

Research Article

Air Pollution Control: Comparative Analysis of VOC Regulations Across Mainland China, the EU, and the US

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Air pollution, especially the rising ground-level ozone (O_3) levels, poses a critical global challenge to public health and environmental sustainability. Volatile organic compounds (VOCs), which are key precursors to O_3 formation, are primarily emitted from various household chemical products. Given the lack of a thorough understanding of the current regulatory control on VOC emissions and the need to identify ways to curb these emissions, a comparative analysis was conducted on the VOC regulations across three major economies: Mainland China, the European Union (EU), and the United States. The analysis reveals distinct regulatory frameworks and approaches: (i) the United States exemplifies a robust control framework characterized by detailed product categorization, stringent VOC limits, and many control parameters; (ii) the EU adopts a relatively streamlined approach, primarily targeting certain types of architectural paints and relying on ecolabel for specific cleaning products; and (iii) Mainland China employs a broad regulatory approach, permitting a range of solvent-borne products with comparatively lenient VOC limits, while tightening penalty mechanisms and broadening the scope of regulated entities. Comparatively, the EU and Mainland China place less emphasis on governing consumer products such as air fresheners, while the United States and Mainland China implement the polluter-pays principle, including VOC taxes. In addition to forging international collaboration to enhance cross-border regulatory control of VOCs, future work is needed to explore establishing stricter emission standards, implementing comprehensive bans on specific high-VOC products, and providing financial incentives and technological upgrades for the transition to low-VOC alternatives.

Keywords: air pollution control; ozone; regulation; VOC content; volatile organic compound

1. Introduction

Globally, approximately 99% of the population is exposed to air quality levels that exceed the World Health Organization (WHO) guidelines, posing significant health risks to the general public [1]. In 2020, it was reported that 93% of individuals lived in areas with peak-season ozone (O_3) levels surpassing the WHO Air Quality Guideline (AQG) updated in 2021 with a figure of $60 \mu\text{g}/\text{m}^3$ [2]. Recent studies reveal alarming trends in O_3 concentrations, particularly in urban regions of both developed and developing countries, including Mainland China, the EU, and the United States. An analysis of hourly O_3 concentration data from 338 cities in

Mainland China between 1 January 2016 and 28 February 2019 demonstrated that O_3 levels frequently exceeded the Ambient Air Quality Standards outlined in the national standard GB 3095-2012 [3], with daily maximum 8-h averages ranging from 100 to $160 \mu\text{g}/\text{m}^3$ [4]. Furthermore, average annual O_3 concentrations in Mainland China rose significantly, at a rate of $1.84 \mu\text{g}/\text{m}^3$ per year, with the proportion of days exceeding maximum standard increasing from 1.2% in 2013 to 28.9% in 2018 [5]. Major urban centers such as Beijing, Chengdu, Guangzhou, and Shanghai experienced severe O_3 pollution, exceeding the WHO's 8-h guideline on more than 30% of recorded days from 2013 to 2015 [6]. Even Hong Kong, a special administrative region of

Mainland China and a financial center located far from industrial regions, reported a 37% increase in O_3 levels from 2013 to 2022, reflecting a concerning regional trend [7].

A similar trend has been observed in the EU, where O_3 concentrations have shown a slight increase from 2005 to 2019, despite a 10% decline in peak levels [8]. In 2022, fewer than 20% of ground-level O_3 monitoring stations met the long-term objectives set by Directive 2008/50/EC of the European Parliament and of the Council, which stipulates that the maximum daily 8-h mean should not exceed $120 \mu\text{g}/\text{m}^3$ [9]. Alarming, 22 countries, including 18 EU member states, reported O_3 levels exceeding this target, highlighting persistent challenges in air quality management. In contrast, mean O_3 concentrations in rural areas have slightly decreased across Europe, North America, and East Asia, while urban areas continue to experience increases [10]. Additionally, stratospheric intrusion—where O_3 from the stratosphere enters the troposphere—may have contributed to elevated ground-level O_3 concentrations during the COVID-19 lockdown period [11].

Exposure to ground-level O_3 is linked to adverse health outcomes, including respiratory and cardiovascular issues, oxidative stress, and chronic diseases, particularly affecting aging population [12, 13]. The increase in ground-level O_3 represents a substantial threat to human health, contributing to an estimated 423,100 O_3 -related deaths globally in 2019, with high-income regions like Asia-Pacific and North America experiencing notable mortality despite emission reduction efforts [14]. Data from multiple regions—including North America, Europe, Asia, Australia, and Africa—indicate an alarming increase in O_3 -related deaths, projected to rise over 100-fold between 2010–2014 and 2050–2054 [15]. The highly oxidant nature of O_3 can create stressors on the growth and metabolism, potentially impacting agricultural productivity and food security on a global scale [16–18]. Addressing O_3 pollution necessitates enhanced efforts and exploration of novel strategies for O_3 control.

1.1. The Importance of VOC Control in Air Quality Control. VOCs are organic chemical compounds characterized by their ability to evaporate under typical indoor atmospheric conditions of temperature and pressure [19]. VOCs are commonly found in many building materials and home care products [20], while plants can also release VOCs through different synthesis pathways [21, 22]. VOCs with nitrogen oxides (NO_x) are two key precursors in the photochemical reaction that lead to O_3 formation in the presence of sunlight. A 3-year study measuring VOCs at three distinct sites within Kaohsiung Harbor in Taiwan revealed a strong correlation between ozone formation potential (OFP) and VOC concentrations. The predominant VOCs identified at the harbor included C_2 -VOC, toluene, and acetone. Importantly, solvent usage in coatings, plastics, and petrochemical applications accounted for 21.1% of the VOC emissions, comparable to emissions from industrial activities (33.7%) and those from vehicles and ships (30.6%) [23]. Sole reduction in NO_x does not necessarily lead to a corresponding decrease in the ground-level O_3 concentration and may even result in an increase [24, 25].

The O_3 concentration increase during Shanghai's lockdown further revealed that significant decrease (56%) in NO_x emission with incomparable decrease (11%) on VOC emission can finally drive O_3 production through efficient $\text{OH}-\text{HO}_2-\text{RO}_2$ radical propagation [26]. Similar phenomenon was observed in London during COVID-19 lockdown, indicating that O_3 formation in urban London was in the VOC-limited regime (refer to atmospheric conditions where O_3 production is primarily constrained by the availability of VOCs rather than NO_x [27]).

Satellite observations reveal that VOC-limited regimes are prevalent in megacity clusters like the North China Plain, Yangtze River Delta, and Pearl River Delta, particularly in developed cities such as Chengdu, Chongqing, Xi'an, and Wuhan. The rise in O_3 levels in major cities is primarily linked to significant NO_x emission control efforts, while VOC control remains limited [28]. For other regions like Pasadena and Redlands in the South Coast Air Basin involving both NO_x -limited and VOC-limited regime, more NO_x reduction is effective to significantly lower O_3 on most days [29].

VOCs not only contribute to the formation of O_3 but also react with O_3 to produce a kind of particulate matter (PM) called secondary organic aerosols (SOAs) through ozonolysis. This process involves larger molecules that condense into particles and evaporate, concentrating components and producing nitrogen-containing compounds that contribute to a brownish color [30, 31]. SOA can also be formed through reaction of VOCs such as limonene with hypochlorous acid (HOCl) and chlorine (Cl_2), commonly found in bleach, upon exposure to light [32]. Overall, VOCs are critical for controlling ground-level O_3 level and, to some extent, the PM level. The role of VOC in the formation of smog, which results from photochemical reactions that produce O_3 and SOA, is illustrated in Figure 1.

