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A Survey on Toxic Volatile Organic Compounds (VOCs): Toxicological Profiles, Health Exposure Risks, and Regulatory Strategies for Mitigating Emissions from Stationary Sources in Taiwan

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Abstract: With the revision of the Air Pollution Control Act in Taiwan announced on 1 August 2018, several provisions or regulations have been added to strengthen the control of hazardous air pollutants (HAPs) from stationary sources. Therefore, this paper conducted a survey of sixty toxic volatile organic compounds (VOCs) designated as HAPs in Taiwan and also performed a comparison between some developed countries (i.e., the USA, Japan, and Korea) using the latest databases issued by the relevant agencies/organizations. Furthermore, these designated HAPs were reviewed by their carcinogenic classifications and occupational exposure limits. Finally, the regulatory measures for controlling the emissions of toxic VOCs from stationary sources in Taiwan were addressed to echo the public concerns about their human health risk. Except for trichloroacetic acid, the designated toxic VOCs in Taiwan are included in the list of HAPs in the USA. By comparison, the number of designated HAPs is obviously higher than those in Japan and Korea. Based on the carcinogen classification by the International Agency for Research on Cancer (IARC), the toxic VOCs as confirmed human carcinogens (Group 1) include benzene, benzidine, 1,3-butadiene, 1,2-dichloroproane, ethylene oxide, formaldehyde, 4,4-methylene bis(2-chloroaniline), trichloroethylene, and vinyl chloride. To achieve the purpose of protecting public health, the follow-up control actions of HAPs from stationary sources in Taiwan involved regulatory countermeasures, including the establishment of emission limits, reporting systems, reduction plans for potential high-risk areas or plants, the incentive of an air pollution fee levy, as well as an ambient air concentration monitoring network.

Keywords: hazardous air pollutants; volatile organic compound; carcinogenic classification; occupational exposure limit; regulatory measure

Citation: Tsai, W.-T. A Survey on Toxic Volatile Organic Compounds (VOCs): Toxicological Profiles, Health Exposure Risks, and Regulatory Strategies for Mitigating Emissions from Stationary Sources in Taiwan. *Atmosphere* **2023**, *14*, 242. https://doi.org/10.3390/atmos14020242

Academic Editor: Evangelos Tolis

Received: 9 December 2022
Revised: 17 January 2023
Accepted: 23 January 2023
Published: 26 January 2023

1. Introduction

Hazardous air pollutants (HAPs), also called air toxics or toxic air pollutants, are those that are known or suspected to cause cancer or other acute and chronic effects on human health, such as reproductive effects or birth defects, or mutagenic effects [1]. These HAPs may be emitted by industrial sources, but also exist in residential areas. For example, benzene is found in gasoline, tetrachloroethylene could be emitted by some dry cleaners, and methylene chloride is widely used as a degreasing solvent and paint stripper. As a consequence, some known carcinogens, including vinyl chloride and benzene, were listed as HAPs during the 1970s under the U.S. Clean Air Act Amendments (CAAA) [2]. Furthermore, the CAAA of 1990 offered a comprehensive plan for achieving significant reductions in the emissions of 188 HAPs from major sources. A major class of these designated HAPs or indoor air pollutants includes volatile organic compounds (VOCs). Some developed countries in Asia, including Japan [3–5] and Korea [6–8], have also promulgated some regulations for controlling HAPs since the late 1990s. In Japan, the environmental quality standards (EQSs) were established by the Basic Environment Law, which aims to protect

human health and also conserve the living environment. Under the authorization of the Air Pollution Control Act in Japan, EQSs in ambient air have been set for benzene, tetrachloroethylene, trichloroethylene, and dichloromethane, and guideline values have been set for acrylonitrile, vinyl chloride, 1,3-butadiene, chloroform and 1,2-dichloroethane [3,4,9].

