Estimation of Anthropogenic VOCs Emission Based on Volatile Chemical Products: A Canadian Perspective

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Abstract
Volatile organic compounds (VOCs) in urban areas are of great interest due to their significant role in forming ground-level ozone and adverse public health effects. Emission inventories usually compile the outdoor VOCs emission sources (e.g., traffic and industrial emissions). However, considering emissions from volatile chemical products (e.g., solvents, printing ink, personal care products) is challenging because of scattered data and the lack of an effective method to estimate the VOCs emission rate from these chemical products. This paper aims to systematically analyse potential sources of VOCs emission in Canada’s built environment, including volatile chemical products. Also, spatial variation of VOCs level in the ambient atmosphere is examined to understand the VOC relationship with ozone and secondary organic aerosol formation. The study shows that VOCs level may vary among everyday microenvironments (e.g., residential areas, offices, and retail stores) depending on the frequency of product consumption, building age, ventilation condition, and background ambient concentration in the atmosphere. However, it is very difficult to establish VOC speciation and apportionment to different volatile chemical products that contribute most significantly to exposure and target subpopulations with elevated levels. Thus, tracer compounds can be used to identify inventory sources at the consumer end. A critical overview highlights the limitations of existing VOC estimation methods and possible approaches to control VOC emissions. The findings provide crucial information to establish an emission inventory framework for volatile chemical products at a national scale and enable policymakers to limit VOCs emission from various volatile chemical products.

Keywords Volatile organic compounds · Volatile chemical products · Emission inventory · Built environment · Solvents

Introduction

The presence of volatile organic compounds (VOCs) is practically inevitable in the urban environment and is considered one of the major indoor air pollutants (USEPA, 2018a). Because of life style changes and recent COVID-19 lockdowns, most people spend a substantial amount of their time in an indoor environment which raises the concern of indoor air quality (IAQ), especially in tightly sealed and poorly ventilated dwellings (Masjedi et al., 2019; Shayegan et al., 2019; Asif et al., 2022). According to the “World Health Organization” (WHO), indoor air pollution (IAP) causes 3.8 million people death annually (WHO, 2022).

In contrast to other air pollutants, VOCs could be easily generated inside buildings because of occupants’ activities, emissions from building materials, volatile chemical products (VCPs), including consumer products (e.g., domestic solvents, paints, dry cleaning, personal care products, fragrance, cleaning products) and other commercial and industrial products (e.g., oil and gas solvents, coating, printing ink, pesticides adhesive and sealants) (Kumar and Imam, 2013; McDonald et al., 2018; Gkatzelis et al. 2021a). High levels of indoor VOCs are associated with many adverse health effects, including breathing difficulty, skin, and eye irritation (Goodman et al., 2017; Verma et al., 2019). Long-term exposure to VOCs increases the risk of asthma and lung cancer, sick building syndrome, and other building-related illness (Van Tran et al., 2020).

VOCs can escape into the ambient atmosphere from their source (e.g., carpeting, paints, ink printing, solvents, personal care products) because of organic compounds’ relatively high vapor pressure and boiling point below 250°C (at ambient atmospheric pressure) (Goodman et al., 2017;
U.S. Environmental Protection Agency, 2018). VOCs in the ambient atmosphere act as a precursor of ground-level ozone and secondary organic aerosols (SOA) (Song et al., 2019). Categorically, VCPs can contribute to 10ppb ground-level ozone in urban areas (Qin et al., 2021), and account for more than 50% of the total anthropogenic VOCs (Coggona et al., 2021).

Previous studies also showed a close correlation between indoor and outdoor pollutants; in fact, most the outdoor VOCs (e.g., traffic, biogenic emissions, oil and gas industries, agricultural activities, energy sector) could penetrate or infiltrate through cracks and window gaps (Wan et al., 2015; Li et al., 2019a; Chen and Zhao, 2017). Thus, the average indoor level of VOCs is five times higher than outdoors (Bari et al. 2015; USEPA, 2018b). Accurately quantifying the VCPs emission would help to strategize the control techniques and attain the United nation’s sustainable development goals (SDGs), specifically “SDG 3: Good health and well-being” and “SDG 12: Responsible consumption and production” (Ansar et al., 2021).

Trends over the past few years have shown a remarkable decrease in VOC emissions (e.g., 49% reduction in 2020 since 1990) due to efforts made at the government level by devising regulations for on-road vehicle and engine emissions (Gkatzelis et al., 2021a). Thus, these significant reductions in VOC levels have drawn attention to non-combustion sources such VCPs, which contribute to a higher fraction of VOC emissions (Goodman et al. 2017; Gkatzelis et al., 2021a). This ubiquitous trend has been observed in many other parts of the world. For example, in China, industrial and domestic solvent products accounted for total VOC emissions from 1.6 Tg (2000) to 10.6 Tg (2017) (Mo et al., 2021). Recent work in New York city, USA shows that VCPs contributed to 78% of total VOC emissions, while mobile sources contributed 22% (Gkatzelis et al., 2021b). In another study in Los Angeles, California, evidence suggested that VCPs contributed as much as 50% to total VOCs from petrochemical products (McDonald et al., 2018). Given this paradigm shift in emission sources, this study helps to identify various VCP sources, thus demonstrating their role in air quality.

There are several standard tests designed at the national level, such as the small chamber test (“American Society for Testing and Materials” (ASTM)-D5116), for evaluating the emission of indoor VOCs (Khoshnava et al., 2020). In Canada, a tool “The indoor air quality emission simulation (IA-Quest)” is developed by National Research Council (NRC) to analyse the VOCs emission (“off-gassing”) of selected material considering the amount of material and ventilation of the indoor environment (Kraus and Juhasova Senitkova, 2019). However, these physical measurements are only suitable to provide VOCs’ emissions from the selected products in a fixed environment and analysis results are not enough to establish emission inventories (Mo et al., 2021). Emission estimation from VCPs is challenging because of the variety of source categories, including stationary and fugitive emissions (McDonald et al., 2018; Kwon et al., 2021; Qin et al., 2021). Also, country-specific emission factors (EF) are not available, and EF adapted in different studies varied significantly because of certain assumptions (e.g., VOCs evaporation rate) (Coggona et al., 2021; Qin et al., 2021; Seltzer et al. 2021). In addition to EF estimation, there are mass balance methods that use mass conservation principles to quantify the emission for specific sources (McDonald et al., 2018; Mo et al., 2021). The mass balance technique is also used in the USA to provide VOC emission for the VCPs (USEPA, 2021). Considering the above-mentioned discrepancies associated with physical methods and other approaches, this study examines the modelling approaches and methods that would help to estimate the emission rate for VCPs.

Overall, this study critically overviews the potential sources of VOCs in the built environment and ambient atmosphere while focusing on volatile chemical products in Canada. The article helps to understand the relation of VCPs emission with ozone and secondary aerosol formations. Moreover, the paper overviews the existing emission inventory method and other possible ways to quantify VOC releases from VCPs. That would help decision-makers to develop strategies and regulatory policies to reduce/minimize VCPs emission into the environment.

In the context of the above-mentioned objectives, this paper is organized as follows: Section “A survey of VOCs emission in Canada” describes the recent VOC trend and contribution of VCPs to the VOC emission in the built environment as well as in the ambient atmosphere. Section “VCPs and VOCs emissions” highlights significant VCPs categories, including “paint and solvents” and other potential consumer-end sources such as cleaning products and personal care products. The next section “Relation of VOCs with ozone and other factors” describes how VCPs emission could act as a precursor for ozone and the role of VOC and NOX sensitive regimes in controlling ozone formation. The last section “VOCs emission inventory based on VCPs” discusses the possible approaches to estimate the emission rate of VOCs from VCPs that would ultimately help to account for VOCs emission inventory.

Material and Methods

Overview

The peer-reviewed literature from the years 2000 and 2022 and relevant studies was searched. Articles mainly were identified from database searches in PubMed Central, arXiv,
and google scholar using PRISMA ("Preferred Reporting Items for Systematic Reviews and Meta-Analyses") guidelines. In addition, the references of relevant records were searched on the web of science to obtain articles that may not have been found in the other database searches. The following search terms were used: "VOCs OR VCPs AND source apportionment"; "VOCs source identification in Canada"; "VOCs in indoor/built environment"; "VOCs AND ambient atmosphere"; "Volatile chemical products AND Solvents in Canada"; "VOCs AND ozone"; "National pollutant emission inventory in Canada AND USA" "VOCs AND inventory emission models". All terms were searched using free text in title, abstract and controlled vocabulary.

**Data Collection**

We gathered information from the selected 10, 40, and 71 articles through arXiv, PubMed Central, and google scholar, respectively. We collected the following data for each study: authors, country, year of publication, journal, study design, modelling method, VOC emissions, concentration values, source apportionment, volatile chemical products, study outcome, uncertainty factors, and other critical comments. Studies that reported mean and median values for individual VOC, as well as total VOCs were considered in analyses. The past survey data of indoor homes, offices, buildings in Canada, and outdoor sources were included. Studies that defined the environmental conditions such as wind speed and direction and seasonal distributions were included for analysis. No restrictions were made concerning VOC sampling techniques. Whereas those studies which did not match the above-mentioned criteria were excluded. In addition, duplicate information, and papers that did not provide quantitative information on indoor and outdoor VOCs concentration and sampling period were also excluded. Fig. 1 shows the structure of selected papers for this study and the eligibility criteria.

**Results**

**A Survey of VOCs Emissions in Canada**

Figure 2 shows the percentage distribution of VOCs across various provinces in Canada based on the recent national
pollution release inventory, in 2020. According to the survey, Alberta has a significant contribution with 31.2% release of total VOCs into the atmosphere, followed by Ontario (21.1%), Saskatchewan (14.6%), Quebec (14.5%), British Columbia (9%), Manitoba (4.2%), and other provinces (5.4%). One of the significant reasons for the highest contribution to VOCs in Alberta is the province’s oil and gas industrial sector, followed by Saskatchewan (Berthiaume et al., 2021). Considering the geographical intensity, Ontario has the highest number of light-duty gasoline vehicles, followed by Alberta, Quebec, and British Columbia (Berthiaume et al., 2021).