1.2. Existing Efforts and Gap in VOC Control. While the importance of VOCs is acknowledged, some scholars introduce coreduction ratio of VOC/NO_x (from a minimum of 0.72 to greater than 2) for effective short-term O_3 control [32–34], which aligns findings from another study using Aura Ozone Monitoring Instrument (OMI) observation [35, 36]. Different Chinese cities including Pearl River Delta Economic Zone and Hong Kong consider these ratios when formulating emission reduction targets [37]. Certain VOCs such as acetaldehyde, 1,3-butadiene, and isoprene were also identified having the highest O_3 production potential in Moscow [38]. Reduction of certain types of VOC such as alkenes and aromatics can significantly offset the negative impact of NO_x reduction relative to zero VOC reduction conditions [39]. While pre-existing efforts lie on emission from cars, power plants, and industrial uses [40], solvent use is found to be an important source of VOC in different regions. In Los Angeles, mobile and solvent are two biggest sectors that contributed most to OFP and SOA formation potential among Top 10 kinds of VOC [41]. In the United Kingdom, due to the efforts in reducing VOC emission from road transport and fugitive fuel emissions, over 60% of VOC

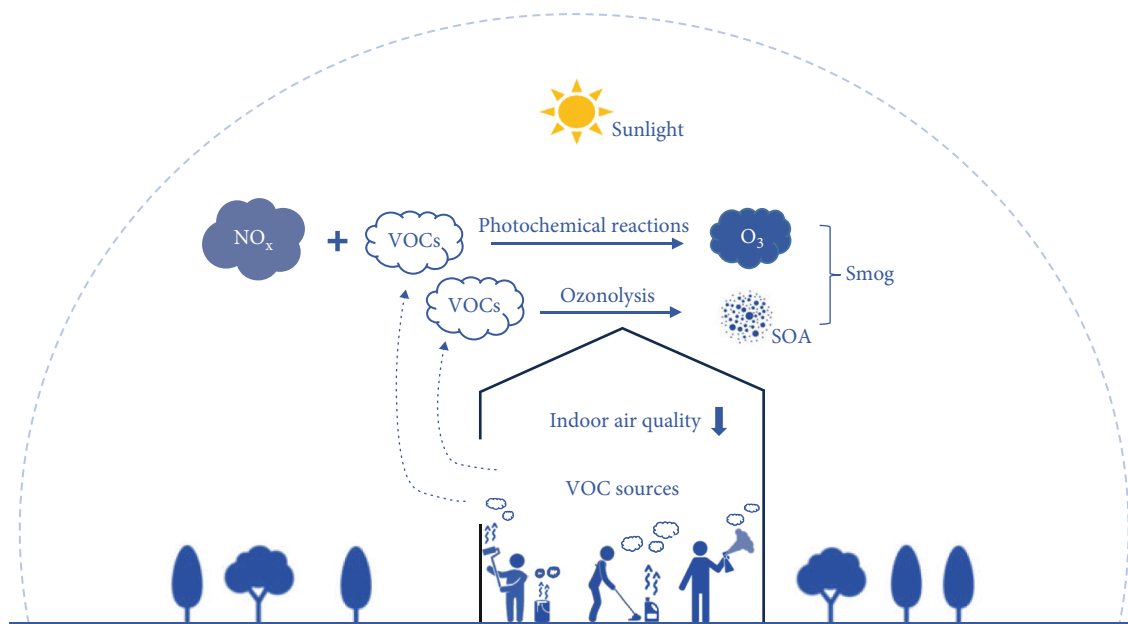


FIGURE 1: Role of VOC in the formation of smog combines O_3 and SOA through photochemical reactions.

emission accounted for solvents and industrial process [42]. Similar cases indicating the dominant contribution of VOC have been reported in Mainland China cities [43–45]. Research on ground-level O_3 has also shifted from transport emission to solvent use [46].

Some scholars recommended prioritizing the reduction of VOCs from solvent usage when the VOC/NO_x ratio exceeds 4.6 [47]. Solvent-borne (SB) architectural coatings were identified as significant contributors to photochemical air pollution, with O_3 production factors ranging from 1176.63 to 1781.82 g O_3 (kg paint) $^{-1}$ and SOA production factors up to 5.31–9.45 g SOA (kg paint) $^{-1}$ [48, 49]. Additionally, significant emission sources include adhesives with VOC emission factors ranging from 33.49 to 654.23 g/L and sealants, with factors up to 132.28 g/L [48–51]. Postoccupancy, consumer products such as air fresheners, insecticides, and hairsprays are prevalent contributors to VOC emissions, and high VOC content has been reported in these products [52–56]. Cleaning products, particularly those with fragrances—such as limonene—have seen increased usage following the pandemic and can contain hundreds of different VOCs [52, 55, 57]. VOC emission from the use of these kinds of products was found to be one to two orders of magnitude greater than those from automobile exhaust, making these products as the largest petrochemical source of urban organic emission in both the United States and Europe [58]. Given that the VOCs emitted from products commonly used in construction, postoccupancy activities, and retrofitting have been inadequately studied in terms of regulatory control [59], there is an urgent need for examining existing regulatory frameworks and providing insight for effectively controlling VOC emissions from these products. This is essential not only to mitigate atmospheric pollution at the source but also to enhance general air quality for public health.

2. Method

The methodology employed in this study consists of a systematic three-step process designed to analyze the regulatory frameworks on certain VOC-containing products in the regions under investigation. The selection of these products is grounded in their prevalent use and substantial VOC contribution as revealed from the above review.

The first step involves the identification of study regions that will serve as focal points for this comparative analysis. We prioritize regions characterized by substantial economic scale and significant contributions to global pollution levels. This selection is grounded in two main rationales. First, there exists a well-documented correlation between economic growth, particularly as measured by gross domestic product (GDP) and air pollution levels. Studies have shown that increased economic activity often correlates with heightened pollutant emissions [60–62]. Second, economies with considerable development typically possess greater resources, obligations, and public willingness to support pollution control measures [63–65]. These selection criteria facilitate a robust examination of the regulatory frameworks in place, as such regions are often better equipped to adopt and enforce stringent environmental regulations.

The second step entails extensive searches to retrieve existing VOC regulations in products within the identified regions (Mainland China, Hong Kong, China, the EU, and the United States), accessing websites or databases of jurisdictional official organizations, authorities, or governments (see Table 1). Relevant resources published by other regions (Government of Canada, United Nations, United Nations Economic Commission for Europe, and WHO), although they were not the focus of this study, were also retrieved to identify any useful information that could augment the analysis of findings.

TABLE 1: Websites or databases of official parties in China, EU, and United States.

Region	Official organizations, authorities, or governments
Mainland China	• Ecology Environment Bureau of Shenzhen Municipality • Environment and Ecology Bureau of the PRC • General Administration of Quality Supervision, Inspection and Quarantine of the PRC • Ministry of Ecology and Environment of the PRC • Ministry of Finance of the PRC • People's Government of Beijing Municipality • People's Government of Guangdong Province • Shanghai Municipal Bureau of Ecology and Environment • Standardization Administration of the PRC • State Administration for Market Regulation of the PRC • State Council of the PRC
Hong Kong	• Legislative Council of Hong Kong
European Union	• The European Environment Agency • The European Parliament • The Council of the European Union • The Commission of the European Communities
The United States	• California Air Resources Board • California Legislative Information • Minnesota Department of Health • United States Congress • United States Environmental Protection Agency

The final step employs an integrative review approach to synthesize relevant perspectives and generate new insights [66]. A manual content analysis was conducted by the research team to scrutinize the provisions of the VOC regulations in the identified regions, appraise their requirements, and compare their characteristics. Through discussing the review findings, implications are identified, signposting the future directions for enhancing VOC control aimed at reducing O₃ pollution.

3. Results

3.1. Existing Regulation Regime on VOC-Containing Products. The VOC regulations of Mainland China, the EU, and the United States were selected for examination for three principal reasons. First, as reported by [67], these regions represent the largest economies globally, making their regulatory frameworks particularly influential in shaping international practice. Second, these regions were major VOC emitters in the world, particularly with 30% of VOC emission attributed to the use of volatile chemical products (VCPs) in these regions [68], highlighting their critical roles in global air quality management. Third, the geographical diversity and varying cultural contexts of these regions provide a rich comparative landscape for analyzing VOC control measures. By scrutinizing the provisions of VOC control laws across these distinct jurisdictions, this study is aimed at delivering a thorough understanding of the current regulatory measures and identifying room for improvement through a comprehensive analysis of the regulatory controls on VOC-containing products, specifically in relation to mitigating O₃ pollution.