In recent years, the health hazards associated with air pollution have become an important public issue in Taiwan because some air pollutants have been listed as Group 1 carcinogens (carcinogenic to humans) by the International Agency for Research on Cancer (IARC) [10]. In response to the global health issue, the Taiwan Environmental Protection Administration (EPA) has focused on reducing the emissions of HAPs since the mid-1990s, such as heavy metals [9]. Considering the impact of other HAPs on public health, industry-specific emission standards for semiconductor manufacturing, polyurethane (PU) synthetic leather, dry cleaning operations, optoelectronic materials and components manufacturing, type manufacturing, and vinyl chloride monomer (VCM) and polyvinyl chloride (PVC) manufacturing have been established by the Taiwan EPA since 1997 so as to control these toxic VOCs. The target VOCs included trichloroethylene, dimethyl formaldehyde, tetrachloroethylene, and vinyl chloride. Under the authorization of the Air Pollution Control Act revised on 1 August 2018 [11], several regulations have been added to control the emissions of HAPs from stationary sources. They include the "First Batch for Categories and Emission Limits of Hazardous Air Pollutants from Stationary Sources", the "Risk Assessment Procedures for Hazardous Air Pollutants from Stationary Sources", and the "Emission Standards of Hazardous Air Pollutant from Stationary Sources". In addition to these regulations, an air pollution fee has been levied on 13 VOCs (i.e., toluene, xylenes, benzene, ethylbenzene, styrene, methylene chloride, 1,1-dichloroethane, 1,2-dichloroethane, chloroform, methyl chloroform, carbon tetrachloride, trichloroethylene, and tetrachloroethylene) since 1999. Furthermore, the actions for HAPs emitted by stationary sources involve regulatory countermeasures, including reporting systems, reduction plans for potential high-risk areas, as well as an ambient air concentration monitoring network [11].

Few works on the description of the regulatory measures for HAPs from stationary sources in Taiwan have been conducted in the literature. The previous case study [12] focused on the management of toxic air pollutants in Taiwan, especially for the emissions of heavy metals and dioxins. As reviewed above, the emissions of toxic VOCs from stationary sources have been highlighted by the Taiwan government due to their chronic effects because they could pose adverse effects on human health, such as carcinogenicity [2]. Therefore, these hazardous substances have been designated as HAPs according to the revision of the Air Pollution Control Act of 2018. According to the updated information about HAPs management, this paper will conduct a survey of toxic VOCs designated as HAPs in Taiwan and some developed countries (i.e., the USA, Japan, and Korea). Furthermore, these designated HAPs were reviewed by their carcinogenic classifications and occupational exposure limits. Finally, regulatory strategies for controlling the emissions of toxic VOCs from stationary sources were addressed to echo the public concerns about the human health risks and highlight their lower ambient levels in comparison with those in Korea and Japan.

2. Data Mining Methods

In this study, an analytical description of the HAP lists and their control measures was facilitated using the latest databases issued by the relevant central government agencies, including the EPA in the USA [13] and Taiwan [14], the Ministry of the Environment in Japan [15], and the Ministry of Environment in Korea [16]. Concerning the carcinogenic classifications of the relevant HAPs, their updated data will be accessed on the IARC [10] and other databases, such as that of the National Toxicology Program (NTP) [17]. In addition to affecting ambient air quality, HAPs also impact the working environment because most of them are released by industrial sources. In this study, the permissible exposure limits (PELs) or occupational exposure limits (OELs) of these toxic VOCs that have been set/recommended were compiled from the competent authorities, including

the Occupational Safety and Health Administration (U.S. Department of Labor) [18], the Occupational Safety and Health Administration (Ministry of Labor, Taiwan) [19], and the Japan Society for Occupational Health [20]. The information about the regulatory measures for controlling the emissions of HAPs from stationary sources was obtained from the official website [11].

3. Results and Discussion

3.1. A Survey on Toxic Volatile Organic Compounds (VOCs) Designated as Hazardous Air Pollutants (HAPs)

As mentioned above, the Taiwan EPA announced revisions for the "Categories and Emission Limits of Hazardous Air Pollutants from Stationary Sources" on 29 July 2022. Among them, 61 organic compounds were listed as HAPs. Except for polychlorinated dibenzo-p-dioxins and polychlorinated dibenzo-furans (PCDDs/PCDFs), the others belong to volatile organic compounds (VOCs). These toxic VOCs, excluding trichloroacetic acid, are also listed as HAPs in the USA, as shown in Table 1 [3,4,6,8,13]. It should be noted that trichloroacetic acid has been documented to mainly originate from the metabolites of commonly used chlorinated compounds, such as methyl chloroform and tetrachloroethene [21].

