of this study are how it underscores the necessity for more measurement data postimplementation of the IAQM Act and the need for risk-based management strategies in future investigations. The current results imply that despite gradual improvements in outdoor environments, the enactment remains essential for enhancing IAQ, particularly for achieving significant improvements in hospitals and libraries. Continuous IAQ management should be maintained, especially in primary schools, to prevent and control acute and chronic diseases, particularly considering biological and chemical pollution. In addition, it is necessary to dedicate training on indoor air quality management in workplaces, and further investigations should formulate management strategies based on health risk assessment.

Data Availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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