3.1.1. Mainland China

3.1.1.1. Evolution of the Statutory Controls. Since 2015, the central government of the People's Republic of China (PRC) has adopted an economic approach to control VOC content in coating. The Ministry of Finance instituted a consumption tax of 4% on the invoice value of coating products—whether imported or locally manufactured—that contain more than 420 g/L of VOC under ready-to-use conditions [69]. This tax applies to coating manufacturers, including those engaged in contract processing, as well as suppliers and importers. Products with a VOC content of less than 420 g/L must undergo independent testing and receive approval from a provincially authorized laboratory. Additionally, the Atmospheric Pollution Prevention and Control Law (APPCL) was amended in 2015 and enacted in 2016, introducing specific VOC control measures as reflected in Articles 44 and 46 [70]. Article 44 regulates the manufacture, import, sale, and use of noncompliant VOC-containing products, while Article 46 mandates that industrial coating enterprises utilize low-VOC coatings and maintain detailed ledgers documenting the consumption, disposal, and VOC content of raw and auxiliary materials, which must be retained for a minimum of 3 years. The actions taken in 2015 demonstrated Mainland China's early efforts to mitigate VOC emissions from VCP.

In 2018, the State Council promulgated the “Three-Year Action Plan for Winning the Blue Sky Defense Battle,” which places VOC control as one of the important directions [71]. Under this plan, the MEE of the PRC further introduce a comprehensive VOC governance plan, which mandated the establishment of national standards for VOC content limits in products such as coatings, inks, adhesives, and

cleaning products by the end of 2019 [72]. Some Chinese cities, for example Shenzhen, have preemptively banned the use and sale of SB coatings to varying extents prior to the establishment of national standards since 2015 [73].

The State Administration for Market Regulation (SAMR) and the Standardization Administration of the PRC released nine national standards pertaining to VOCs, including GB 38468-2019 for interior floor coatings (Table S1), GB 18582-2020 for architectural wall coatings (Tables S2 and S3), GB 33372-2020 for adhesive (Table S4), and GB 38508-2020 for cleaning products, which standardize VOC content limits and testing method for the regulated products [75]. Also, the technical requirement for low-VOC coating product (GB/T 38597-2020) (Tables S5 and S6) was published to standardize specifications for low-VOC coating products, aiding enforcement of the APPCL [76]. In 2020, the MEE further announced the “2020 VOC Management Plan,” urging local governments to oversee manufacturers’ compliance with new standards [77]. This plan introduced a “positive list” and a “green procurement list” to encourage the use of VOC-compliant products. In 2022, the capital of Mainland China, Beijing, identified as one of the cities with the worst air quality [78, 79], published its local standard—limit standards of volatile organic compounds of architectural coatings and adhesives (DB11/1983-2022) (Tables S7 and S8), which is one of the first local standards established following the implementation of above national standards. The comparison between the Beijing standard (DB11/1983-2022) and national standards (GB/T 38597-2020, GB 18582-2020, and GB 38468-2019) for water-borne (WB) and solvent-based (SB) architectural coatings. In 2021, the National People’s Congress of the PRC adopted the Outline of the 14th Five-Year Plan (2021–2025) for National Economic and Social Development and Vision 2035, which emphasizes pollution prevention and control. Key objectives include the coordinated management of PM and O₃, aiming for a reduction of NO_x and VOC emissions by over 10% during this period [80]. In 2023, the State Council furthered these goals with the Action Plan for Continuous Improvement of Air Quality, outlining a comprehensive strategy that includes optimizing industrial structures for greener production and updating the legal and regulatory framework to support environmental and economic policies [81].

As shown in Figure 2, SB architectural coatings are at least or above the median VOC content limits set by relevant standards. Notably, WB coatings exhibit substantially lower VOC content limits in comparison to their SB counterparts. Except for GB 35468-2019 and GB 18552-2020, respectively, tailored for floor wall coating, GB/T 38597-2020 and DB11/1983-2022 cover more types of coating on VOC content limit. GB/T 38597-2020 and DB11/1983-2022 encompass a wider array of coating types with varying VOC content constraints. The former records a higher median value (median = 200, interquartile range [IQR] = 245) relative to the latter (median = 120, IQR = 65). Remarkably, SB anti-corrosion coatings for building and fire-proof coating exhibit the highest VOC content limits. Within DB11/

1983-2022, these categories emerge as outliers beyond the upper whisker, signaling an exceptional elevation in VOC content levels within the dataset. Moreover, DB11/1983-2022 demonstrates a reduced variability when juxtaposed with GB/T 38597-2022, as evidenced by its narrower IQR. The trends observed within DB11/1983-2022 suggest a trajectory toward enhanced standards and an impending stringency in VOC content regulations.

As shown in Figure 3, SB and WB adhesives exhibit a stark contrast in VOC content limit across the two standards. Most SB adhesives fall outside the first quartile (Q1), whereas the majority of WB adhesives cluster near the third quartile (Q3), forming two distinct extremes. Although DB11/1983-2022 imposes more stringent VOC limits for exterior applications compared to GB 33372-2022 (median: 125 vs. 325 g/L), the median VOC content for WB adhesives under both standards remains identical (75 g/L), with a range of 50–100 g/L. Particularly, certain adhesives formulated with specific chemical compositions—such as chloroprene rubber and styrene-butadiene-styrene block copolymers—consistently rank among the highest VOC-emitting products, with comparable VOC limits across all standards (600–650 and 480–550 g/L, respectively). This suggests that current regulatory frameworks exert limited control over VOC emissions based on chemical composition.

3.1.1.2. Consequences for Violation of Law. APPCL addresses four key dimensions: manufacturing, importation, sales, and use for VOC control in products. First, Article 103 imposes penalties for the manufacture and sale of noncompliant products, including confiscation and fines ranging from one to three times the product’s value. This robust framework serves as a deterrent against noncompliance in the marketplace. Second, Article 104 extends analogous penalties to the importation of noncompliant products, thereby ensuring that imported goods adhere to the same standards as domestically produced items. Third, Article 108 specifically targets the use of noncompliant VOC products, particularly within industrial coating enterprises. These entities are mandated to utilize low-VOC coatings and maintain accurate records of raw material consumption and VOC content. Violators of this provision may face corrective orders and fines between 20,000 and 200,000 yuan, with the possibility of operational suspension for repeated offenses.

In addition, all products fall under the purview of the Product Quality Law (PQL) of the PRC, which sets forth the duties and obligations of manufacturers and sellers, as well as the authority of SAMR. Article 13 mandates compliance with national and industry standards, emphasizing the protection of human health and the safety of individuals and assets. Articles 26 and 27 require manufacturers to possess valid quality test reports and adhere to applicable standards. Furthermore, Articles 33 and 34 obligate sellers to implement quality acceptance systems, verify quality certificates, and ensure the integrity of their products. While the penalties for manufacturing and selling noncompliant products are largely comparable, the PQL stipulates that serious violations may result in license revocation and potential criminal liability. Noteworthy, Article 50 delineates penalties for

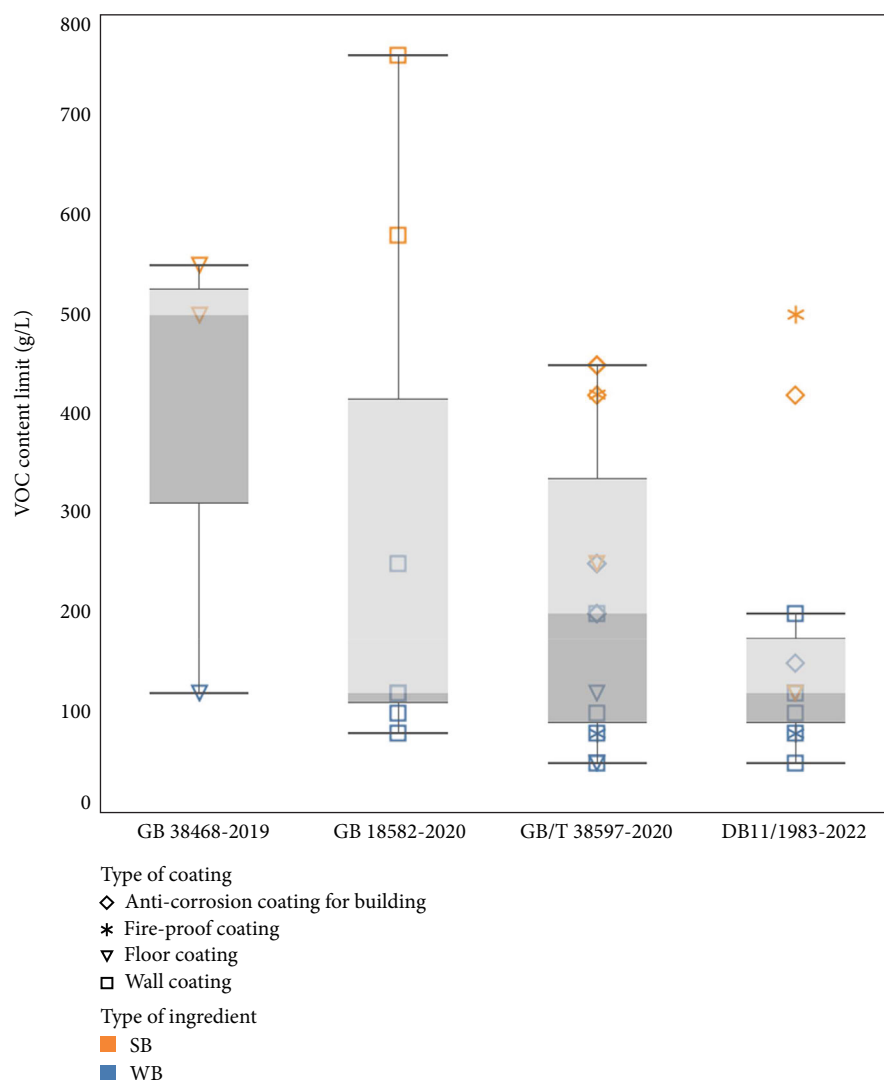


FIGURE 2: VOC content limits of selected coating products (under Beijing standard and certain national standards).