Table 1. Lists of Taiwan's toxic VOCs regulated as hazardous air pollutants in connection with the USA, Japan, and Korea.

Toxic VOC (CAS No.) [1]	USA	Japan	Korea
Acetaldehyde (75-07-0)	v [2]	v	v
Acetamide (60-35-5)	v		
Acrolein (107-02-8)	v		
Acrylamide (79-06-1)	v		
Acrylonitrile (107-13-1)	v	v	v
Allyl chloride (107-05-1)	v		
Aniline (62-53-3)	v		v
o-Anisidine (90-04-0)	v		
Benzene (71-43-2)	v	v	v
Benzidine (92-87-5)	v		v
Benzotrichloride (98-07-7)	v		
Benzyl chloride (100-44-7)	v		
Bis(2-ethylhexyl) phthalate (117-81-7)	v		
Bromoform (75-25-2)	v		
1,3-Butadiene (106-99-0)	v	v	v
Carbon tetrachloride (56-23-5)	v		v
Catechol (120-80-9)	v		
Chloroform (67-66-3)	v	v	v
Chloroprene (126-99-8)	v		
1,4-Dichlorobenzene (106-46-7)	v		
1,1-Dichloroethane (75-34-3)	v		
1,2-Dichloroethane (107-06-2)	v	v	v
1,1-Dichloroethylene (75-35-4)	v		
1,2-Dichloropropane (78-87-5)	v		
3,3′-Dimethyl-[1,1′-biphenyl]-4,4′-diamine (119-93-7)	v		
N,N-Dimethylformamide (68-12-2)	v		
1,1-Dimethylhydrazine (54-14-7)	v		
1,4-Dioxane (123-91-1)	v		
Epichlorohydrin (106-89-8)	v		
1,2-Epoxypropane (75-56-9)	v		v
Ethyl acrylate (140-88-5)	v		
Ethylbenzene (100-41-4)	v		v
Ethylene dibromide (106-93-4)	v		
Ethylene oxide (75-21-8)	v	v	v
Ethylene imine (151-56-4)	v		
Ethylene thiourea (96-45-7)	v		
Formaldehyde (50-00-0)	v	v	v
Hexachlorobenzene (118-74-1)	v		
Hexachloroethane (67-72-1)	v		
Hydroquinone (123-31-9)	v		
Methyl bromide (74-83-9)	v		
Methyl chloride (74-87-3)	v		

Table 1. *Cont.*

Toxic VOC (CAS No.) [1]	USA	Japan	Korea
4,4′-Methylene bis(2-chloroaniline) (101-14-4)	v		
Methylene chloride (75-09-2)	v	v	v
4,4′-Methylenedianiline (101-77-9)	v		
Nitrobenzene (98-95-3)	v		
N-Nitrosodimethyl amine (62-75-9)	v		
Phenol (108-95-2)	v		v
Styrene (100-42-5)	v		v
1,1,2,2-Tetrachloroethane (79-34-5)	v		
Tetrachloroethene (127-18-4)	v	v	v
Toluene (108-88-3)	v		
2,4-Toluene diisocyanate (584-84-9)	v		
Trichloroacetic acid (76-03-9)			
1,1,1-Trichloroethane (71-55-6)	v		
1,1,2-Trichloroethane (79-00-5)	v		
Trichloroethene (79-01-6)	v	v	v
Vinyl acetate (108-05-4)	v		
Vinyl chloride (75-01-4)	v	v	v
Xylenes (1330-20-7)	v		

[1] CAS: Chemical Abstracts Service; [2] Listed.

3.1.1. USA

Based on the definition by the U.S. Environmental Protection Agency (US EPA), the HAPs are a variety of toxic air pollutants that can cause acute illness, such as nausea and other respiratory injuries, and chronic diseases, such as carcinogenicity and teratogenicity [22]. Since the 1970s, some carcinogenic chemicals have been specified as HAPs according to the National Emission Standards for Hazardous Air Pollutants (NESHAP), which was authorized by the Clean Air Act Amendments. They included vinyl chloride in 1975 and benzene in 1977 [2]. In 1990, the Clean Air Act Amendments requires the US EPA to regulate toxic air pollutants, also known as air toxics or HAPs, from categories of industrial facilities in two phases (i.e., the first phase is "technology-based" and the second phase in "risk-based"). This original list included 189 HAPs. Since 1990, the US EPA has modified the list through rulemaking to include 188 HAPs. Most of them are VOCs.