Total VOC (TVOC) measures the overall amount of VOCs in the ambient air; thus, it represents a group of compound classes (e.g., alkanes, alkenes, alkyenes, aromatics, halocarbons, and oxygenated VOCs) (Song et al., 2008). Alkanes in the group accounted for a significant fraction of ambient VOCs, contributing up to 50% of the total measured concentration (Xiong et al., 2020). The chemical composition of VOCs varies depending on multiple factors, including primary emissions sources and the photochemical oxidation process (Song et al., 2008). It is difficult to continuously monitor various VOCs (e.g., benzene, toluene, xylene) (Smith, 2020). No standard method is available to interpret different VOCs in their TVOC grouping or assign different weights when calculating TVOC (Smith, 2020). Identifying sources of VOCs and understanding factors contributing to risk exposures are essential to establishing control strategies and regulatory guidelines to limit their release into the environment (Bari et al., 2015). Hence, the contribution of VOC emission to the national inventory varies because of spatial variation. Each country has its unique geography, economic situation, industrial activities, and population density. Fig. 3 shows the 2019 percentage distribution of annual VOC emissions in Canada, including the indoor and primary outdoor sources (ECCC, 2021). As shown in Fig. 3, the oil and gas industry are the primary emitter with 39.4% of total VOCs contribution to the atmosphere, followed by the paints and solvents category, which is responsible for 18.1%. The transportation and mobile equipment sector contributes 17.3% of the total VOCs at the national level (ECCC, 2021). The oil and gas sector is an important contributor to the Canadian economy, and VOCs could easily be escaped from the oil mass during crude oil processing, the extraction process, and transportation of oil to storage tanks and refineries (Aklilu et al., 2018; Rajabi et al., 2020). Surprisingly, the second significant category of VOCs emitter is the “paint and solvents”. This category includes dry cleaning, printing, surface coatings and paints, and general solvent products (ECCC, 2021). Whereas, the “general solvents” sub-type further consists of personal care products (Yeoman et al., 2020), cleaning agents, air fresheners (Singer et al., 2006), and industrial volatile chemical products (McDonald et al., 2018). Although this indoor source is not discussed widely in many studies, it may adversely impact the consumer.

Other major VOCs emission is observed in the transportation sector (120 kt) due to off-road gasoline/LPG/NG vehicles and equipment usage (e.g., air transportation, railway, light-duty gasoline trucks, and other vehicles) (ECCC, 2021). Overall, for the transportation and mobile equipment sector, a decrease of 76.0% is observed in 2019 compared to 1990 (ECCC, 2021). The commercial, residential, and institutional category (10.2%) includes service stations, fuel combustion, cooking at the commercial level, and mobile wood burning. Among these activities, mobile wood burning contributed 110 kt of the total VOCs (ECCC, 2021). Berthiaume et al. (2021) reported that this source was highest in Quebec and Ontario. At the national level, a moderate (42%) emission decrease from 1990 (190 kt) to 2019 (110 kt) was observed for mobile wood burning (ECCC, 2021). A recent study shows that the increased use of advanced methods in fireplace inserts, stoves, and furnaces, limits wood consumption for heating purposes (Berthiaume et al., 2021). Other significant contributions to national VOC emissions are due to agriculture (6.9%) and manufacturing (6.1%) (ECCC, 2021).

Comparing the significant VOC sources in UK, for the period 2019 to 2020, domestic solvent use (VCPS) represented 23% of the emissions which is the primary source followed by agriculture (16.59%), food and beverages industry (14.55%), fugitive emissions (13.50%), other sectors (12.1%), industrial solvents and processes (11.32%)
and coating application (8.88%) (DEFRA-UK, 2022). Stricter emission standards in the UK have fallen the VOCs emission level in many sectors in 2020, including transportation (others), and industrial sectors. Whereas, domestic solvent use gradually increased to 15% since 1990 because of population growth (DEFRA-UK, 2022). In most European union (EU) countries, VOCs are reported as non-methane VOC (NMVOC) and a significant decrease has been observed in recent years since 2010 (e.g., 20.7% in France and 22.5% in Germany) (EEA, 2021). In 2015, in the EU national inventory “solvent and product use” category is considered a sub-category of industrial processes, including paint, dry cleaning, and other solvents as a significant source (EEA, 2021).

To understand VOCs emission from volatile chemical products, it is important to divide the sources into two main categories: (1) built environment/indoor and (2) ambient atmosphere.

**VOCs emissions in the built environment**

The potential indoor VOCs may include building materials such as plywood, particleboard, glues, coatings, adhesives (Adamová et al., 2020), and burning fuels such as gas, wood, and kerosene tobacco products (Verma et al., 2019). VOCs can be emitted from personal care products (Yeoman et al., 2020), cleaning agents, dry cleaning fluid, air fresheners (Singer et al., 2006), paints, lacquers, varnishes, and copying and printing machines (Kowalska et al., 2015). Other VOC indoor sources may include natural gas leakage, pesticides, cooking, and combustion of wood, coal, and candles (Raw et al., 2004). Limited studies focus on the VOC sources in the Canadian indoor environment. For instance, Bari et al. (2015) investigated that approximately 70% of VOCs were attributed to different indoor sources within residences in Edmonton, Canada. The primary contributor to VOCs emission were household products (44%, 648 µg/m³), followed by combustion processes and environmental tobacco smoke (10.5%, 153 µg/m³), deodorizers and sprays (8.4%, 122 µg/m³), and emissions from building materials (5.9%, 86 µg/m³).

Zhu et al. (2005) examined that in selected dwellings in Ottawa, VOCs were present at significantly higher levels in indoor air (0.005–455.87 µg/m³) than in outdoor air (0.005–32.80 µg/m³). A high level of acetone was detected indoors, followed by 2-propanol, dichloromethane, and toluene (Zhu et al. 2005). In Canadian homes, Wheeler et al. (2013) reported high levels of all BTEX (Benzene, toluene, ethylbenzene, m-, p-xylene, and o-xylene) with an attached garage. Other significant predictors of the presence of BTEX included a garage, regular indoor smoking, number of occupants, recent renovations, use of paint remover, and frequency of fragrance used. Similarly, high levels of benzene and xylene, in addition to chloroform and styrene, were reported by Adgate et al. (2004) in urban households in Minnesota, USA, which had smokers and attached garages compared to households without an attached garage and smokers. Thus the possible predictors for a high level of VOCs (BTEX) would be the age of the home, attached garage, smoking, new furniture or rugs, use of hair sprayers, and air conditioner (Héroux et al., 2010).

A few studies are available that reported the speciation of VOCs from the indoor environment, including VCPs. For instance, Zhu et al. (2013) conducted a national-level survey of 84 VOCs in about 3800 residential homes in Canada, including sampling locations in Atlantic, Ontario, Quebec, Prairies, and British Columbia. The study found that most of the measured VOC levels were high in apartments compared to houses based on the sampling data from 2009 to 2011. Li et al. (2019b) also reported similar findings by surveying 88 selected VOCs from 3524 residential homes in Canada as part of the “Canadian Health Measures Survey” (CHMS), considering the database from 21012 to 2013. Li et al. (2019b) selected similar attributes as chosen by a previous survey conducted by Zhu et al. (2013), i.e., the characteristics of the dwellings (age, type, the smoking rate in the apartments and houses, etc.). Fig. 4 illustrates the arithmetic mean of various VOCs found during the survey result by Li et al. (2019b) and Zhu et al. (2013) study. To understand the difference in emission sources, both studies are compared with Chin et al. (2014) analysis based on VOC levels in 126 homes in Detroit, Michigan, USA. Thus, showing the levels of 29 different VOCs compounds from Canada and USA homes in Fig. 4 would help to identify the major contributor and their associated source or activity. Both Li et al. (2019b) and Zhu et al. (2013) studies show the highest level of limonene followed by toluene, m-p xylene, α-pinene, pentane, and decane. In Chin et al. (2014) study, the highest levels of VOCs are observed as limonene followed by toluene, naphthalene, ethyl-acetate, and m-p-xylene. The possible sources of terpenes (limonene and α-pinene) would be cleaning products, deodorizers, cigarette, polishes, and fabric softeners (Nazaroff and Weschler 2004). The emissions of aromatic hydrocarbons (e.g., toluene, xylene) are because by paints, fragrances, evaporated fuel, vehicle emissions, and adhesive materials (Wheeler et al., 2013). The presence of aliphatic hydrocarbons (e.g., decane, undecane, heptane) is due to photocopiers, carpeting, and paints (Chin et al., 2014). Ethylacetate is mainly used in nail polish remover, glue, and other products (Chin et al., 2014). Naphthalene is found in deodorants and pest repellents (Jia and Batterman, 2010).

VOCs level may differ between residences and workplaces in North America because of different product usage. For example, n-dodecane, trichloroethene, and tetrachloroethene concentrations were three times higher in...
office buildings than in residential buildings (Hodgson and Levin, 2003). The possible reason for the elevated level of Dodecane is a component of an isoparaffinic solvent that might be used in wet-process photocopiers (Kowalska et al., 2015). Also, chlorinated solvents may be used more in various office and cleaning products (Hodgson and Levin, 2003). In contrast, less concentration of pentanal, α-pinene, δ-limonene, 1,4-dichlorobenzene, and dichloromethane are found in offices because of the lower prevalence of wood products (Adamová et al., 2020). Hodgson and Levin (2003) concluded that newly constructed buildings have a high concentration of VOCs as compared to existing ones.

VOC level in commercial spaces is critical while focusing on the health risk during shopping (Jia et al., 2019). Research has found that stores have the highest VOCs level compared to other everyday microenvironments like residences, offices, or even vehicles because of the numerous products, e.g., paints, detergents, solvents, tools, clothes, toys, and cleaning products (USEPA, 2021). For example, Jia et al. (2019) examined 32 different retail stores in the Greater Memphis Area, Tennessee, U.S.A, and found that the median store-level total-VOC (TVOC) concentrations were 536, 235, 152, 151, and 141 ppb in hardware stores, multipurpose stores, grocery, specialty store, and supermarket respectively. In addition, the highest level of VOCs was found in the paint section, followed by home accessories, household, and self-care products (Jia et al., 2019). The duration in which sampling takes place also influences the measurements. According to Jia et al. (2019) study, VOC levels were elevated in the mornings and evenings, possibly due to low ventilation and cleaning activities at the beginning and end of business hours. In most U.S. commercial buildings, aldehyde, aromatic, aliphatic, and halogenated compounds are the common VOCs (Loh et al., 2006).