adulterating products or misrepresenting substandard goods as compliant. Such violations may lead to cessation orders, confiscation of illegal goods, and fines ranging from 50% to three times the product's value. Severe violations can also culminate in license revocation and criminal consequences.

The effectiveness of VOC control measures in one region can be significantly undermined by pollution originating from elsewhere, as the characteristics of air pollution are influenced by the use of products that may not be locally manufactured or sold. Insufficiently robust regulatory and enforcement frameworks can lead to the phenomenon of long-range transboundary air pollution (LRTAP), where pollutants traverse national borders, complicating local efforts to manage air quality effectively.

3.1.2. EU

3.1.2.1. Evolution of the Statutory Controls. Following the VOC Solvents Emission Directive (1999/13/EC) which addresses direct VOC emissions from specific industrial

activities such as printing and surface cleaning, Directive 2004/42/CE was enacted to regulate VOC content for painting product, including 12 nos. of architectural paints [82, 83]. The VOC content control under Directive 2004/42/CE is divided into two phases: Phase I, effective from January 1, 2007, and Phase II, effective from January 1, 2010 (Table S9). The directive also mandates labeling requirements that specify product subcategories, relevant VOC limit values, and maximum VOC content in ready-to-use conditions. More importantly, it distinguishes VOC content limit between WB and SB coatings, setting equivalent figures for interior wall and ceiling coatings, multicolored coatings, and decorative effect coatings, implying ban of SB coatings within these categories.

Subsequent to this, Commission Decisions 2009/543/EC and 2009/544/EC established criteria (Tables S10 and S11) for awarding the community ecolabel to paints and varnishes intended for both indoor and outdoor use [84, 85]. These criteria were further revised in Commission Decision 2014/312/EU (Table S12), which introduced

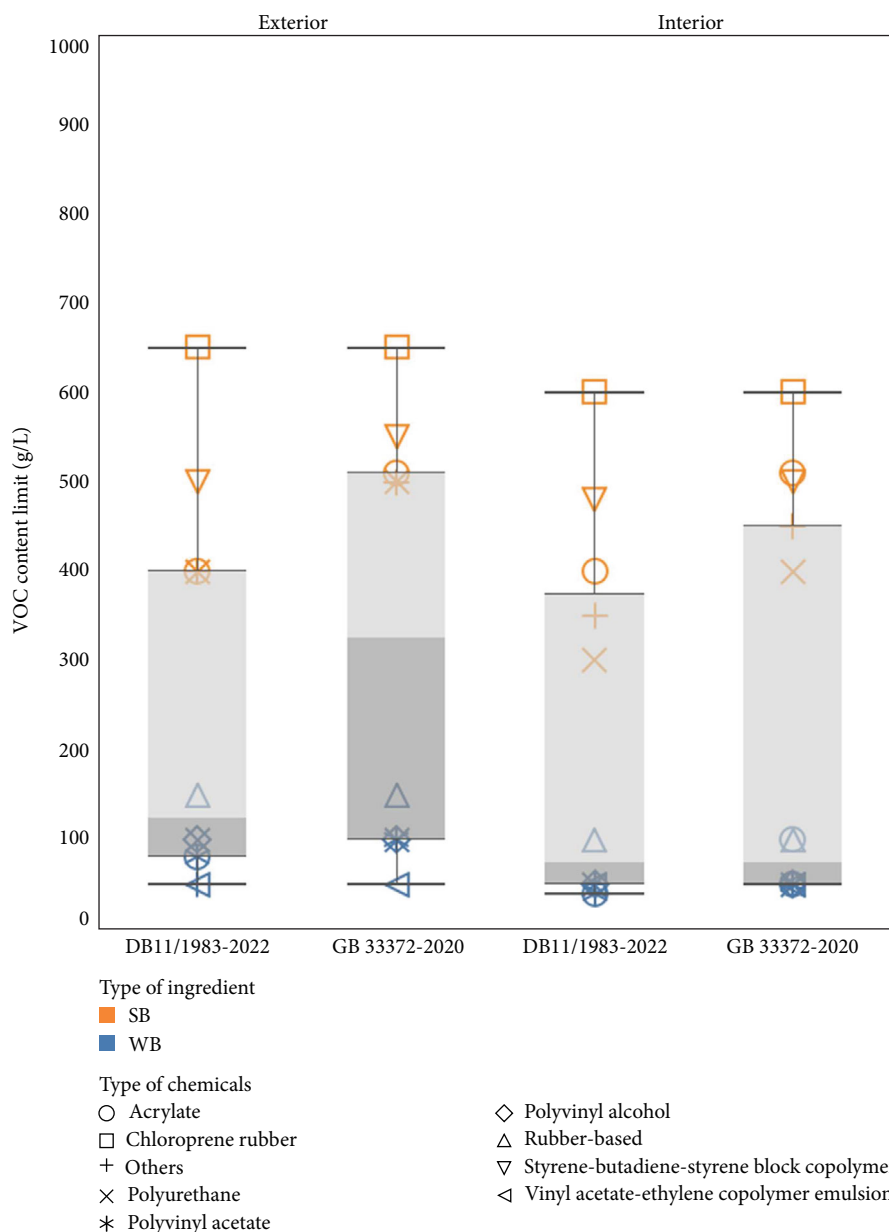


FIGURE 3: VOC content limits of architectural adhesives (under Beijing standard and certain national standards).

limits for semi-VOC (SVOC) content [86]. In the Commission Decision, SVOC is defined as organic compounds with boiling points greater than 250°C, in contrast to VOC, which are typically defined as compounds with boiling points below 250°C. The Commission Decision 2017/1217 introduced EU ecolabel criteria including toxicity, biodegradability, and VOC content for specific types of hard surface cleaning products (Table S13) [87]. According to Regulation (EC) No. 66/2010 on the EU ecolabel, EU ecolabel criteria are based on the best products available on the EEA market in terms of environmental performance throughout the life cycle and correspond indicatively to the best 10%–20% of the products available on the European Economic Area market in terms of environmental performance at

the moment of their adoption [88]. The EU ecolabel serves to inform stakeholders, particularly consumers, enabling informed choices beyond regulatory requirements or national standards. Currently, EU ecolabel covers a wide range of product groups including but not limited to cleaning products and lubricants.