3.1.2. Japan

In Japan, the fundamental law or act is the Air Pollution Control Act (Act No. 97 of 1968), which aims to protect the health of the people and also preserve the living environment from the effects of air pollution. According to the definition by the Act, the term "hazardous air pollutant" refers to an airborne substance that could cause air pollution and also be harmful to human health. Various carcinogenic VOCs, including benzene and chlorinated VOCs (e.g., trichloroethylene), have been detected in the ambient air in low concentrations [3]. Concerning the effects of HAPs on human health, the central government must venture jointly with local governments to conduct studies on the air quality deterioration by HAPs by the use of scientific knowledge. Based on the monitoring data, the human health risks posed by HAPs must be also evaluated and periodically disclosed by the central government. In Japan, 23 substances have been designated as priority HAPs for which measures should be taken with special actions. Among them, 13 toxic VOCs were listed as priority HAPs, but chloromethyl methyl ether (CAS No. 107-30-2) is not listed in Table 1. In this regard, environmental standards on the basis of annual averages for benzene, trichloroethylene, tetrachloroethylene, and dichloromethane have been established [9].

3.1.3. Korea

Currently, 35 substances are designated as HAPs in Korea under the Clean Air Conservation Act, based on their toxicities, environmental and physicochemical properties, impact on ecosystems, atmospheric emission volume, ambient concentration level, and international regulations. Among them, 13 types of VOCs have been measured by 31 stations in the monitoring network to identify the contamination status of specific HAPs in urban

areas or nearby industrial complexes [6,8]. They include five chlorinated VOCs (i.e., carbon tetrachloride, chloroform, ethyl dichloride, tetrachloroethylene, and trichloroethylene) and eight non-chlorinated VOCs (i.e., acetaldehyde, acrylonitrile, benzene, 1,3-butadiene, ethylbenzene, formaldehyde, propylene oxide, and styrene).

3.2. A Survey on Toxic VOCs Designated as HAPs for Their Carcinogenic Classifications

Based on the epidemiological report [23], high cancer risks from exposure to toxic VOCs have been strongly supported. These substances, such as benzene and vinyl chloride, were specified as HAPs in the NESHAP under the USA Clean Air Act Amendments of 1970 and 1977. Regarding the assessment and designation of a chemical substance as carcinogenic in humans, the International Agency for Research on Cancer (IARC) should be the most important agency in the world. Based on the strength of evidence for carcinogenicity in humans, five groups were categorized, as follows [10]:

- Group 1: Carcinogenic to humans;
- Group 2A: Probably carcinogenic to humans;
- Group 2B: Possibly carcinogenic to humans;
- Group 3: Not classifiable to be carcinogenic to humans;
- Group 4: Probably not carcinogenic to humans.

Other significant classifications include the NTP of the U.S. Department of Health and Human Services, which is mandated to produce a biennial *Report on Carcinogens* [17]. Currently, 256 substances have been classified into two groups:

- Known to be a human carcinogen;
- Reasonably anticipated to be a human carcinogen.

Table 2 lists the classification of carcinogenicity regarding toxic VOCs designated as HAPs in Taiwan. Based on the classification of carcinogenicity by the IARC, the toxic VOCs designated as confirmed human carcinogens (Group 1) include benzene, benzidine, 1,3-butadiene, 1,2-dichloroproane, ethylene oxide, formaldehyde, 4,4-methylene bis(2-chloroaniline), trichloroethylene, and vinyl chloride.

Table 2. Carcinogenicity classification (group) of toxic VOCs designated as HAPs in Taiwan.