**VOCs emissions in the ambient atmosphere**

The outdoor sources are considered in this study as ambient VOCs can infiltrate easily into indoor spaces such as buildings and residential houses. The source apportionment of outdoor VOC emissions and a comparison of VOC concentration in different cities of Canada are presented in Table 1 to understand the spatial variation of VOC emissions. All the reported studies in Table 1 considered seasonal variation, wind direction/speed, and traffic emissions (as a part of other sources). Whereas, weekends and weekdays were only discussed in McCarthy et al. (2013) study. The largest source of VOCs in Calgary downtown was oil and gas products because of alkanes emitted from fuel evaporation and fossil-fuel combustible products (Bari and Kindzierski, 2018a). In addition, several industries were located in the Southwest, Southeast, and South of the monitoring station and were responsible for VOCs pollution in the Southeast during summer as the dominant source direction and Southwest during winter (Bari and Kindzierski, 2018a). Fuel-based products are the second-largest source in Calgary downtown because of the possible influence of residential wood-burning and open wood burning (e.g., agricultural slash burning) during winters (Berthiaume et al., 2021). The highest concentrations observed during winters were due to the occurrence of stable atmospheric conditions (low temperature, low mixing height along with temperature inversion) (Bari and Kindzierski, 2018a). Most halogenated VOCs (e.g., Freon groups, chloroform, carbon tetrachloride, dichloromethane, dichlorobenzene) have long atmospheric lifetimes (Odabasi, 2008) and are considered background pollutants (Bari and Kindzierski, 2018a). It is noteworthy that some of these species’ commercial production (e.g., carbon tetrachloride) was phased out and has been well controlled in
Canada and the United States since the Montreal Protocol – 1989 (Bari et al., 2015). The oil and gas industrial products are the predominant source of VOCs (23 µg/m³) in Edmonton and Mckay (23.623 µg/m³). Moreover, two major oil refineries (Imperial oil and Suncor Energy with crude oil) were located in eastern region of Edmonton, contributing to the VOCs (Bari et al., 2015). In combustible fuel products, Bari et al. (2015) included biomass smoke fire due to several forest fire incidents that occurred in Alberta and nearby provinces such as British Columbia and Manitoba during the 2010 summer (e.g., episodes during June 24, July 13–29, and August 6) (Natural Resources Canada, 2010). In other sources category, most studies considered diesel and gasoline combustion during traffic and biogenic, including forest fires. Overall, during winter, in addition to frequent occurrence of temperature inversion, increased car idling duration and cold state emissions were related to the traffic emissions in Edmonton, including downtown area (McCarthy et al., 2013; Bari et al., 2015). Moreover, the highest VOC levels were observed on the South and East sides because of dominant wind originating from the South and Southwest in Edmonton (Bari et al., 2015). McCarthy et al. (2013) observed traffic emissions as major VOCs emitter in Edmonton; found that diesel and exhaust activities were higher on weekdays in contrast to weekends. In addition, McCarthy et al. (2013) also included natural gas in other sources, originating from natural gas combustion and industrial processing to extract ethane and propane contributing 19 µg/m³ of the total VOC emissions. The oil and gas sector is the largest source in McMurray and Mckay ports in the northern Athabasca oil sand communities (Bari and Kindzierski 2018b). It is observed that VOC emissions in the reported years are associated with the 7.8% increased oil sand production per annum (Bari and Kindzierski, 2018b). Like other studies, the VOCs level was dominant during winters. Other sources included mixed fuel influences from local sources, e.g., traffic, land development, and commercial/residential heating (Bari and Kindzierski, 2018b). In Metro Vancouver, industries made the most significant portion of the total VOCs at port Moody followed by traffic sources (Xiong et al., 2020). In Burnaby South, industries contributed the least, and traffic (other sources) is the primary source of VOC emissions (Xiong et al., 2020). Several coating and paint stores are located to the Northeast and Northwest of Burnaby and Port Moody, contributed to the VOCs. Moderate VOCs contribution from Northwest under high wind speed (20–30 km/hr) were observed in Port Moody, whereas, the contribution of VOCs from the wind originated from South-Southeast wind (30–40 km/hr) were observed in Burnaby (Xiong et al., 2020).

Edmonton city VOCs are 39.9% more than Edmonton downtown because of oil and gas products, chemical manufacturing-related products, industrial coating, and

### Table 1 Comparison of VOCs emission in different cities in Canada and outdoor source apportionment

| Sources                              | Calgary downtown | Edmonton downtown | McMurray, Alberta | Mckay, Alberta | Burnaby South, Vancouver | Port Moody, Vancouver |
|--------------------------------------|-----------------|------------------|-------------------|---------------|-------------------------|----------------------|
| Time period                          | (2010-2015)     | 2010             | (2003-2009)       | (2010-2015)   | (2012-2016)             |
| References                           | (Bari and Kindzierski, 2018a) | (Bari et al., 2015) | (McCarthy et al., 2013) | (Bari and Kindzierski, 2018b) | (Xiong et al., 2020) |
| Sources                              | µg/m³           | µg/m³            | µg/m³             | µg/m³         | µg/m³                   | µg/m³                |
| Oil and gas products                 | 10.72           | 23               | 11                | 18            | 23.6                    | –                    |
| Industrial coating and solvents      | 4.82            | 3.3              | –                 | –             | –                       | 4.2                  |
| Manufacturing related products       | –               | 13.3             | –                 | –             | –                       | 4.5                  |
| Fuel based products                 | 8.1             | 10.5             | –                 | 7.1           | 7.5                     | –                    |
| Background concentration            | 7.63            | 14.4             | 7                 | 12            | 13.6                    | 8.3                  |
| Other sources*                      | 5.37            | 27.3             | 42                | 8.4           | 7.9                     | 25.5                 |
| Dry cleaning                        | 1.36            | –                | –                 | –             | –                       | 14.3                 |
| Fugitive                            | 4               | –                | 5                 | 8.7           | –                       | –                    |
| TVOCs**                             | 42              | 108.3            | 65                | 54.2          | 52.6                    | 38                   |
| Median                              | 6.4             | 89               | –                 | 22.4          | 26.5                    | 34.02                |

*Includes biogenic sources and traffic-related emissions; ** TVOCs values were directly obtained from the literature; – Not available; a–c: 24 h. duration samples were collected every 6 days through National Air Pollution Surveillance (NAPS) network program and then annual average values were obtained.
solvents. Whereas Edmonton downtown VOCs are 35% more because of the high traffic sources than Calgary downtown. The consistency in VOC source contributions across different cities within western Canada implied that industries-related products, fuel combustion products, and background sources (e.g., traffic, biogenic) were the dominant contributors of VOCs in an ambient atmosphere. However, the population, topography, and industrial structures may differ across the cities in Canada. McMurray and Mckay, Alberta VOCs are comparable to the Saskatchewan average VOCs emissions (~50 µg/m³) (Mintz and McWhinney, 2008). Whereas in Burnaby South, Vancouver’s contribution to ambient VOCs is comparable to Toronto’s average VOCs emission (36 µg/m³) and Hamilton’s downtown (39 µg/m³) (Bari and Kindzierski, 2018a).

The indoor to outdoor (I/O) ratios hold significant importance. If the I/O ratio is larger than 1 for VOCs, indoor sources and poor ventilation provide a more substantial contribution to the levels of VOC indoors (Paciência et al., 2016). However, if the I/O ratio is close to ≤1, indoor concentrations would be affected by outdoor emission sources (such as traffic and industries, which strongly depend on the degree of urbanization). Also, outdoor-to-indoor air penetration supplies an essential contribution to VOCs and levels observed indoors (Paciência et al., 2016). For example, the I/O ratio for benzene estimated by Xu et al. (2016) for selected Canadian residential houses is 1.7, while Geiss et al. (2011) calculated 0.90 for European cities. Hence, the I/O ratio varies for the same compound depending on the sources present in that area and represents whether indoor sources are dominant over outdoor sources for VOC emissions. Among all sources, volatile chemical products (VCPs) (discussed in the next section) have a high exposure risk to both near fields (nominally indoor, during, or in the vicinity of product use) and ambient atmosphere (outdoor), where compounds can evaporate and react in the atmosphere producing secondary pollutants (Gkatzelis et al., 2021a).

### Volatile Chemical Products (VCPs) and VOCs Emissions

#### VCPs Emissions at the National Level

Volatile chemical products (VCPs) contain mixtures of complex organic species that experience a wide volatility range and span an oxidation state (Qin et al., 2021). VCP emissions are pervasive in US and European cities and expand with population density (Qin et al., 2021). Previously, the USA’s dominant source of organic emissions has been traffic and motor vehicles (McDonald et al., 2018). However, over the past few years, effective emission reduction strategies have dramatically reduced mobile VOC emissions (Gkatzelis et al., 2021a) and drawn attention to VCPs as a significant source of organic emissions (Seltzer et al., 2021). The U.S. EPA has reported for VCPs in the National Emissions Inventory (NEI) as the “solvent sector” that includes the sub-category of dry cleaning, degreasing, graphic arts, industrial surface coating, and non-industrial surface coating (USEPA, 2017). Whereas VCPs are considered under the “paints and solvents” sector in Canada’s emission inventory, one of the most significant contributors and includes the sub-category of dry cleaning, printing, surface coating, and general solvents (ECCC, 2021), as shown in Table 2. In Canada-APEI, the “general-solvent” has the highest (69.9%) of the total VOCs emissions of paints and solvent category. The “general solvent” category may consist of a wide range of applications (e.g., cleaning products, personal care products, commercial products, pesticides, degreasing, adhesives and sealants, aerosols, blowing agents, and resin manufacturing), occurring in residential, industrial, commercial, and institutional settings (ECCC, 2021). Surface coatings encompass 21.98% emissions from paints and solvents, followed by printing (7.8%) and dry cleaning (0.062%). Printing covers emissions from the manufacturing or usage of printing inks, flexographic, letterpress, lithographic, gravure, and other printing (Aydemir and Özsoy, 2021).

| Sector: Solvents | Canada (ECCC, 2021) |
|------------------|---------------------|
| Year: 2017       | Year: 2019          |
| Sub-sectors      | Values (tonnes)     |
| Total VOCs       | Total VOCs          |
| Dry cleaning     | 3697                |
| Graphic arts     | 345827              |
| Industrial surface coating & solvent use | 492382 |
| Non-Industrial surface coating | 337414 |
| Consumer & commercial solvent use | 1610196 |
| Degreasing       | 182832              |
| Total VOCs       | 2972348             |
|                   | Dry cleaning        |
|                   | 190                 |
|                   | Printing            |
|                   | 24000               |
|                   | Surface coating     |
|                   | 66000               |
|                   | General solvents    |
|                   | 210000              |
|                   | Total VOCs          |
|                   | 300,190             |

Table 2 Comparison of the USA and Canada national VCPs emission inventory

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After cleaning values are compared with the German AGÖF institute standard for indoor VOC levels (1000 µg/m³) (AGÖF, million on household products (e.g., chemical products, Canadians spent approximately $641 per annum on cleaning products (Jamal, 2018). In the window sprays) and spent nearly $200-$300 per household exists in Canada (Berthiaume et al., 2021). Therefore, the is no established standard for indoor total VOC levels from randomly tested household products in Canada. There spectroscopy (Data source: Environmental defence organization, 2015). The total VOCs increased by green products (average increase of 320) (Environmental increase of 920) were three times higher compared to the VOCs increases for conventional products (average

Consumer-level VOCs emission from VCPs

At the consumer end, VCPs can come from cleaning agents, dry cleaning fluid, air fresheners (Singer et al., 2006), personal care products such as perfume and hair products (shampoo, conditioner, shower gel), moisturizers, cosmetics (e.g., liquid foundation) (Yeoman et al., 2020), paints, lacquers, varnishes, and from copying and printing machines (Kowalska et al., 2015). Other VOCs indoor sources may include natural gas leakage, pesticides, cooking, and combustion of wood, coal, and candles (Raw et al., 2004). One survey (2014-2015) shows that among all chemical products, Canadians spent approximately $641 million on household products (e.g., floor cleaners and window sprays) and spent nearly $200-$300 per household per annum on cleaning products (Jamal, 2018). In the above context, Fig. 5 represents the VOCs emission level from randomly tested household products in Canada. There is no established standard for indoor total VOC levels exists in Canada (Berthiaume et al., 2021). Therefore, the values are compared with the German AGÖF institute’s standard for indoor VOC levels (1000 µg/m³) (AGÖF, 2013) to get an idea that if the indoor air quality is acceptable in the context of total VOCs. VOCs in 12 out of 14 households are observed to exceed the German recommended level for indoor VOC levels (Environmental defence organization, 2015) after cleaning. Moreover, VOCs increases for conventional products (average increase of 920) were three times higher compared to the green products (average increase of 320) (Environmental defence organization, 2015). The total VOCs increased by an average of 120% because of conventional cleaners, 35% with certified green products, and 100% with green products that did not disclose ingredients (Environmental defence organization, 2015).