Figure 4 demonstrates a progressive reduction in VOC regulatory limits across EU architectural coating standards. The evolution from Directive 2004/42/CE (median = 135 g/L, IQR = 300) to Commission Decision 2014/312/EU (median = 52.5 g/L, IQR = 30) underscores a substantial 50% decrease in median VOC limits over the decade (2004–2014), signaling a decisive regulatory pivot toward lower emissions. While the comparison between 2009/543/EC (median = 90, IQR = 50) and 2009/544/EC

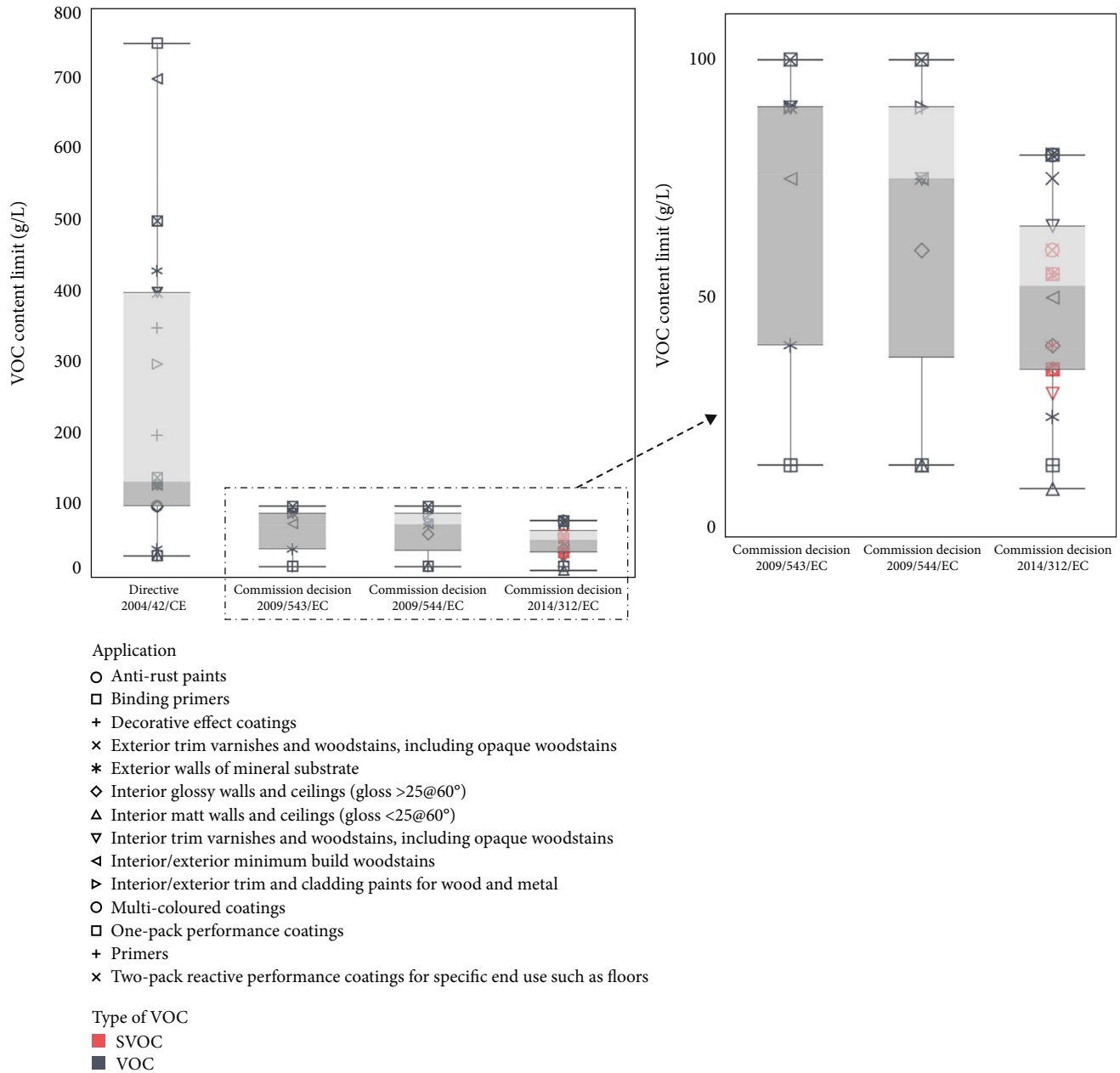


FIGURE 4: VOC content limits* under Directive 2004/42/CE, Commission Decisions 2009/543/EC, 2009/544/EC, and 2014/312/EU. (*Note: Commission Decision 2009/543/EC focuses on exterior coating while Commission Decision 2009/544/EC is for interior coating. Directive 2004/42/CE has the same VOC control on both interior or exterior coating. Detailed requirements refer to the respective standards.)

(median = 75, IQR = 52.5) reveals no substantial disparity, the latter's inclusion of three additional paint categories results in a marginal elevation in median VOC levels. Noteworthy is the introduction by Commission Decision 2014/312/EU of first-time controls for SVOCs, with limits positioned below the first quartile in the dataset. SVOC medians, at least 60% lower than VOC content limits and means exhibiting a 20% decrease relative to VOC benchmarks, underscore a focused endeavor on curbing less volatile yet enduring pollutants. This regulatory landscape accentuates a dual emphasis on mitigating both volatile and persistent pollutants.

3.1.2.2. Consequences for Violation of Law. Directive 2004/42/CE mandates that member states establish penalties for infringement that should be effective, proportionate, and dissuasive. Given the variations in legal frameworks and linguistic nuances across member states, the enactment of laws in Ireland serves as an illustrative case for detailed examination. The transposition of the Directive into Irish legislation occurred through the implementation of the Limitation of Emissions of Volatile Organic Compounds due to the use of certain Paints, Varnishes, and Vehicle Refinishing Products Regulations 2007. This initial legislation was subsequently superseded by S.I. No. 564 of 2012—European

Union (Paints, Varnishes, Vehicle Refinishing Products, and Activities) Regulations 2012, which underwent amendments via S.I. No. 398/2014 and S.I. No. 356/2024.

In terms of penalties for noncompliance with the law, the original legislation prescribed penalties including summary conviction leading to a fine not exceeding a Class A fine (as per the Fines Act 2010, i.e., a fine not surpassing €5000) or imprisonment for a maximum duration of 6 months or both. Furthermore, individuals found guilty upon conviction on indictment were subject to fines not surpassing €100,000 or imprisonment for a period not exceeding 1 year or both. However, the 2024 amendment introduced a new mechanism incorporating fixed payment notices, with fines set at €1000 for violations of major provisions and €500 for breaches of other stipulations. These notices are issued by authorized officers based on reasonable grounds indicating the commission of an offense.

3.1.3. United States

3.1.3.1. Evolution of the Statutory Controls. The United States was the pioneer in addressing photochemical smog, which gained prominence in Los Angeles in 1943. This concern spurred a series of national initiatives, including the enactment of the Clean Air Act (CAA) in 1963, the establishment of the California Air Resources Board (CARB) in 1967, and the formation of the South Coast Air Quality Management District (SCAQMD) in 1976 through the consolidation of four local agencies in the Greater Los Angeles region [89]. Thus, the United States has developed a long-standing framework for VOC emission control, particularly in products such as architectural paints [90].

In 1970, Environmental Protection Agency (EPA) was established to implement various mandates of the CAA, which has undergone multiple amendments over the years. Notably, the 1990 amendment (Section 183(e)) directed the EPA to study VOC emissions from consumer and commercial products and to regulate those products that contribute to at least 80% of VOC emissions in areas exceeding National Ambient Air Quality Standards (NAAQS) for O₃ [91]. Following the study report submission to the US Congress in 1995, the EPA issued 40 CFR Part 59—National Volatile Organic Compound Emission Standards for Consumer and Commercial Products—thereby regulating a broad spectrum of products, including architectural coatings (Table S14) and consumer products such as air fresheners, hairsprays, insecticides, and cleaners (Table S15).

Prior to the establishment of this federal standard, CARB served as an oversight agency, providing assistance to air districts by developing Suggested Control Measures (SCMs) for architectural coatings. Since the introduction of the first SCM for architectural coatings in 1977, the SCM has been updated in 1985, 1989, 2000, 2007, 2019, and 2020 [92]. In terms of VOC content control for architectural paints, the SCAQMD implements the most stringent regulations (Rule 1113) (Table S16) worldwide, even being more stringent than the 2019 SCM established by CARB [92, 93]. Other than architectural coatings, SCAQMD has specific VOC standard for adhesive and sealant (Rule 1168) and

developed a voluntary certification program called “Clean Air Choices” cleaner certification program for cleaning product with VOC content less than 10 g/L. Additionally, in 1990, CARB approved Consumer Products Regulations, which became legally effective in 1991, setting VOC limits for numerous categories of consumer products. The regulation has undergone amendments through 2022 (Table S17), expanding to cover over 130 consumer product categories under the principle of commercial and technological feasibility, while ensuring that product forms are not eliminated through market surveys [94]. Both SCAQMD and CARB (although the latter has phased out such requirements since 2011) mandated annual report submissions detailing the sales and usage amounts of architectural paints by manufacturers. Additionally, architectural coating manufacturers are subject to fees based on an Annual Quantity Fee and an Annual Emission Fee. Specifically, the Annual Quantity Fee is set at \$0.051 per gallon of paint, while the Annual Emission Fee is \$366.89 per ton of VOC emissions. These fees are designed to support SCAQMD personnel and operational costs and they may incentivize manufacturers to reduce overall emissions by promoting a greater volume of low-VOC coatings.