Toxic VOC	IARC	USNTP
Acetaldehyde	2B	RAHC [1]
Acetamide	2B	-
Acrolein	2A	-
Acrylamide	2A	RAHC
Acrylonitrile	2B	RAHC
Allyl chloride	3	-
Aniline	2A	-
Benzene	1	Known
Benzidine	1	Known
Benzotrichloride	2A	RAHC
Benzyl chloride	2A	-
Bis(2-ethylhexyl) phthalate	2B	RAHC
Bromoform	3	-
1,3-Butadiene	1	Known
Carbon tetrachloride	2B	RAHC
Catechol	2B	-
Chloroform	2B	RAHC
Chloroprene	2B	RAHC
1,4-Dichlorobenzene	2B	RAHC
1,2-Dichloroethane	2B	RAHC
1,1-Dichloroethylene	2B	-
1,2-Dichloropropane	1	-
3,3′-Dimethyl benzidine	2B	RAHC

Table 2. *Cont.*

Toxic VOC	IARC	USNTP
N,N-Dimethylformamide	2A	-
1,1-Dimethylhydrazine	2B	RAHC
1,4-Dioxane	2B	RAHC
Epichlorohydrin	2A	RAHC
1,2-Epoxypropane	2B	RAHC
Ethyl acrylate	2B	-
Ethylbenzene	2B	-
Ethylene dibromide	2A	RAHC
Ethylene oxide	1	Known
Ethylene imine	2B	-
Ethylene thiourea	3	RAHC
Formaldehyde	1	Known
Hexachlorobenzene	2B	RAHC
Hexachloroethane	2B	RAHC
Hydroquinone	3	-
Methyl bromide	3	-
Methyl chloride	3	-
4,4-Methylene bis(2-chloroaniline)	1	RAHC
Methylene chloride	2A	RAHC
4,4′-Methylenedianiline	2B	RAHC
Nitrobenzene	2B	RAHC
N-Nitrosodimethyl amine	2A	RAHC
2-Methoxyaniline	2A	RAHC
Phenol	3	-
Styrene	2A	RAHC
1,1,2,2-Tetrachloroethane	2B	-
Tetrachloroethene	2A	RAHC
Toluene	3	-
2,4-Toluene diisocyanate	2B	RAHC
Trichloroacetic acid	2B	-
1,1,1-Trichloroethane	2A	-
1,1,2-Trichloroethane	3	-
Trichloroethene	1	Known
Vinyl acetate	2B	-
Vinyl chloride	1	Known
Xylenes	3	-

[1] RAHC: Reasonably anticipated to be a human carcinogen.

3.3. A Survey on Toxic VOCs Designated as HAPs for Their Occupational Exposure Limits

It is well known that most of the toxic VOC emissions come from industrial sources, thus causing their low concentration levels in the ambient air. The effect of exposure to them on occupational workers has attracted the concern of laborers, decision-makers, and lawmakers. Therefore, permissible exposure limits (PELs) or occupational exposure limits (OELs) of these toxic VOCs have been set/recommended by the competent authorities. These limits are acceptable/allowable concentrations or reference values for hazardous substances airborne in the workplace to prevent adverse health effects on workers caused by occupational exposure to them for 8 h a day, 40 h a week under a moderate workload. Table 3 lists the updated values of PELs in Taiwan and the USA, and OELs in Japan. The PELs in Taiwan and USA are set by the Occupational Safety and Health Administration (OSHA) [18], part of the Department of Labor. In contrast, the OELs in Japan are recommended by the Japan Society for Occupational Health (JSOH) [20], one of the competent professional associations. In general, the PELs or OELs are based on information from industrial experience and animal experiments. They cannot be used simply as a relative scale of toxicity or be applied as reference values in non-occupational environments due to the variances in individual susceptibilities and prerequisite (or working) conditions.

Therefore, we should be careful to prevent misunderstanding and misuse of the PELs/OELs when quoting them, especially for occupational carcinogens.

Table 3. Permissible exposure limits (PELs)/occupational exposure limits (OELs) of toxic VOCs in Taiwan, the USA, and Japan.