Data were collected by an Environmental defence organization using an air sampler for 30 min on two consecutive days from 14 different houses. Then before and after samples were analysed in a laboratory using mass spectroscopy (Data source: Environmental defence organization, 2015).

It is critical to trace VOCs linked to specific VCPs categories (Gkatzelis et al., 2021a). For instance, cyclic volatile methyl siloxanes (cVMS) have been identified in both consumer products (e.g., deodorants, shampoos) and outdoor air (NOAA news, 2018). A recent study showed that decamethylcyclopentasiloxane (D5- siloxane) is the main ingredient added to personal care products to provide smoothness (Gkatzelis et al., 2021a). Thus, it is considered a valuable tracer for VOC emissions from personal care products and can persist for one week in the air (Coggon et al., 2018). Another example of cVMS is octamethyloclootetrasiloxane (D4), which has severe environmental risk and is suggested by many authorities to phase out from the products; in contrast, UK environmental agency considered D5 as a bio-accumulative substance (Brooke et al., 2009).

In 2011, Environment Canada reported that D5 is not bio-accumulative but can persist for ~1 week in the air (Environment Canada, Health Canada, 2011). Coggon et al. (2018) investigated that D5-siloxane emissions peaked in the morning as people mostly put on personal care products before going out into their cars or buses where benzene emissions exist. Emissions of both chemicals reduced during the daytime due to evaporation of the products applied, then peaked again during the evening commute. Wang et al. (2009) studied that 4.8% of D4 and 14.3% of D5 were determined in 252 personal care products and cosmetics. Table 3 shows Wang et al. (2009) analysis results for D5 as a tracer for VOCs emissions from VCPs products (e.g., fragrances, hair care products, deodorants, nail polishes, and a variety of baby products) collected from retail stores in several provinces in Canada. D5 has the highest concentration of 680 mg/g in an antiperspirant, followed by baby products (150 mg/g in a diaper cream). Yeoman et al. (2020) examined that in cosmetics and toiletries, D5 had the highest emission rate of $2.5 \times 10^5$ kg/year, followed by limonene (monoterpene) with an emission rate of $1.5 \times 10^5$ kg/year from 36 VCPs in the UK. Yeoman et al. (2020) results are comparable with Gkatzelis et al. (2021a) analysis for D5($2.2 \times 10^5$ kg/year) and monoterpene ($1.65 \times 10^5$ kg/ year) from various USA VCPs. D5-siloxane can be used as a tracer for personal care products, while monoterpene can be utilized for fragranced VCPs, wood combustion, and cooking in the urban environment (Gkatzelis et al., 2021a). Table 3 also shows Yeoman et al. (2020) analysis results for D5 tracer in hair care products (shampoo, conditioner), moisturizers, and cosmetic products. Horii and Kannan

![Fig. 5 Total VOCs values in cleaning household products in several different households in Canada. Note: Tested household 1–9 represents conventional cleaning products; 10–12 represents certified green cleaning products showing ingredients on their label; 13–14 uncertified green cleaning products with no ingredient label. Data were collected by an Environmental defence organization using an air sampler for 30 min on two consecutive days from 14 different houses. Then before and after samples were analysed in a laboratory using mass spectroscopy (Data source: Environmental defence organization, 2015).](image-url)
also determined D5 emissions from various personal-care products from retail stores in Albany, New York, and Tsukuba, Japan (see Table 3).

### Relation of VOCs with Ozone and Other Factors

A brief of the relationship between VOCs with O_3, NOx, and PM

The ground-level ozone (O_3) is produced because of a photochemical mechanism that involves volatile organic compounds (VOCs) and oxides of nitrogen (NOx) as precursors (Li et al., 2019a). Thus, ground-level ozone (O_3) and particulate matter (PM) are the two integral components of smog (Zou et al., 2015). According to the recent Health Canada report 2021, the highest concentrations of PM_{2.5} were observed in the most populous census divisions based on 2014 to the 2017 database, such as Calgary–Edmonton in Alberta, the Lower Fraser Valley (LFV) of British Columbia, and Windsor–Quebec City Corridor in Ontario and Quebec (Health Canada, 2021). The concentrations did not exceed the annual average Canadian ambient air quality standards (CAAQS), i.e., 8.8 µg.m^{-3} (Health Canada, 2021). However, southern British Columbia and northern Alberta regions were on the borderline in the 6.7 to 8.8 µg.m^{-3} range because of the frequent wildfires and winter temperature inversion in these regions (Matz et al., 2020). As PM_{2.5}, higher NOx was observed in the above-mentioned regions and southern Saskatchewan (Health Canada, 2021).

As VOCs, the speciation is time-consuming, and analysis requires a lot of effort. Therefore, in addition to D5-siloxane and monoterpenes, Gkatzelis et al. (2021a) discussed additional tracer compounds indicating specific sources' presence in the selected area. For instance, D4-siloxane, p-dichlorobenzene, para-chlorobenzotrifluoride, and texanol could be used to indicate the inventory sources of adhesive, insecticides, solvent-based coating, and water-based coating, respectively.
five years (2012–2016) monitoring data for 56 most photochemically reactive VOCs species from industries’ plume and traffic emissions (Xiong and Du 2020). According to 2016–2018 data, only 2 out of 41 stations reported ozone levels >63 ppb in British Columbia (Environmental Reporting BC 2020). During the first wave of COVID-19 in Ontario, it was observed that NOx concentrations reduced to 69% compared to the past 10 years of data (2010 to 2019) considering the local lockdown measures, while no decrease was observed for O3 concentrations and 10% increased values were observed for weekdays (Gough and Anderson, 2022). This observation implies that Ontario exists in a NOx-saturated or VOCs-sensitive environment (Gough and Anderson, 2022). In such urban environments, the O3 formation is sensitive to VOCs, and ultimately reduction in VOC emissions may influence shrinking ozone peaks (Ainslie and Steyn, 2007). For example, Lower Fraser Valley in British Columbia (BC) province was consistently under a VOCs-sensitive regime, and VOC regulations should be implemented before NOx (FVRD, 2014). Controlling the wrong precursor in that specific area may worsen the situation by inadvertently increasing the O3 (Li et al., 2019a).

Over the past decade, trends of NOx and VOCs have decreased in many parts of Canada (Stroud et al., 2020; Gough and Anderson, 2022). However, still O3 continues to be a significant health risk in many areas, including the Hamilton area in Toronto because of local meteorological conditions (Stroud et al., 2020). Moreover, a transition from VOC-sensitive to NOx-sensitive regime was observed during the June and July season in North Toronto in the past few years due to lake breeze fronts (Stroud et al., 2020). During the VOC-sensitive regime, Stroud et al. (2020) investigated that a reduction of 10% of VOCs would result in an approximately 7.2% decline in O3 levels. While in the same regime a 10% decrease in NOx level would increase the O3 level by 4.5%. On the contrary, during the NOx-sensitive regime, the same amount of NOx level reduction would reduce the O3 level by 6%. Similar results are found by Jhun et al. (2015) while studying the impact of NOx level decrease on O3 in the USA. Hence, NOx reduction may act as an O3 quencher especially during winters, while VOC reductions have been more beneficial in reducing peak concentration of O3 (Jhun et al., 2015; Mazzuca et al., 2016; Stroud et al., 2020). Li et al. (2019a) examined that the concentrations of aliphatic hydrocarbons and aromatics compounds were usually higher in winter and in June and July regardless of the location. In contrast, the oxygenated hydrocarbons (e.g., ketones, aldehydes) were higher in warmer months. In addition to seasonal variations, pollution is strongly influenced by several meteorological conditions such as humidity, wind flow, atmospheric stability, and cloud coverage (Asif et al., 2018). High temperatures are usually accompanied by calm winds and atmospheric stability conditions, which allow pollutants to accumulate and ozone levels to rise (Zou et al., 2015).

Emissions from VCPs also contributed to the oxygenated species which have the potential to yield secondary organic aerosols (SOA), particularly alkane, alkene (isoprene), and aromatic hydrocarbons, including volatile and semi-volatile compounds contributed significantly to SOA formation (Pereira et al., 2015). Han et al. (2018) examine that the concentration of total VOCs, alkanes, and alkenes changes dramatically in the presence of low PM2.5 concentration and changes little in the high PM2.5 domain. Whereas aromatic hydrocarbons vary dramatically in the extremely polluted domain of PM2.5 (Han et al., 2017). Therefore, quantifying the emission rates of VOCs from various VCPs is important that would assist in controlling VOCs at the production level as well as consumer end (see further details in section “control of VOCs”).

Integrated VOC emission identification together with other air pollutants

As mentioned, reducing organic emissions from VCPs would help to mitigate ozone pollution and near-field chemical exposure (McDonald et al., 2018); however, each species has different lifetime and kinetics reactivity rates. These species persist in the atmosphere and contribute to ozone formation (Xiong and Du, 2020). For example, ethane can stay for weeks in the atmosphere compared to propene; thus, its contribution to ozone formation is smaller than propene in an urban area (Alvim et al., 2018). Ozone formation potential (OFP) is a parameter that has been widely used to describe the role of individual VOC (emitted from VCPs) in O3 formation with varying OH radical reaction rates and spatially for each species (e.g., OFP for xylene in an urban area: 4.59; industrial area: 8.08) (He et al., 2020). Commonly two methods, namely, propylene-equivalent (Propy-Equiv) concentration and maximum incremental reactivity (MIR) weighted concentration, could be used to evaluate the production of ozone by VCPs (Xiong and Du, 2020). The ratio of ΔVOCs/ΔNOx (ratio < 8.1 = VOC limited; ratio > 8.1 = NOx limited) has been commonly used to differentiate whether ozone formation should be controlled by NOx or VOCs in a specific region (Xiong and Du, 2020). For instance, Sarnia, Ontario is considered VOC-sensitive area (Xiong and Du, 2020). Thus, the nonlinear relationship among O3, VOCs, and NOx complicates the strategy for controlling ozone pollution. SOA potential can be calculated using chemical...
models (e.g., Master Chemical Mechanism) and SOA yield models that could be widely applied in three-dimensional chemical transport models (Wu et al., 2017). Usually, the change in concentration is used to understand the gradient between the VOCs and PM$_{2.5}$ pollutants and expressed as $\Delta$VOC/PM$_{2.5}$ gradient ratio (Han et al. 2018). Wu and Xie (2018) investigated that reducing VOC emissions would help mitigate particulate matter. Wu et al. (2017) examined that key contributors to both ozone and SOA were industrial solvent/VCPs (Ozone: 24.7%; SOA: 22.9%), industry process (Ozone: 23.0% SOA: 34.6%), and domestic combustion (Ozone:17.8%, SOA: 19.6%). Overall, ozone and SOA can simultaneously be estimated from VCPs and their emissions using OFP and SOA yield. Coggona et al. (2021) found that emissions from fragranced personal care and cleaning products (VCPs), contributed to approximately 50% of the ozone formation. Thus, product reformulations and proper labeling of the ingredients could help to reduce organic emissions from these VCPs (Gkatzelis et al., 2021a) and ultimately their contribution to the OFP and SOA yield.