3.1.3.2. Consequences for Violation of Law. Under 40 CFR 59.201, regulated entities encompass manufacturers or importers of products, as well as any distributors identified on product labels, with primary compliance responsibility resting on the manufacturer or importer regarding VOC content and emission limits. Sections 40 CFR 59.404 and 40 CFR 59.403 delineate two compliance pathways for entities selling or distributing architectural coatings that exceed the established VOC limits: the “tonnage exemption” and the “exceedance fee.” The tonnage exemption permits manufacturers or importers to sell or distribute limited quantities of noncompliant architectural coatings, provided that the total mass of VOCs does not exceed 10 tonnes, calculated based on the volume of coatings manufactured or imported. Conversely, the exceedance fee represents an economic incentive mechanism, allowing manufacturers and importers to opt for compliance by paying a fee of \$0.0028 per gram of excess VOC in lieu of adhering to the VOC content limits.

Failure to comply with VOC content limits may constitute a violation of 42 U.S.C. § 7413(c)(2)(A), which stipulates that any person who knowingly makes false material statements, representations, or certifications; omits material information; or alters, conceals, or fails to file or maintain required documents under the CAA may be subject to severe penalties. Such violations can result in penalties of up to 2 years of imprisonment or fines, dependent on the nature of the misdemeanors or violations involved [19]. Rather than litigation, EPA often uses settlement agreement involving monetary penalties to handle violating cases as a strategy to foster compliance with VOC content limits and labeling requirements [95].

Section 42402 of the California Health and Safety Code (HSC) establishes strict liability penalties not exceeding

\$10,000 per day, with adjustments based on the California Consumer Price Index [96, 97]. However, if a civil penalty exceeding \$5000 per day is sought, the accused may avoid liability under this provision by asserting, as an affirmative defense, that the violation resulted from conduct that was neither intentional nor negligent. According to CARB's enforcement policy, the agency prioritizes discussions aimed at persuading authorities that a violation either did not occur or was incorrectly assessed. These negotiations typically involve mutual settlement and case resolution, including potential penalties [98]. The specific penalty is determined based on the severity of the violation, considering all relevant circumstances, which include eight statutory factors, as well as general considerations such as deterrence, investigation costs, litigation risks, and voluntary disclosure. The eight statutory factors are as follows:

1. The extent of harm to public health, safety, and welfare caused by the violation
2. The nature and persistence of the violation, including the magnitude of the excess emissions
3. The compliance history of the defendant, including the frequency of past violations
4. The preventative efforts taken by the defendant, including the record of maintenance and any program to ensure compliance
5. The innovative nature and the magnitude of the effort required to comply and the accuracy, reproducibility, and repeatability of the available test methods
6. The efforts of the defendant to attain, or provide for, compliance prior to violation
7. The cooperation of the defendant during the course of the investigation and any action taken by the defendant, including the nature, extent, and time of response of any action taken to mitigate the violation
8. The financial burden to the defendant

In 2024, civil penalties imposed on various regulated entities ranged from \$30,000 to \$375,000, determined on a case-by-case basis [99]. The total amount collected through civil penalties from noncompliant VOC-containing product amounted to \$444,000, which was allocated for Air Pollution Control Fund for the purpose of carrying out CARB's duties and functions to ensure the integrity of its air pollution control programs. SCAQMD's enforcement authority for civil penalties follow California HSC.

3.2. Comparisons of Regulatory Framework. The focus of regulatory approaches across the studied regions are summarized in Table 2, showing that Mainland China, the EU, and the United States have relevant regulatory provision for VOC control in products while many differences exist; however, significant differences exist among these frameworks.

3.2.1. Regulated Entity. The regulated entity varies across the study regions. In the United States, the statutory responsibility is primarily placed on manufacturers and importers, extending to distributors if their name appears on the product label. This highlights a clear chain of accountability within the regulatory structure. Conversely, the EU's Directive 2004/42/EC employs the term "placing on the market," which encompasses making products available to third parties, regardless of whether there is a financial transaction involved. Furthermore, importation into the community customs territory is explicitly deemed to constitute "placing on the market" for the purposes of this directive. This implies that any entity significantly involved in the importation of products is subject to the regulatory requirements.

Taking Ireland as a specific example within the EU, Section 9(1) of S.I. No. 564 of 2012 explicitly prohibits any person or entity from selling or placing noncompliant paints and varnishes on the market. The use of the term "placing" in this context further underscores a proactive regulatory stance that seeks to prevent noncompliant products from reaching consumers.

In contrast, Mainland China's regulatory framework addresses the control of a wide range of activities of manufacturing, importing, and selling VOC noncompliant products and using them (only for industrial enterprise), deeming such actions illegal. This broad scope potentially encompasses the entire supply chain, implicating manufacturers, importers, distributors, and even specific end-users that utilize VOC noncompliant paints. This multientity control approach contrasts with the limited-entity controls seen in the United States and EU, where regulatory focus tends to emphasize the responsibilities of manufacturers and importers.

3.2.2. Control Focus. The regulatory landscape for VOC content in products reveals significant regional disparities, although architectural paints are a commonly regulated category across Mainland China, the EU, and the United States. In the United States, VOC limits have been established for 63 types of architectural paints, with specific regulatory frameworks such as the CARB Standard governing 51 types and SCAQMD addressing approximately 59 types. In contrast, the EU regulates only 12 types of architectural paints, while Mainland China has set defined limits for 26 specific categories, including both WB and SB coatings.

A notable aspect of the US regulatory framework is its meticulous and comprehensive definitions for various types of coatings. For example, fire retardant or resistive coatings are categorized into clear and opaque types, with respective VOC limits of 850 and 450 g/L. These levels of specificity stand in sharp contrast to the Mainland China standards (GBT 18395-7-2020 and DB11/1983-2022), which primarily classify coatings as either SB or WB without further delineation.

Moreover, the SCAQMD standard illustrates the complexity of US regulations, wherein primers are classified into multiple subcategories, such as bituminous roof primers, pretreatment wash primers, and specialty primers. In comparison, the EU's regulatory framework adopts a more streamlined approach, distinguishing only between primers

TABLE 2: VOC controls in Mainland China, the EU, and the United States.

		Mainland China	EU	United States
Relevant hard/soft law		Atmospheric Pollution Prevention and Control Law, Product Quality Law	Directive 2004/42/CE, Commission Decisions 2009/543/EC, 2009/544/EC, 2014/312/EU, and 2017/1217	Federal level: 40 CFR 59.201, State level: (California) HSC § 42402
Regulated entity under hard law	Manufacturer	✓	—	✓
	Importer	✓	✓	✓
	Distributor	✓	c	✓ ^a
	Retailer	✓	c	—
	End-user	✓	—	—
		(Industrial enterprises)		
Coverage of selected products	Architectural coating	✓	✓	✓
	Adhesive/sealant	✓	—	✓
	Air freshener	—	—	✓
	Cleaning product	✓	Ecolabel	✓
	Hairspray	Ecolabel	—	✓
	Insecticides	Ecolabel	—	✓
Control parameter	Notification/approval prior importation	—	—	✓
	VOC content	✓	✓	✓
	Product label	✓	✓	✓
	Recordkeeping	✓	—	✓
	Periodic report	—	—	Only for alternative compliance ^b
Economic instrument		✓ (VOC Tax)	—	✓ (SCAQMD only, annual quantity fee and annual emission fee)
Penalty		Confiscation of goods and fines ranging from one to three times the product's value/¥20,000–200,000, with potential operational suspension for repeated offenses	Max. €1000	\$0.0028/g of excess VOC, ≤ \$10,000 per day (California)
Exemption		—	Buildings with particular historical and cultural value	Annual tonnage exemption ≤ 10 tons of VOC; small volume/container exemption ^d ; fragrances up to a certain concentration

Note: “✓” means the hard control has been in place; “—” means there is no such control; detailed requirements refer to the respective laws.

^aApplicable only when no manufacturer or importer is identified on the product label.

^bFor using the adjusted VOC content of recycled, paying an annual exceedance fee and claiming an annual tonnage exemption.