Toxic VOC	PEL—Taiwan	PEL—USA [1]	OEL—Japan [2]
Acetaldehyde	100 ppm	100 ppm	10 ppm (C)
Acetamide	-	-	
Acrolein	0.1 ppm	0.3 ppm	
Acrylamide	0.03 mg/m^3	0.03 mg/m^3	0.1 mg/m^3
Acrylonitrile	2 ppm	2 ppm	2 ppm
Allyl chloride	1 ppm	1 ppm	1 ppm
Aniline	2 ppm	2 ppm	1 ppm
o-Anisidine			0.1 ppm
Benzene	1 ppm	10 ppm	(Group 1) [3]
Benzidine	-	-	-
Benzotrichloride	-	-	(Group 1)
Benzyl chloride	1 ppm	1 ppm	
Bis(2-ethylhexyl) phthalate	5 mg/m^3	5 mg/m^3	
Bromoform	0.5 ppm	0.5 ppm	0.1 ppm
1,3-Butadiene	5 ppm	1 ppm	(Group 1)
Carbon tetrachloride	2 ppm	2 ppm	5 ppm
Catechol	-	-	
Chloroform	10 ppm (C)	50 ppm (C)	3 ppm
Chloroprene	10 ppm	25 ppm	
1,4-Dichlorobenzene	75 ppm	75 ppm	10 ppm
1,1-Dichloroethane	100 ppm		100 ppm
1,2-Dichloroethane	10 ppm	1 ppm	10 ppm
1,1-Dichloroethylene	200 ppm	200 ppm	
1,2-Dichloropropane	75 ppm	75 ppm	1 ppm (Group 1)
3,3′-Dimethyl-[1,1′-biphenyl]-4,4′-diamine	-	-	1 ppm (Group 1)
N,N-Dimethylformamide	10 ppm	10 ppm	10 ppm
1,1-Dimethylhydrazine	-	0.01 ppm	
1,4-Dioxane	25 ppm	0.28 ppm	1 ppm
Epichlorohydrin	2 ppm	5 ppm	
1,2-Epoxypropane	20 ppm	2 ppm	
Ethyl acrylate	25 ppm	25 ppm	
Ethylbenzene	100 ppm	100 ppm	20 ppm
Ethylene dibromide	20 ppm	0.13 ppm (C)	-
Ethylene oxide	1 ppm	1 ppm	1 ppm (Group 1)
Ethylene imine	0.5 ppm	0.5 ppm	0.05 ppm
Ethylene thiourea	-	-	-
Formaldehyde	1 ppm	1 ppm	0.1 ppm
Hexachlorobenzene	-	-	
Hexachloroethane	1 ppm	1 ppm	1 ppm (Provisional)
Hydroquinone	2 mg/m^3	2 mg/m^3	
Methyl bromide	5 ppm	5 ppm	1 ppm
Methyl chloride	50 ppm	50 ppm	50 ppm
4,4′-Methylene bis(2-chloroaniline)	0.02 ppm	0.02 ppm	
Methylene chloride	50 ppm	50 ppm	50 ppm
4,4′-Methylenedianiline	50 ppm	25 ppm	0.4 mg/m^3
Nitrobenzene	1 ppm	1 ppm	1 ppm
N-Nitrosodimethyl amine	-	-	-
2-Methoxyaniline	0.1 ppm	0.1 ppm	
Phenol	5 ppm	5 ppm	5 ppm
Styrene	50 ppm	50 ppm	10 ppm (Provisional)
1,1,2,2-Tetrachloroethane	1 ppm	1 ppm	1 ppm
Tetrachloroethene	50 ppm	25 ppm	(Pending)
Toluene	100 ppm	10 ppm	50 ppm
2,4-Toluene diisocyanate	0.005 ppm	0.005 ppm	
Trichloroacetic acid	-	-	
1,1,1-Trichloroethane	350 ppm	350 ppm	200 ppm
1,1,2-Trichloroethane	10 ppm	10 ppm	10 ppm
Trichloroethene	50 ppm	25 ppm	25 ppm (Group 1)
Vinyl acetate	10 ppm	-	
Vinyl chloride	1 ppm	1 ppm	(Group 1)
Xylenes	100 ppm	100 ppm	50 ppm

[1] PEL: Permissible exposure limit set by the Occupational Safety and Health Administration (OSHA) [18]. [2] OEL: Recommended by the Japan Society for Occupational Health (JSOH) [20]. [3] Human carcinogen classified by the IARC.