**Modelling Approaches to Determine VOCs Emissions from VCPs**

Analytical studies can determine VOC emissions from various solvents and indoor building materials such as paints and coating through experiments, but it is time-consuming and costly (Yang et al., 2001a). Moreover, the dynamics of VOC emissions from wet materials (e.g., paints) can be affected by many factors (e.g., internal diffusion or evaporation due to the interaction of the material applied surface with adjacent air) (Yang et al., 2001a). Therefore, it might be unfeasible to examine the emissions merely by experiments and draw the attention of researchers toward mathematical modelling (Yang et al., 2001a; Haghighat and Huang, 2003). In the past, first-order decay models and exponential models were applied to fit the time-related emission data from experiments (Deng and Kim, 2004). However, these models usually underestimate long-term emissions. Because of the empirical nature of these models, it is critical to scale up at a larger scale (Li et al., 2006). To overcome such issues, another approach known as the mass transfer-based model has been used by many scientists (Yang et al., 2001b; Haghighat and Huang, 2003). For example, Haghighat and Huang (2003) developed an integrated indoor air quality model to predict the VOCs emission rate of building materials (vinyl floor tile/glue/plywood) and indoor VOC concentration with both sources and sink materials. Hu et al. (2007) developed an analytical mass transfer model to estimate VOC emission from furniture and other building material such as layered wall structures. Using a mass transfer model, Yang et al. (2001a) estimated VOC emissions from the wet coating (e.g., interior architectural coatings). These studies mainly focused on dry and wet sources of the indoor built environment and did not discuss the application of such numerical model (e.g., mass transfer model) for other VCPs. There are many scientists who used 3D Computational Fluid Dynamics (CFD) model to predict the VOCs emissions from the building material (Panagopoulos et al., 2011), photocopiers and printers (Nandan et al., 2020) and attempted to manage the indoor air quality under various ventilation, air velocity and temperature settings (Panagopoulos et al., 2011). However, these studies adapted the conservative pollutants emission factor to yield the contamination in buildings (Panagopoulos et al., 2011; Nanand et al., 2020). Life cycle assessment (LCA) modelling can help to generate VOC emission inventory, including VOC speciation and its environmental impacts. For instance, Chaudhary and Hellweg (2014) developed VOCs off-gassing inventory of wood-based products for indoors and their environmental impacts. Liu et al. (2020) also used the LCA approach to analyze VOCs and other pollutants as fugitive emissions from petroleum refining products. Hence, there are very few modelling studies that address the VOC emissions from personal care products and household cleaning products, pesticides in addition to adhesive, coating, fuel, and other industries. For example, Qin et al. (2021) estimated VOCs from VCPs using the emission factor method by considering the sector-specific emission factor (units of kg per person per annum) and activity data (e.g., population and product use in a specific sector). In addition, Qin et al. (2021) focused on the organic part of the product usage that was either attenuated by washing down the drain (assumed as a sink of VOCs) or otherwise sequestered from the air. McDonald et al. (2018) also focused on VCPs (personal care, cleaning products, pesticides, coating, and adhesives) and estimated emission rates by using the following expression:

$$E_{VCP} = \sum_i A_i \times W_i \times (f_{VOC,i} V_{FVOC,i} + f_{S/IVOC,i} V_{FS/IVOC,i}) \times (1-\eta)$$

(1)

where $E_{VCP}$ is the total VOC emissions from VCPs to the ambient atmosphere (g/yr), $A_i$ represents sales of product $i$ (g product/yr), $W_S$ is the organic solvent content in the product $i$ (g solvent/g product), $f_{VOC,i}$ is the fraction of organic solvents as VOCs in the product $i$ (g VOC/g solvent), $V_{FVOC,i}$ is the volatilization fraction of VOCs for the product $i$ (g emitted/g dispensed), $f_{S/IVOC,i}$ is the fraction of organic solvents as S/IVOCs in the product $i$ (g S/IVOC per g of solvent), $V_{FS/IVOC,i}$ is the

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volatilization fraction of S/IVOCs for the product i (g emitted/g dispensed), $\eta$ is the emission control efficiency for industrial product.

Seltzer et al. (2021) reported that all VCPs have a first-order product composition profile, which disaggregates the total mass of each product into its water, inorganic, and organic fractions. Thus, the organic fraction tends to evaporate into the atmosphere. For instance, paints have a 90% fraction of organic compounds to evaporate, whereas most organic compounds in detergents and soaps dissolve in water and end up in drainage (Shin et al., 2015). McDonald et al. (2018) classified VOCs as semi-volatile organic compounds (SVOCs: $C < 0.3 \mu g/m^3$), intermediate volatility organic compounds (IVOCs: $C = 0.3$ to $3 \times 10^6 \mu g/m^3$), and higher volatility organic compounds (VOCs: $C > 3 \times 10^6 \mu g/m^3$). The estimated VOCs emissions as a function of the organic solvent content in a chemical product before use and the fractional amount that volatilizes as VOCs and IVOCs.

Recently, Seltzer et al. (2021) developed a new framework to model organic emissions from the VCPs known as VCPy, including a spatial allocation to the county level in the USA for the 10 product use categories (PUCs: cleaning products, personal care products, adhesives and sealants, Paints and coatings, Printing and coatings, printing inks, pesticides, dry cleaning, oil and gas, fuels and lighters). VCPy framework is specifically designed to address the VCPs. However, there are uncertainties related to this framework, such as the VCPy framework assumes that organics, if evaporated, would reach the ambient atmosphere, regardless of source (Seltzer et al., 2021).

It is difficult to apportion the source if only VOCs emission rate or ambient atmospheric concentration is known. Several studies have been carried out worldwide to understand indoor VOCs using univariate and multivariate analyses, variance component analyses, linear regression models, and other techniques (Bari et al., 2015). Receptor-oriented models can be applied to identify emission sources and estimate contributions of all recognized sources to the total measured VOC concentrations in the time of interest. Different receptor modelling approaches, e.g., positive matrix factorization (PMF) (Song et al., 2019), principal component analysis (PCA)/absolute principal component scores (APCS) (Geng et al., 2009), have been widely used to estimate source contributions to ambient VOC, and apportion indoor/outdoor sources of VOCs using a single day measurement at multiple homes. In comparison with PCA, PMF produces a better fit to the data and provides non-negative factors, error estimates, and better data treatment, including missing values, and has been widely used for source apportionment of ambient VOCs (Wang et al., 2018).

VOCs Emission Inventory based on VCPs

Emissions factors are important in developing emissions inventories for air quality management and in developing emissions control strategies (USEPA, 2021). An emissions factor represents the quantity of a pollutant (e.g., VOCs) released into the atmosphere with an activity associated with the specific sources (e.g., volatile chemical products). VOC emissions can be calculated by taking the quantity of solvent used multiplied by the estimated percentage of controlled VOCs in an application area (Thunis et al., 2016; ECCC, 2021).

$$E_{\text{voc}} = Q_p \times (100\% - \eta)$$

where $E_{\text{voc}}$ is the emission estimated for VOCs, $Q_p$ is the quantity of solvent or the product used by the consumer or industrial level, and $\eta$ is the emission control efficiency. If there is no estimated efficiency of control technologies, then it is assumed that 100% of the solvent evaporates.

The VOCs emission factor

Accurate emission inventories are essential to understanding the contribution of various anthropogenic sources that help to predict changes in atmospheric composition and cost-effective design control techniques (Elguindi et al., 2020). The two most common methodological approaches for compiling emission inventories, referred to as “top-down” and “bottom-up,” exist worldwide (Thunis et al., 2016; Elguindi et al., 2020). The significant difference between “top-down” and “bottom-up” methods relies on the specificity of the emission factor selected and the temporal and spatial data aggregation level in which the specific activity is collected, considering the availability of data (Holoboff, 2021). In the top-down approaches, the emissions are estimated for a total area and then distributed attending to different allocation patterns or down-scaling related to the emission source or could use indicators to distribute emissions to a regional scale from more aggregated datasets such as those at the national level (Dios et al., 2012). Whereas a bottom-up approach considers the detailed calculation of the emissions from all the individual sources of an area, which are then aggregated to obtain the emissions from the total area (Murrells et al., 2018). It is possible to use both top-down and bottom-up methodologies to develop a single emission inventory (Thunis et al., 2016). Establishing an emission inventory using a bottom-up approach poses a significant challenge as required detailed information for a large variety of sources needs to be collected (Lewis et al., 2020). Therefore, emission inventories in many parts of the world at national scales mostly follow the top-down method (Zhang et al., 2018). For instance, in Canada-APEI, a top-down
mass balance approach estimates total VOCs from potential sources, including solvents (ECCC, 2021). Many scientists adopted a top-down approach for their research work, such as Kwon et al. (2021) used a top-down approach to investigate the anthropogenic VOC emissions at the regional level in South Korea using formaldehyde vertical column densities from aircraft. On the other hand, in the UK (Lewis et al., 2020) and many other reported studies (Elguindi et al., 2020; H. Wang et al., 2009; Zhang et al., 2018) bottom-up approach is used to construct an emission inventory. More specifically, in UK bottom-up approach is used for facility levels such as refinery processes, oil and gas production, chemicals industry, and certain types of solvent used in the industry (e.g., coating of road vehicles and printing of flexible packaging) (Lewis et al., 2020). These approaches have limitations as time-series data is needed to determine emissions from various sources by splicing together multiple datasets from different data providers and activities. Therefore, there is a risk that a time series might not be entirely consistent, and estimates for other years may be subject to varying levels of uncertainty (Lewis et al., 2020). In addition, the emission factors used to quantify VOCs are often referenced from those collected from other countries, potentially leading to errors due to the discrepancies across the local sources, therefore needing country-specific emission factors (Li et al., 2021).