^cSubject to the exact statute, for example, in Ireland, selling or placing noncompliant paints and varnishes on the market is illegal.

^dThis exemption provision applies to certain architectural coatings in containers having capacities of 1 L or less.

and binding primers. Conversely, Mainland China's standards tend to focus on its composition and broad applications—such as coatings for floors or walls—rather than emphasizing the specific application or layers of the coatings themselves.

This variability in classification criteria extends to VOC regulations concerning adhesives. The United States employs an application-based classification system, while Mainland China relies on the field of application and composition of adhesives to determine VOC content limit. This fundamental divergence reflects differing regulatory priorities in addressing VOC emissions and ensuring consumer safety.

In the domain of consumer products, the United States has established a comprehensive regulatory framework that encompasses a wide array of items, addressing VOC emissions across diverse categories. In contrast, Mainland China's regulatory focus has been primarily concentrated on cleaning products. To complement these regulatory efforts, both Mainland China and the EU have embraced voluntary compliance mechanisms, such as ecolabeling; specifically, Mainland China utilizes ecolabels to regulate VOC content in insecticides, while the EU employs ecolabeling for cleaning products.

Beyond VOC content, regulatory provisions in these three regions mandate compulsory labeling on products to

disclose essential information, including VOC content. Additionally, both Mainland China and the United States require adequate recordkeeping that encompasses product details and sales volumes. On the one hand, product labeling serves to better inform consumers about the contents and safety of the products they purchase. On the other hand, the disclosed information and accompanying records facilitate inspection and enforcement, thereby enhancing regulatory compliance and consumer protection.

3.2.3. Punishment and Exemption. Penalties serve as a common and principal method of enforcement across the regulatory frameworks of the three regions, aligning with the polluter-pays principle rather than favoring imprisonment. However, the specific application and setting of penalties vary significantly among these regions.

In Mainland China, penalties for the importation and sale of noncompliant VOC-containing products are determined based on the value of the goods. For industrial enterprises utilizing noncompliant VOC paints, penalties are capped within a range of ¥20,000–¥200,000, with the potential for operational suspension in cases of repeated offenses. Notably, some provinces/municipality (e.g., Shanghai, Guangdong, and Beijing) have established Measures for Regulating the Discretionary Powers in Imposing Administrative Penalties, which allow for adjustments to penalties based on factors such as the severity of the illegal act (including environmental damage), the duration and frequency of violations, the presence of complaints, and the violator's correcting action [100–102]. This practice bears resemblance to the CARB enforcement policy, which formulates specific penalties based on the severity of the violation, considering all relevant circumstances.

At the federal level in the United States, an emphasis is placed on alternative compliance. A fixed unit rate for exceedance fees is established at \$0.0028 per gram of excess VOC, with no ceiling on total penalty. In California, penalties for illegal acts can be assessed on a daily basis, capped at \$10,000 per day. In the EU, Ireland employs a system of “fixed payment notices” with a maximum penalty of €1000. While this amount may appear relatively low, it serves as a straightforward and easily implementable enforcement mechanism, reducing the need for complex litigation and prolonged negotiations.

The US regulatory framework also incorporates a flexible approach to noncompliance, with annual tonnage exemptions for VOC emissions set at ≤ 10 tons, as well as allowances for coatings sold in containers of ≤ 1 L and fragrances within certain concentration thresholds. This flexibility is aimed at striking a balance between regulatory compliance and practical business operations, facilitating adherence to environmental standards while accommodating the realities of production and distribution.

3.2.4. Key Evolution Timeline. As illustrated in Figure 5, the development of VOC control regulations varies significantly among Mainland China, the EU, and the United States. In the United States, national VOC regulations have been in place since 1997, with the first Rule 1113 for architectural

coatings established in 1978 and the CARB SCM introduced in 1977. Between 2004 and 2014, similarly, the EU made efforts to curb VOC emissions from architectural paints through combining regulatory mandates with voluntary compliance measures such as the EU ecolabel.

In Mainland China, while ecolabel standards for aerosol insecticides existed, substantial regulatory efforts began in 2015 with the introduction of a consumption tax on coating products and specific VOC controls under the APPCL. This was followed by national limits on various products set in 2020. Meanwhile, the United States has continuously tightened and expanded VOC content standards for architectural paints and consumer products.

3.3. Control Limit Values

3.3.1. Architectural Coatings. Figure 6 presents the VOC content limits for selected architectural coatings/paints that are under stringent controls. It reveals that the EU and the United States maintain relatively stricter VOC limits, while Mainland China's thresholds are higher. The depth and coverage of VOC regulations may correlate with economic development trajectories. Moving forward, more comprehensive strategies and plans to enhance VOC control measures from Mainland China is anticipated.

3.3.2. Consumer Products and Cleaning Products. Table 3 summarizes the regulatory limits for VOC content in hair products in Mainland China and the United States, while Figures 7, 8, and 9 present comparative data for insecticides (including insect repellents) and air fresheners in these two regions. In contrast, our findings suggest that VOC control limits for consumer products remain limited under EU regulations.

As Table 3 shows, the California Consumer Product Regulations (CCPR) impose stringent and comprehensive VOC controls on various hair products, including hair finishing spray and hairspray. For instance, the VOC limit for finishing sprays under CCPR is set at 50% by weight (wt.%), representing a 37.5% reduction compared to the 80% limit specified in the US national standard.

Similarly, in the case of insecticides (see Figure 7), the CCPR stands out as the most stringent regulation when compared to the federal standard and the Mainland China environmental label. It encompasses aerosol insect repellents and enhances the VOC limit for aerosol insecticides targeting crawling bugs, reducing it from 15 to 8 wt.% by 2030, representing a substantial 45% decrease. The current value is also at 37.5% of the federal standard and the Mainland China limit.

For flying bug insecticides, the Mainland China standard and CCPR have relaxed regulations compared to crawling bug insecticides (112.5% and 133.3%, respectively), while the US national standard has tightened its restrictions to 87.5% of crawling bug insecticides. Regarding air fresheners (see Figure 8), apart from liquid/pump sprays and solid/semisolid types, the CCPR maintains stricter controls than the US national standard. The double-phase aerosol type exhibits a reduction of 33.3% compared to the US standard,