3.4. Regulatory Strategies for Controlling the Emissions of Toxic VOCs from Stationary Sources

This Act (updated on 1 August 2018) aims to control air pollution, maintain the living environment and public health, and enhance quality of life. Under the authorizations of Article 20/Article 28 in the law, the Taiwan EPA promulgated relevant regulations for controlling the emissions of air pollutants from stationary sources. On the other hand, the Taiwan EPA also set up 79 air quality observation stations, which can be categorized into 5 industrial stations, 6 traffic stations, 5 background stations, 2 national park stations, and 61 general stations based on the observation purposes. Concerning the ambient levels of VOCs for health risks and ozone formation potential, they include BTEX (benzene, toluene, ethylbenzene, and xylenes), which are monitored in the industrial stations [24,25]. According to the hourly monitoring data during 2016 [24], the highest average VOC concentrations were 0.98, 0.33, 0.25, and 0.08 ppbv for toluene, xylenes, benzene, and ethylbenzene, respectively. These results were significantly lower than those reported by other countries, such as Korea [8,26] and Japan [27].

In the APCA, Article 20 refers to the countermeasures against air pollution [11], including:

- The stationary sources that emit air pollutants shall comply with emission standards. Herein, the stationary sources may include point and area sources;
- The EPA, in consultation with relevant agencies, shall determine the emission standards based on specially designated industry categories, facilities, pollutant items, or areas;
- The above-mentioned emission standards shall include hazardous air pollutants, and the emission standards shall be determined based on the result of health risk evaluation and feasibility of control technology;
- The EPA shall officially announce types of hazardous air pollutants and the operation of health risk evaluation.

Concerning the control measures for HAPs, the Taiwan EPA thus promulgated staged regulations, which will be described below.

1. "First Batch for Categories and Emission Limits of Hazardous Air Pollutants from Stationary Sources"

On 5 October 2019, the Taiwan EPA announced this Regulation, which stipulates 73 types of HAPs as the prioritized targets, including volatile organic HAPs (61 substances), heavy metals and their compounds (8 substances), and others (4 substances). The first batch of the 73 HAPs was mainly based on the lists of HAPs covered by the Clean Air Act Amendments of 1990 (USA), the Air Pollution Control Act (Japan), and the Clean Air Conservation Act (Korea). The regulations were then finalized after taking into consideration the health risk assessments published by the International Agency for Research on Cancer (IARC). In addition, the emission limits of five substances were promulgated in the first batch, which included vinyl chloride at 20 ppm and trichloroethylene at 5000 ppm.

2. "Risk Assessment Procedures for Hazardous Air Pollutants from Stationary Sources"

On 5 October 2019, the Taiwan EPA announced this Regulation, which shall set the standardized health risk assessment procedures for the HAPs designated by the Taiwan EPA and the impacts on the human risk of inhalation exposure. These procedures must include the following four steps.

- Hazard identification: This step must assess the categories of HAPs, their chronic toxicities (e.g., carcinogenicity, reproductive toxicity, and mutagenicity), and emission statuses (e.g., source and amount);
- Dose–effect assessment: This step shall determine the inhalation cancer slope factors or inhalation unit risks for a given carcinogenic HAP. For a given non-carcinogenic HAP, their reference acute and chronic concentrations shall be stated;
- Exposure assessment: This step shall assess the total inhalation exposure dose for residents living in the affected area due to the dispersion and/or diffusion of HAPs;

- Description of risk characteristics: Based on the abovementioned results, this step shall determine the increased carcinogenic and non-carcinogenic risks for the affected residents caused by the exposure to HAPs. The risk assessment shall be analyzed for uncertainty within a 95% upper confidence limit.

3. "Emission Standards of Hazardous Air Pollutant from Stationary Sources"

On 26 February 2021, the Taiwan EPA announced this Regulation, which designated the emission standards (emission pipe standards and peripheral boundary standards) for 22 HAPs, including volatile organic HAPs (15 substances) and heavy metals/inorganic elements and their compounds (6 substances). These substances designated as HAPs included seven chlorinated VOCs (i.e., 1,2-dichloroethane, methylene chloride, trichloroethylene, chloroform, tetrachloroethylene, carbon tetrachloride, and vinyl chloride) and eight non-chlorinated VOCs (i.e., 1,3-butadiene, ethylbenzene, xylenes, acrylonitrile, toluene, formaldehyde, benzene, and styrene). However, the emission pipe standards shall be measured in accordance with the methods listed in Article 7 of the Regulation. In response to the different testing methods and available technologies, the Regulation will be implemented in two stages for the existing sources.