**Control of VOCs emission**

Seltzer et al. (2021) proposed two approaches to control VOCs emission from VCPs: (1) limit VOCs emission by reformulating the product during manufacturing; (2) post-use control or on-site abatement technologies. In the first approach, different strategies can be adapted to reduce the emissions at the consumer end. For instance, replacing high volatile products with low volatility ingredients; replacing hydrocarbon solvent-based products (e.g., paints) with water-based products; substituting less reactive organic compounds; and using refillable aerosol containers (Seltzer et al., 2021). Moreover, consumer products should provide mandatory on-label ingredient disclosure, including fragrance ingredients. According to the amendment of the Canadian Food and Drugs Act and the Cosmetic Regulations in 2006, all ingredients used in cosmetics must be disclosed on the label regardless of the concentration used in the product (Government of Canada, 2006; Wang et al., 2009). Regulators often set VOC concentration limits for chemical products, such as “VOC Concentration Limits for Automotive Refinishing Products Regulations in 2009”, including surface cleaners (SOR/2009-197) (Government of Canada, 2021), and other regulations are discussed in section 5.3. The second approach is based on add-on controls while considering industrial emission sources. According to the literature studies, limited work has been done to devise control strategies for VOC emissions from VCPs (Seltzer et al., 2021). The control techniques can be applied for printing, surface coatings (e.g., aircraft, automotive equipment), dry cleaning, and manufacturing (e.g., adhesives and sealants, and resin manufacturing) (Mo et al., 2018). The most common control methods applied to these sources are adsorption, condensation, catalytic-thermal-oxidation, and thermal-oxidation (Inglezakis and Poulopoulos, 2006). Thermal oxidation can be used for flexographic and gravure printing (Aydemir and Özoğ, 2021). There is a need to conduct further research on abatement methods that are practically possible to control VOC emissions on-site. It is suggested to identify the potential sources types, select chemical species or related properties to be included in the calculation, and estimate the fraction of each chemical species contained in each source type (Mo et al., 2018).

**Conclusions**

The paper has presented a broad-ranging review of VCPs to better understand their contribution to VOC emissions. In addition, by considering the theme of the study, this review aimed to highlight significant VCPs in the built environment, to gain insights on potential categories (e.g., consumer end products) that would become part of future national pollution inventory. The analysis shows that the driver of downward VOC trends is the transportation and mobile equipment category, and the Manufacturing sector due to stringent regulations and government measurements. Therefore, leveraging the VCPs as the second largest contributor to the national total VOC emissions and there is immense need to understand its impact on the air quality. A range of studies confirmed that the indoor levels of VOCs are higher than outdoors because of direct exposure to VCPs. However, there are so many other factors that should be considered while reporting the VCPs emission also known as “predictors” such as regular indoor smoking, number of occupants, recent renovations, use of paint remover, frequency of fragrance used, and ventilation conditions. Minimal studies provided speciation of VOCs that help to understand which chemical compound should be reduced. Many compounds can be used as a tracer to indicate the presence of specific sources in the study areas, such as D5-siloxane could be the tracer for personal care products. Literature data show that limonene has the highest ambient levels, followed by toluene, m-p xylene, α-pinene, pentane, and decane. Limonene belongs to the terpene category found in
cleaning products, deodorizers, cigarettes, polishes, and fabric softeners. The speciation of some VOCs may differ between residences and office buildings because of different product usages such as photocopiers and printers. VOC levels are elevated in the morning and evening, probably due to cleaning activities at the beginning and end of business hours and low ventilation. Moreover, cleaning products may increase the total VOCs level in the built environment by 35–120% more than the background levels. Reported studies also encountered the issue that the consumer products did not fully disclose the ingredients in their labeling. It is also suggested to devise a VOC limit for consumer products and guidelines for residential total VOC level. It is crucial to consider the I/O ratio because most outdoor sources (e.g., traffic, industrial areas, biogenic emissions) may influence the indoor VOC concentration and vice versa. VCPs can contribute to forming ozone and SOA, and the controlling strategy of ozone is dependent on NOx-limited and VOC-limited sensitive regimes. Despite the downward trend of NOx and VOCs, VCPs are prevalent across the mega cities in Canada and may impact air quality as well as ozone pollution.

An in-depth analysis of various modelling approaches to estimate emission factors and associated barriers are discussed, such as uncertainty in the database, and adapted emission factors from other countries, which potentially lead to errors in current methodologies due to the discrepancies across the local sources. Very few modelling approaches or frameworks (e.g., VCPy) are available to help estimate VOCs from VCPs. To establish inventory, both top-down and bottom-up approaches could be used. Undoubtedly, the activity data is critical to determining VCPs emission, including analytical and statistical assessment. Overall, more research is required to develop an effective modelling approach to quantify the VOCs from volatile chemical products.

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References

Adamović T, Hradecký J, Pánek M (2020) Volatile organic compounds (VOCs) from wood and wood-based panels: methods for evaluation, potential health risks, and mitigation. Polymers 12:2289. https://doi.org/10.3390/polym12102289

Adgate JL, Eberly LE, Stroebel C, et al. (2004) Personal, indoor, and outdoor VOC exposures in a probability sample of children. J Expos Anal Environ Epidemiol 14 Suppl 1:S4–S13. https://doi.org/10.1038/sj.jeea.7500353

AGÖF (2013) AGÖF Guidance values for volatile organic compounds in indoor air. http://agoef.de/agoef/oewerte/orientierungswerte_englisch.html. Accessed 24 Jul 2021

Ainslie B, Steyn DG (2007) Spatiotemporal trends in episodic ozone pollution in the Lower Fraser Valley, British Columbia, in relation to mesoscale atmospheric circulation patterns and emissions. J Appl Meteorol Climatol 46:1631–1644. https://doi.org/10.1175/JAM2547.1

Aklilu YA, Cho S, Zhang Q, Taylor E (2018) Source apportionment of volatile organic compounds measured near a cold heavy oil production area. Atmos Res 206 https://doi.org/10.1016/j.atmosres.2018.02.007

Alvim DS, Gatti LV, Corrêa SM et al. (2018) Determining VOCs reactivity for ozone forming potential in the megacity of São Paulo. Aerosol Air Qual Res 18:2460–2474. https://doi.org/10.4209/aaqr.2017.10.0361

Anser MA, Assawadithalerd M, Tipmanee D, et al. (2021) Occupational exposure to hazards and volatile organic compounds in small-scale plastic recycling plants in Thailand by integrating risk and life cycle assessment concepts. J Clean Prod 329. https://doi.org/10.1016/j.jclepro.2021.129582

Asif Z, Chen Z, Guo J (2018) A study of meteorological effects on PM2.5 concentration in mining area. Atmos Pollut Res 9:688–696. https://doi.org/10.1016/j.apr.2018.01.004

Asif Z, Chen Z, Stranges S, et al. (2022) Dynamics of SARS-CoV-2 spreading under the influence of environmental factors and strategies to tackle the pandemic: A systematic review. Sustain Cities Soc 81. https://doi.org/10.1016/j.scs.2022.103840

Aydemir C, Özyörü SA (2021) Environmental impact of printing inks and printing process. J Graph Eng Des 11. https://doi.org/10.24867/JGED-2020-2-011

Bari MA, Kindzierski WB (2018a) Ambient volatile organic compounds (VOCs) in Calgary, Alberta: Sources and screening health risk assessment. Sci Total Environ 631–632:627–640. https://doi.org/10.1016/j.scitotenv.2018.03.023

Bari MA, Kindzierski WB (2018b) Ambient volatile organic compounds (VOCs) in communities of the Athabasca oil sands region: Sources and screening health risk assessment. Environ Pollut 235, https://doi.org/10.1016/j.envpol.2017.12.065

Bari MA, Kindzierski WB, Wheeler AJ, et al. (2015) Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada. Build Environ 90. https://doi.org/10.1016/j.buildenv.2015.03.023

Berthiaume A, Galarneau E, Marson G (2022) Polycyclic aromatic compounds (PACs) in the Canadian environment: Sources and emissions. Environ Pollut 269:116008. https://doi.org/10.1016/j.envpol.2020.116008

Brooke D, Crookes M, Gray D, Robertson S (2009) Environmental Risk Assessment Report: Decamethylcyclopentasiloxane. Published by Environment Agency, UK. pp 37. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/2902561/scho0309/bpexe-e-e.pdf

Chaudhary A, Hellweg S (2014) Including indoor offgassed emissions in the life cycle inventories of wood products. Environ Sci Technol 48. https://doi.org/10.1021/es5045024
Chen C, Zhao B (2017) A modified Brownian force for ultrafine particle penetration through building crack modeling. Atmos Environ 170:143–148. https://doi.org/10.1016/j.atmosenv.2017.09.035

Chin JY, Godwin C, Parker E, et al. (2014) Levels and sources of volatile organic compounds in homes of children with asthma. Indoor Air 24:. https://doi.org/10.1111/ina.12086

Coggon MM, McDonald BC, Vlasenko A et al. (2018) Diurnal variability and emission pattern of Decamethylcyclopentasiloxane (D5) from the application of personal care products in two North American cities. Environ Sci Technol 52:5610–5618. https://doi.org/10.1021/acs.est.8b00506

Coggonia MM, Gkatzelis GI, McDonald BC, et al. (2021) Volatile chemical product emissions enhance ozone and modulate urban chemistry. Proc Natl Acad Sci U S A 118. https://doi.org/10.1073/pnas.2026653118

DEFRA-UK (2022) Emissions of air pollutants in the UK—Non-methane volatile organic compounds (NMVOCs). https://www.gov.uk/government/statistics/emissions-of-air-pollutants/emissions-of-air-pollutants-in-the-uk-non-methane-volatile-organics-nmvocs. Accessed 13 June 2022

Deng B, Kim CN (2004) Physical-based double-exponential model for VOC emissions from carpet. Atmos Environ 38. https://doi.org/10.1016/j.atmosenv.2004.04.004

Dios M, Souto JA, Casares JJ, et al. (2012) A mixed top-down and bottom-up methodology in spatial segregation of emissions based on GIS tools. WIT Trans Ecol Environ 157. https://doi.org/10.2495/AIR120201

ECCC (2021) Canada’s Air Pollutant Emissions Inventory Report 1990-2019-Environment and Climate Change Canada. https://publications.gc.ca/collections/collection_2021/eccc/En81-30-2019-eng.pdf. Accessed 15 Aug 2021

EEA (2021) Non-methane volatile organic compounds (NMVOC) emissions. https://www.eea.europa.eu/data-and-maps/indicators/eea-32-non-methane-volatile-1/assessment-4. Accessed 16 Sep 2022

Elguindi N, Granier C, Stavroukou T, et al. (2020) Intercomparison of magnitudes and trends in anthropogenic surface emissions from bottom-up inventories, top-down estimates, and emission scenarios. Earth’s Future 8:. https://doi.org/10.1029/2020EF001520

Environment Canada and Health Canada (2011) The Challenge 473 Siloxanes and Silicones, di-Me, hydrogen-terminated Chemical Abstracts-CAS Registry Number 70900-21-9. https://www.canada.ca/en/health-canada/services/chemical-substances/challenge/batch-11/mhdnmh.html. Accessed 4 Aug 2021

Environmental defence organization (2015) The dirty truth how toxic cleaning products are putting Canadians at risk. https://environmentaldefence.ca/wp-content/uploads/2016/01/TheDirtyTruth_ENG.pdf. Accessed 5 Nov 2021

Environmental Reporting BC (2020) Status of Ground-Level Ozone in B.C. (2016-2018)-State of Environment Reporting, Ministry of Environment and Climate Change Strategy, British Columbia, Canada. https://www.env.gov.bc.ca/soe/indicators/air/ozone.html. Accessed 25 Sep 2021

FVRD (2014) Regional ground level ozone strategy For the Canadian Lower Fraser Valley Region. http://www.metrovancouver.org/services/air-quality/AirQualityPublications/RGLOS2014.pdf. Accessed 9 Aug 2022

Geiss O, Giannopoulos G, Tirendi S et al. (2011) The AIRMEX study - VOC measurements in public buildings and schools/kinder-gartens in eleven European cities: Statistical analysis of the data. Atmos Environ 45:3676–3684. https://doi.org/10.1016/j.atmosenv.2011.04.037

Geng F, Cui C, Tie X, et al. (2009) Analysis of VOC emissions using PCA/APCS receptor model at city of Shanghai, China. J Atmos Chem 62:. https://doi.org/10.1007/s10874-010-9150-5

Gkatzelis GI, Coggon MM, McDonald BC, et al. (2021a) Identifying Volatile Chemical Product Tracer Compounds in U.S. Cities. Environ Sci Technol 55:. https://doi.org/10.1021/acs.est.0c05467

Gkatzelis GI, Coggon MM, McDonald BC, et al. (2021b) Observations Confirm that Volatile Chemical Products Are a Major Source of Petrochemical Emissions in U.S. Cities. Environ Sci Technol 55:. https://doi.org/10.1021/acs.est.0c05471

Goodman NB, Steinemann A, Wheeler AJ et al. (2017) Volatile organic compounds within indoor environments in Australia. Build Environ 122:116–125. https://doi.org/10.1016/j.buildenv.2017.05.033

Gough WA, Anderson V (2022) Changing Air Quality and the Ozone Weekend Effect during the COVID-19 Pandemic in Toronto, Ontario, Canada. Climate 10:. https://doi.org/10.3390/cli10030041

Government of Canada (2022a) National Pollutant Release Inventory Substrate Overview; Volatile organic compounds. https://www.canada.ca/en/environment-climate-change/services/national-pollutant-release-inventory/tools-resources-data/volatile-organic-compounds.html. Accessed 2 Aug 2022

Government of Canada (2022b) National Pollutant Release Inventory data search. https://pollution-waste.canada.ca/national-release-inventory/?fromYear=2020&toYear=2020& substance=14242&category=2&direction=ascending&order=NPRIL Id&filter=sarnia&length=10&page=1. Accessed 22 Sep 2022

Government of Canada (2020) Industry Guide for the labelling of cosmetics. https://www.canada.ca/en/health-canada/services/consumer-product-safety/reports-publications/industry-professionals/labelling-cosmetics.html#one1. Accessed 21 Oct 2021

Government of Canada (2021) Volatile Organic Compound (VOC) Concentration Limits for Automotive Refinishing Products Regulations. https://laws-lois.justice.gc.ca/eng/regulations/SOR-2009-197/page-1.html#.B7-479420. Accessed 1 Jul 2021

Haghhighat F, Huang H (2003) Integrated IAQ model for prediction of VOC emissions from building material. Build Environ 38:1007–1017. https://doi.org/10.1016/S0360-1323(03)00064-7

Han D, Gao S, Fu Q et al. (2018) Do volatile organic compounds (VOCs) emitted from petrochemical industries affect regional PM2.5? Atmos Res 209:123–130. https://doi.org/10.1016/j.atmosres.2018.04.002

Han D, Wang Z, Cheng J, et al. (2017) Volatile organic compounds (VOCs) during non-haze and haze days in Shanghai: characterization and secondary organic aerosol (SOA) formation. Environ Sci Pollut Res 24:. https://doi.org/10.1007/s11356-017-9433-3

He K, Shen Z, Sun J, et al. (2020) Spatial distribution, source apportionment, ozone formation potential, and health risks of volatile organic compounds over a typical central plain city in China. Atmosphere (Basel) 11. https://doi.org/10.3390/atmos110121365

Health Canada (2021) Health Impacts of Air Pollution in Canada: Estimates of morbidity and premature mortality outcomes–2021 Report. https://www.canada.ca/content/dam/hc-sc/documents/services/publications/healthy-living/2021-health-effects-indoor-air-pollution/hiap-report-eng.pdf. Accessed 5 Aug 2021

Héroux ME, Clark N, van Ryswyk K et al. (2010) Predictors of indoor air concentrations in smoking and non-smoking residences. Int J Environ Res Public Health 7:3080–3099. https://doi.org/10.3390/ijerph7083080

Hodgson AT, Levin H (2003) Volatile organic compounds in homes of children with asthma. Concentration Limits for Automotive Refinishin Materials. https://www.canada.ca/en/health-canada/services/consumer-products/health-safety/make-up-regulations.html. Accessed 22 Sep 2022

Holmberg J (2021) Which is better-bottom-up or top-down emissions estimates? In: Air Emiss. Manag Process Ecol. https://processecology.com/articles/which-is-better-bottom-up-or-top-down-emissions-estimates
Horig Y, Kannan K (2008) Survey of organosilicone compounds, including cyclic and linear siloxanes, in personal-care and household products. Arch Environ Contam Toxicol 55:701–710. https://doi.org/10.1007/s00244-008-0972-z

Hu HP, Zhang YP, Wang XK, Little JC (2007) An analytical mass transfer model for predicting VOC emissions from multi-layered building materials with convective surfaces on both sides. Int J Heat Mass Transf 50. https://doi.org/10.1016/j.ijheatmasstransfer.2006.11.024

Inglezakis VJ, Pouloupolous SG (2006) Adsorption, ion exchange and catalysis: design of operations and environmental applications. 1st Edition. Amsterdam; Boston: Elsevier. https://doi.org/10.1016/B978-0-444-52783-7.X5000-9

Jamal S (2018) Tips & tricks for non-toxic spring cleaning. In: Toxics. https://environmentaldefence.ca/2017/04/13/tips-non-toxic-spring-cleaning/. Accessed 13 Jul 2021

Jhan I, Coull BA, Zanobetti A, Koutrakis P (2015) The impact of nitrogen oxides concentration decreases on ozone trends in the USA. Air Qual Atmos Heal 8:283–292. https://doi.org/10.1007/s11869-014-0279-2

Jia C, Batterman S (2019) Variability of total volatile organic compounds (Tvoc) in the indoor air of retail stores. Int J Environ Res Public Health 16. https://doi.org/10.3390/ijerph16234622

Khoshrav SM, Rostami R, Zin RM, et al. (2020) The role of green building materials in reducing environmental and human health impacts. Int J Environ Res Public Health 17: https://doi.org/10.3390/ijerph17072589

Kowalska J, Pniewska M (2015) Measurements of chlorinated volatile organic compounds emitted from office printers and photocopiars. Environ Sci Pollut Res 22. https://doi.org/10.1007/s11356-014-3672-3

Kraus M, Juhasova Senitkova I (2019) Material VOC Emissions and Indoor Air Quality Simulation. In: IOP Conference Series: Mater Sci Eng 603. https://doi.org/10.1088/1757-899X/603/5/052082

Kumar S, Imam B (2013) Footprints of air pollution and changing environment on the sustainability of built infrastructure. Sci Total Environ 444. https://doi.org/10.1016/j.scitotenv.2012.11.056

Kwon HA, Park RJ, Oak YJ, et al. (2021) Top-down estimates of anthropogenic VOC emissions in South Korea using formaldehyde vertical column densities from aircraft during the KORUS-AQ campaign. Elementa 9. https://doi.org/10.1525/elementa.2021.00109

Lewis AC, Hopkins Jr, Carlaw DC, et al. (2020) An increasing role for solvent emissions and implications for future measurements of volatile organic compounds: Solvent emissions of VOCs. Philos Trans R Soc A Math Phys Eng Sci 378. https://doi.org/10.1098/rsta.2019.0328

Li B, Ho SSH, Gong S, et al. (2019a) Characterization of VOCs and their related atmospheric processes in a central Chinese city during severe ozone pollution periods. Atmos Chem Phys 19. https://doi.org/10.5194/acp-19-617-2019

Li Y, Cakmak S, Zhu J (2019b) Profiles and monthly variations of selected volatile organic compounds in indoor air in Canadian homes: Results of Canadian national indoor air survey 2012–2013. Environ Int 126:. https://doi.org/10.1016/j.envint.2019.02.035

Li B, Ho SSH, Li X, et al. (2021) A comprehensive review on anthropogenic volatile organic compounds (VOCs) emission estimates in China: Comparison and outlook. Environ Int 156:1–14. https://doi.org/10.1016/j.envint.2021.106710

Li F, Niu J, Zhang L (2006) A physically-based model for prediction of VOCs emissions from paint applied to an absorptive substrate. Build Environ 41:1317–1325. https://doi.org/10.1016/j.buildenv.2005.05.026

Liu Y, Lu S, Yan X, et al. (2020) Life cycle assessment of petroleum refining process: A case study in China. J Clean Prod 256:. https://doi.org/10.1016/j.jclepro.2020.120422

Loh MM, Houseman EA, Gray GM et al. (2006) Measured concentrations of VOCS in several non-residential microenvironments in the United States. Environ Sci Technol 40:6903–6911. https://doi.org/10.1021/es606197g

Masjedi MR, Taghizadeh F, Hamzehali S, et al. (2019) Air pollutants associated with smoking in indoor/outdoor of waterpipe cafes in Tehran, Iran: Concentrations, affecting factors and health risk assessment. Sci Rep 9. https://doi.org/10.1038/s41598-019-39684-3

Matz CJ, Egyed M, Xi G, et al. (2020) Health impact analysis of PM2.5 from wildfire smoke in Canada (2013–2015, 2017–2018). Sci Total Environ 725:. https://doi.org/10.1016/j.scitotenv.2020.138506

Mazzuca GM, Ren X, Loughner CP et al. (2016) Ozone production and its sensitivity to NOx and VOCs: Results from the DISCOVER-AQ field experiment, Houston 2013. Atmos Chem Phys 16:14463–14474. https://doi.org/10.5194/acp-16-14463-2016

McCarthy MC, Aklilu YA, Brown SG, Lyder DA (2013) Source apportionment of volatile organic compounds measured in Edmonton, Alberta. Atmos Environ 81:. https://doi.org/10.1016/j.atmosenv.2013.09.016