4. "Categories and Emission Limits of Hazardous Air Pollutants from Stationary Sources" (Draft)

On 28 July 2022, the Taiwan EPA preannounced this draft Regulation based on the previous Regulation on 5 October 2019 and the above Regulation on 26 February 2021. The draft expanded the categories and emission standards of HAPs from stationary sources, tightening the emission limit for a HAP (i.e., trichloroethylene) and adding new emission limits for 23 HAPs. Among them, 15 toxic VOCs were designated as HAPs in Taiwan. The draft classified two types of emissions limits for exhaust pipes and illegal clandestine discharges. Table 4 lists the emission limits of these toxic VOCs. By calculating the emission concentrations in exhaust pipes and also using the air dispersion model, the draft also defined the emission limits of designated HAPs based on environmental risks. The environmental risk of a toxic pollutant after being emitted from exhaust pipes is calculated as 1.0×10^{-4} of its highest concentration on the ground surfaces of surrounding environments. This risk is equivalent to the upper threshold throughout their whole life that an individual is able to withstand under long-term exposure to it in the atmosphere. Herein, human health is at risk if the anticipated concentration is above such an emission limit. Furthermore, the emission limit of a given HAP for illegal clandestine discharges is set at 1/100th of that through exhaust pipes.

Table 4. Emission limits of toxic VOCs designated as HAPs in Taiwan.

Toxic VOC	Emission Limit		Comments
	Emission Pipe	Illegal Emission Pipe	
Acrylonitrile	35 ppm	0.35 ppm	1. The standard for calculating the concentration of all pollutants shall be based on a non-diluted dry exhaust volume at 273 K and 1 atm. 2. Illegal emission is defined as follows: Collection equipment is used to capture process exhaust gas, which is not introduced into the flue, stack, or exhaust pipeline, but introduced into plant ventilation holes for emission.
Benzene	50 ppm	0.5 ppm	
1,3-Butadiene	20 ppm	0.2 ppm	
Carbon tetrachloride	50 ppm	0.5 ppm	
Chloroform	20 ppm	1.2 ppm	
1,2-Dichloroethane	175 ppm	1.75 ppm	
Ethylbenzene	175 ppm	1.75 ppm	
Formaldehyde	70 ppm	0.7 ppm	
Methylene chloride	120 ppm	1.2 ppm	
Styrene	120 ppm	1.2 ppm	
Tetrachloroethene	120 ppm	1.2 ppm	
Toluene	180 ppm	1.8 ppm	
Trichloroethene	55 ppm	0.55 ppm	
Vinyl chloride	50 ppm	0.2 ppm	
Xylenes	175 ppm	1.75 ppm	

4. Conclusions and Recommendations

In this paper, updated information about the toxic volatile organic compounds (VOCs) designated as hazardous air pollutants (HAPs) in Taiwan is extensively described and compared between the USA, Japan, and Korea. The carcinogenic health risks and occupational exposure limits of these toxic VOCs and the regulatory strategies for controlling their emissions from stationary sources are addressed. The findings show that the designated toxic VOCs in Taiwan, excluding trichloroacetic acid, are included in the list of HAPs in the USA. Obviously, the number of designated HAPs in Taiwan is higher than those in Japan and Korea.

Although the Taiwan government promulgated some regulations governing the emissions of HAPs from stationary sources since 2019, some recommendations are further made, as follows.

- By referring to the environmental quality standards/guidelines in Japan and the data on mass production/consumption in Taiwan, the government should set the air quality guidelines or standards for carcinogenic VOCs as priority targets, including benzene, formaldehyde, 1,3-butadiene, ethylene oxide, vinyl chloride, and trichloroethylene;
- To satisfy the right to know of the public, the government should also establish monitoring systems for carcinogenic HAPs in hot areas near industrial parks and open these monitoring results to the public regularly;
- Based on the monitoring results, the government should perform epidemiological surveillance for the residents living in the hot areas or near the industrial parks, which can be connected to the National Health Insurance Research Database.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data is contained within the article.

Conflicts of Interest: The author declares no conflict of interest.

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