McDonald BC, De Gouw JA, Gilman JB et al. (2018) Volatile chemical products emerging as largest petrochemical source of urban organic emissions. Science (80-) 359:760–764. https://doi.org/10.1126/science.aao524

Mintz R, McWhinney RD (2008) Characterization of volatile organic compound emission sources in Fort Saskatchewan, Alberta using principal component analysis. J Atmos Chem 60:. https://doi.org/10.1007/s10874-008-9110-5

Mo Z, Cui R, Yuan B et al. (2021) A mass-balance-based emission inventory of non-methane volatile organic compounds (NMVOCs) for solvent use in China. Atmos Chem Phys 21:13655–13666. https://doi.org/10.5194/acp-21-13655-2021

Mo Z, Shao M, Liu Y, et al. (2018) Species-specific VOC emissions derived from a gridded study in the Pearl River Delta. Sci Rep 8:. https://doi.org/10.1038/s41598-018-21296-y

Murrells T, Brown P, Wakeling D, Pang Y (2018) Methodology for the UK’s Road Transport Emissions Inventory: Version for the 2016 National Atmospheric Emissions Inventory. Report for the Department of Business, Energy and Industrial Strategy. Ricardo Energy & Environment reference: ED59803130(1). https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1804121004_Road_Transport_Emissions_Inventory_Version_for_the_2016_National_Atmpheric_Emissions_Inventory_Report_for_the_DBEIS_14474. https://doi.org/10.5194/acp-16-13655-2021

Nandan A, Siddiqui NA, Kumar P (2020) Estimation of indoor air pollutant during photocopy/printed operation: a computational fluid dynamics (CFD)-based study. Environ Geochim Health 42:. https://doi.org/10.1007/s10653-020-00589-0

Natural Resources Canada (2010) Canadian Wildland Fire Information System (CWFIIS). https://cwfiis.cfs.nrcan.gc.ca/home. Accessed 2 Aug 2021

Nazaroff WW, Weschler CJ (2004) Cleaning products and air fresheners: Exposure to primary and secondary air pollutants. Atmos Environ 38:. https://doi.org/10.1016/j.atmosenv.2004.02.040

NOAA news (2018) Study: Pollution from personal care products comparable to tailpipe emissions in Boulder. https://research.noaa.gov/article/ArtMID/587/ArticleID/2349/Study-Pollution-from-personal-care-products-comparable-to-tailpipe-emissions-in-Boulder. Accessed 15 Jul 2021

Odabasi M (2008) Halogenated volatile organic compounds from the use of chlorine-bleach-containing household products. Environ Sci Technol 42:1445–1451. https://doi.org/10.1021/es702355u

Pacienca I, Madureira J, Rufo J, et al. (2016) A systematic review of evidence and implications of spatial and seasonal variations of...
volatile organic compounds (VOC) in indoor human environments. J Toxicol Environ Heal- Part B Crit Rev 19:47–64. https://doi.org/10.1080/10937404.2015.1134371

Panagopoulos IK, Karayannis AN, Kassomenos P, Aravossis K (2011) A CFD simulation study of VOC and formaldehyde indoor air pollution dispersion in an apartment as part of an indoor pollution management plan. Aerosol Air Qual Res 11:758–762. https://doi.org/10.4209/aair.2010.11.0092

Pereira KL, Hamilton JF, Rickard AR et al. (2015) Insights into the Formation and Evolution of Individual Compounds in the Particulate Phase during Aromatic Photo-Oxidation. Environ Sci Technol 49:13168–13178. https://doi.org/10.1021/acs.est.5b03377

Qin M, Murphy BN, Isaacs KK, et al. (2021) Criteria pollutant impacts of volatile chemical products informed by near-field modelling. Nat Sustain 4:. https://doi.org/10.1038/s41893-020-00614-1

Rajabi H, Hadi Mosleh M, Mandal P et al. (2020) Emissions of volatile organic compounds from crude oil processing-Global emission inventory and environmental release. Sci Total Environ 727:138654

Raw GJ, Coward SKD, Brown VM, Crump DR (2004) Exposure to air pollutants in English homes. J Expos Anal Epidemiol 14:885–894. https://doi.org/10.1038/sj.see.5500363

Selzter KM, Pennington E, Rao V et al. (2021) Reactive organic carbon emissions from volatile chemical products. Atmos Chem Phys 21:5079–5100. https://doi.org/10.5194/acp-21-5079-2021

Shayegan Z, Haghghat F, Lee CS (2019) Photocatalytic oxidation of volatile organic compounds for indoor environment applications: Three different scaled setups. Chem Eng J 357:533–546. https://doi.org/10.1016/j.cej.2018.09.167

Shin HM, McKone TE, Bennett DH (2015) Contribution of low vapor pressure volatile organic compounds (LVP-VOCs) from consumer products to ozone formation in urban atmospheres. Atmos Environ 108:. https://doi.org/10.1016/j.atmosenv.2015.02.067

Singer BC, Destaillats H, Hodgson AT, Nazaroff WW (2006) Cleaning products and air fresheners: Emissions and resulting concentrations of glycol ethers and terpenoids. Indoor Air 16:. https://doi.org/10.1111/j.1600-0668.2005.00414.x

Smith D (2020) Understanding TVOC: What You Need To Know About Volatile Organic Compounds. In: kaiterra.https://learn.kaiterra.com/en/air-academy/understanding-tvoc-volatile-organic-compounds/

Accessed 26 Aug 2021

Song SK, Shon ZH, Kang YH et al. (2019) Source apportionment of VOCs and their impact on air quality and health in the megacity of Seoul. Environ Pollut 247:763–776. https://doi.org/10.1016/j.envpol.2019.01.102

Song Y, Dai W, Shao M, et al. (2008) Comparison of receptor models for source apportionment of volatile organic compounds in Beijing, China. Environ Pollut 156:. https://doi.org/10.1016/j.envpol.2007.12.014

Stroud CA, Ren S, Zhang J, et al. (2020) Chemical analysis of surface-level ozone exceedances during the 2015 Pan American Games. Atmosphere (Basel) 11:. https://doi.org/10.3390/atmos11060572

Thunis P, Degraeuwe B, Cuvelier K, et al. (2016) A novel approach to screen and compare emission inventories. Air Qual Atmos Heal 9:. https://doi.org/10.1007/s11869-016-0402-7

U.S. Environmental Protection Agency (2018) Fundamentals of Indoor Air Quality in Buildings. www.epa.gov/indoor-air-quality-iaq/fundamentals-indoor-air-quality-buildings (Accessed on Jan 2, 2020).

USEPA (2018) Volatile Organic Compounds’ Impact on Indoor Air Quality. https://www.epa.gov/indoor-air-quality-iaq/volatile-organic-compounds-impact-indoor-air-quality. Accessed 18 Sep 2021

USEPA (2021) 2017 National Emissions Inventory: January 2021 Updated Release. Technical Support Document-EPA-454/R-21-001

USEPA (2017) National Emission Inventory USA. https://www.epa.gov/air-emissions-inventories/2017-national-emissions-inventory-nei-data#doc. Accessed 2 Aug 2021

Van Tran V, Park D, Lee YC (2020) Indoor air pollution, related human diseases, and recent trends in the control and improvement of indoor air quality. Int J Environ Res Public Health 17:2927. https://doi.org/10.3390/ijerph17082927

Verma M, Pervez S, Majumdar D, et al. (2019) Emission estimation of aromatic and halogenated VOCs from household solid fuel burning practices. Int J Environ Sci Technol 16:. https://doi.org/10.1007/s13762-018-1920-7

Wan Y, Chen C, Wang P, et al. (2015) Infiltration characteristic of outdoor fine particulate matter (PM2.5) for the Window Gaps. Procedia Eng. 121:191–198

Wang F, Zhang Z, Acciai C, et al. (2018) An integrated method for factor number selection of PMF model: Case study on source apportionment of ambient volatile organic compounds in Wuhan. Atmosphere 9:. https://doi.org/10.3390/atmos9100390

Wang R, Moody RP, Koniecki D, Zhu J (2009) Low molecular weight cyclic volatile methylsiloxanes in cosmetic products sold in Canada: Implication for dermal exposure. Environ Int 35:. https://doi.org/10.1016/j.envint.2009.03.009

Wheeler AJ, Wong SL, Khoury C, Zhu J (2013) Predictors of indoor BTEX concentrations in Canadian residences. Heal Rep. 24:11–17

WHO (2022) Household air pollution and health. WHO Media Cent. https://www.who.int/news-room/fact-sheets/detail/household-air-pollution-and-health. Accessed 5 Jan 2022

Wu R, Xie S (2018) Spatial distribution of secondary organic aerosol formation potential in China derived from speciated anthropogenic volatile organic compound emissions. Environ Sci Technol 52:8146–8156. https://doi.org/10.1021/acs.est.8b01269

Wu W, Zhao B, Wang S, Hao J (2017) Ozone and secondary organic aerosol formation potential from anthropogenic volatile organic compounds emissions in China. J Environ Sci 53. https://doi.org/10.1016/j.jes.2016.03.025

Xiong Y, Bari MA, Xing Z, Du K (2020) Ambient volatile organic compounds (VOCs) in two coastal cities in western Canada: Spatiotemporal variation, source apportionment, and health risk assessment. Sci Total Environ 706. https://doi.org/10.1016/j.scitotenv.2019.135970

Xiong Y, Du K (2020) Source-resolved attribution of ground-level ozone formation potential from VOC emissions in Metropolitan Vancouver, BC. Sci Total Environ 721. https://doi.org/10.1016/j.scitotenv.2020.137698

Xu J, Szyzkwiczek M, Jovic B, et al. (2016) Estimation of indoor and outdoor ratios of selected volatile organic compounds in Canada. Atmos Environ 143:. https://doi.org/10.1016/j.atmosenv.2016.07.031

Yang X, Chen Q, Zeng JS, et al. (2001b) Numerical simulation of VOC emissions from dry materials. Build Environ 36:.https://doi.org/10.1016/S0360-1323(00)00078-0

Yeoman AM, Shaw M, Carslaw N, et al. (2020) Simplification of atmospheric volatile organic compound emission rates from non-aerosol personal care products. Indoor Air 30. https://doi.org/10.1111/ina.12652

Zhu J, Newhook R, Marro L, Chan CC (2005) Selected volatile pollutants in English homes. J Expos Anal Environ Epidemiol 15:727–731. https://doi.org/10.1093/jeea/jiah013
Zhu J, Wong SL, Cakmak S (2013) Nationally representative levels of selected volatile organic compounds in canadian residential indoor air: Population-based survey. Environ Sci Technol 47:13276–13283. https://doi.org/10.1021/es403055e

Zou Y, Deng XJ, Zhu D et al. (2015) Characteristics of 1 year of observational data of VOCs, NOx and O₃ at a suburban site in Guangzhou, China. Atmos Chem Phys 15:6625–6636. https://doi.org/10.5194/acp-15-6625-2015

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