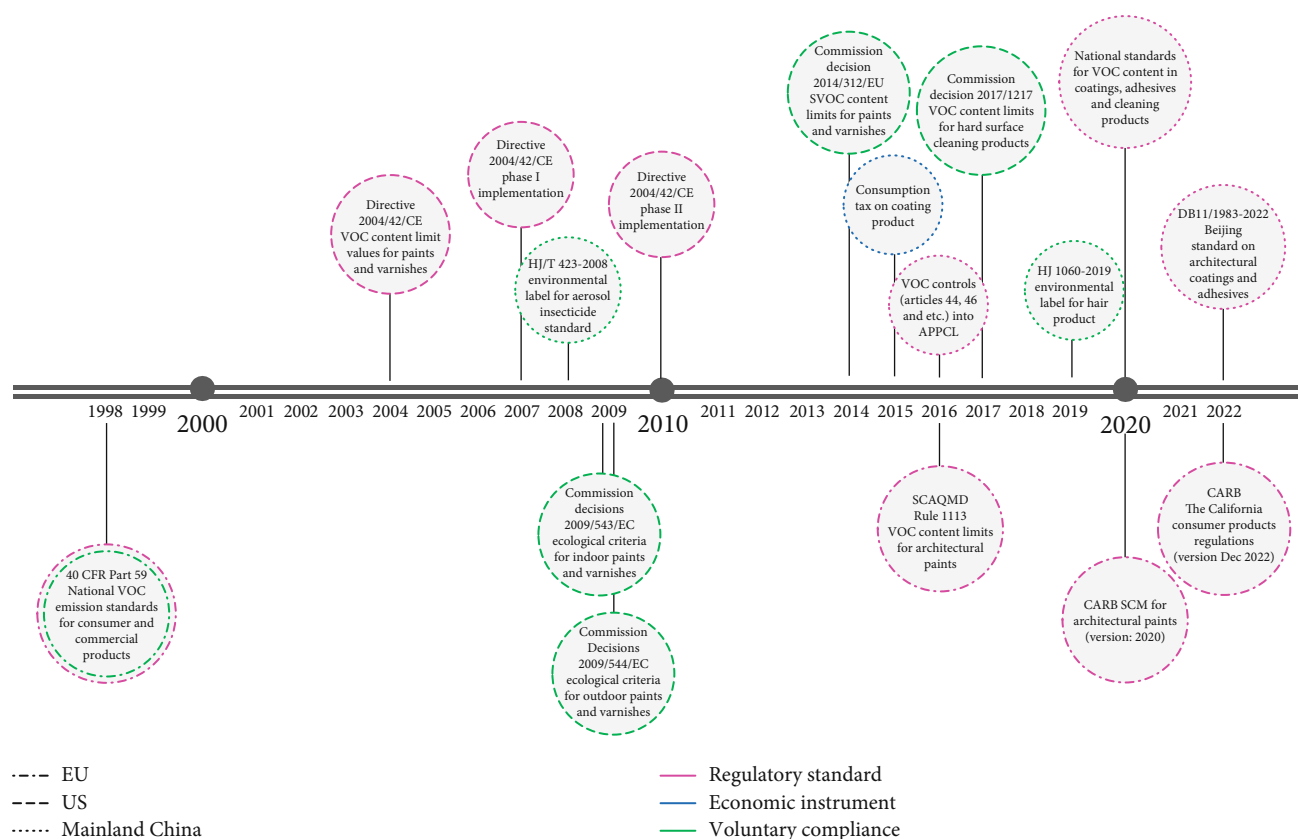


FIGURE 5: Policy evolution timeline of Mainland China, the EU, and the United States.

and the single-phase aerosol type shows a reduction of 57%. Noteworthy, the Mainland China standard is limited to hairspray and insecticides, focusing on ecolabeling practices.

Mainland China, the EU, and the United States have all established VOC content limits for cleaning products. However, a notable distinction arises in the units used for these limits: Mainland China and the EU employ “gram/liter” measurements, while the United States utilizes “wt.%.” This discrepancy poses challenges in directly comparing regulatory standards across these regions. The VOC content limits for cleaning products stipulated in GB 38508-2020 and EU 2017/1217 are illustrated in Tables 4 and 5, while the comparison between the CCPR and the US national standards is shown in Figure 9.

Tables 4 and 5 illustrate that Mainland China and the EU have adopted different categorizations despite utilizing the same measurement units. Mainland China has implemented a four-tier control system for VOC content in cleaning product, categorizing them into water-based, semiwater-based, organic solvent, and low-VOC cleaning agents. In contrast, the EU ecolabel system specifies VOC limit on specific types of cleaners, enhancing product transparency and consumer protection. From a numerical perspective, only the limits for water-based and low-VOC products in the Mainland China standard are directly comparable to the EU standards. The allowances for semiwater-based and organic solvent products, which can contain up to 300 and

even 900 g/L, are remarkably lenient and warrant attention for their potential environmental impact and consumer health implications.

The comparison of VOC controls between the CCPR and the US national standard is depicted in Figure 9. Similar to the EU ecolabel, both standards enforce VOC regulations on specific categories of cleaners, including aerosol and non-aerosol types. The CCPR stands out for its stringent and comprehensive approach, extending its control to areas such as toilet/urinal care and disinfectants/sanitizers, which are not covered by the US national standards. From a quantitative standpoint, the VOC limits set by the CCPR are generally 16%–20% lower than those of the US national standards, with the exception of bathroom and tile cleaners. Notably, in the nonaerosol category, the disparity is even more pronounced, with VOC limits in the CCPR being 62.5%–90% lower compared to the US national standards. This substantial difference underscores the rigorous and environmentally conscious approach taken by the CCPR in regulating VOC emissions in cleaning products, particularly in nonaerosol variants.

In the future, it is imperative to address the discrepancies in categorizations and units of measurement (e.g., wt.% vs. gram/liter) to establish consistency. This harmonization will not only lay the foundation for direct comparisons of regulatory frameworks but also streamline compliance across regions and enable the effective implementation of cross-border environmental policies.

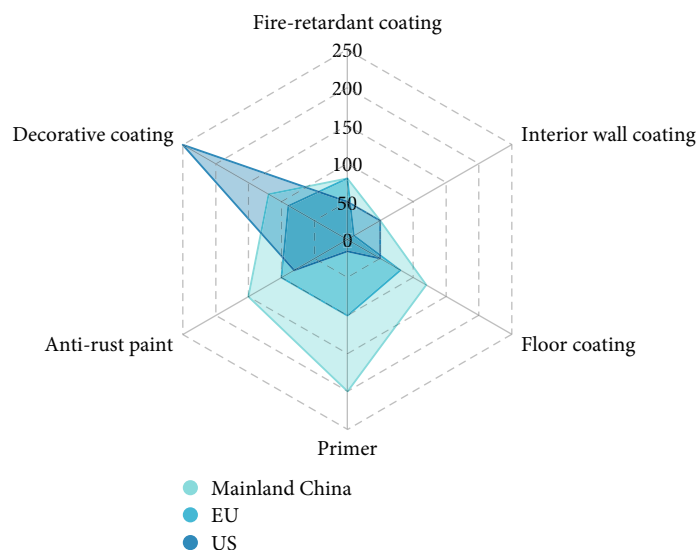


FIGURE 6: VOC content limits for selected coating/paints in Mainland China, EU, and United States. Note: (1) The SCM control limit under CARB is applied for all US analyses due to its extensive coverage and stringent criteria, while antirust/corrosion coatings only specified in SCAQMD Rule 1113 is adopted for the analysis. (2) For Mainland China, the WB fire-resistant coating limit from GB 38597-2020 is adopted, consistent with GB 12441-2018, which includes flame control testing. In the EU, the control limit for one-pack performance coatings is utilized, as it encompasses flame retardant applications. The flat coating control limit per CARB SCM is applied for US fire-retardant coatings. (3) The control limit for WB floor coatings under GB 38468-2019 is employed in Mainland China due to its stringent regulation. (4) The WB primer limit from GB 38468-2019 is applied. Noteworthy, the control limit of SCM is same as Rule 1113 by SCAQMD. (5) The flat coating control limit under CARB is applied for US analyses based on general characteristics, consistent with SCAQMD Rule 1113. In the EU, a lower gloss limit (≤ 25 at 60°) for interior matte walls and ceilings is adopted due to its rigor. (6) The control limit of WB primer under GB 38468-2019 is applied for Mainland China analysis due to stringent control. Noteworthy, the control limit of SCM is same as Rule 1113 by SCAQMD. (7) For Mainland China, the WB decorative coating limit specified under GB 18582-2020 is applied. In the United States, multicolor coatings are analyzed, as their definition includes multiple colors serving a similar decorative purpose. Notably, the SCM control limit is consistent with SCAQMD Rule 1113.

TABLE 3: VOC content limits of hair products between Mainland China and the United States.

Product type	Subcategory	Environmental label (HJ/T 423-2008 and HJ 1060-2019) (Tables S18 and S19)	California Consumer Product Regulations (2022)	National Volatile Organic Compound Emission Standards for Consumer Products
Finishing spray	All forms	10 wt. %	50 wt. %	80 wt. %
	Aerosol/pump spray	Not specified	6 wt. %	Not specified
Styling product	Nonaerosol	Not specified	2 wt. %	6 wt. % (styling gels) 16 wt. % (hair mousses)

Note: Detailed requirements refer to the respective standards.

4. Discussion

4.1. Enforcement Challenge. The implementation of VOC controls in products presents a multifaceted array of challenges that are critical for assessing the efficacy of current regulatory frameworks. These challenges can be systematically analyzed through the lens of regulatory effectiveness, as well as pollution control and remediation.

Figure 10 illustrates the typical supply chain trajectory of VOC-containing across two separate economic and jurisdictional regions (e.g., from Region A to Region B). This trajectory involves multiple stakeholders including chemical suppliers, manufacturers, logistics providers, distributors, retailers, and online shopping platforms. For instance, after

an end-user places a product's purchase order through either an online shopping platform or a retailer followed by a distributor, the order would reach the product manufacturer, who then procures chemicals from suppliers for production. The finished product is then delivered to distributors via logistics services, followed by distribution to downstream segments (e.g., from distributor to retailer to end-user). When the stock level at the distributor is forecasted to be insufficient to meet downstream demand, this cycle is repeated. This intricate journey typically comprises at least six distinct parties before the product eventually reaches the end-user.

Regulatory frameworks in the EU and United States, as outlined in Table 2, predominantly target downstream entities (e.g., importers and distributors). Conversely, Mainland

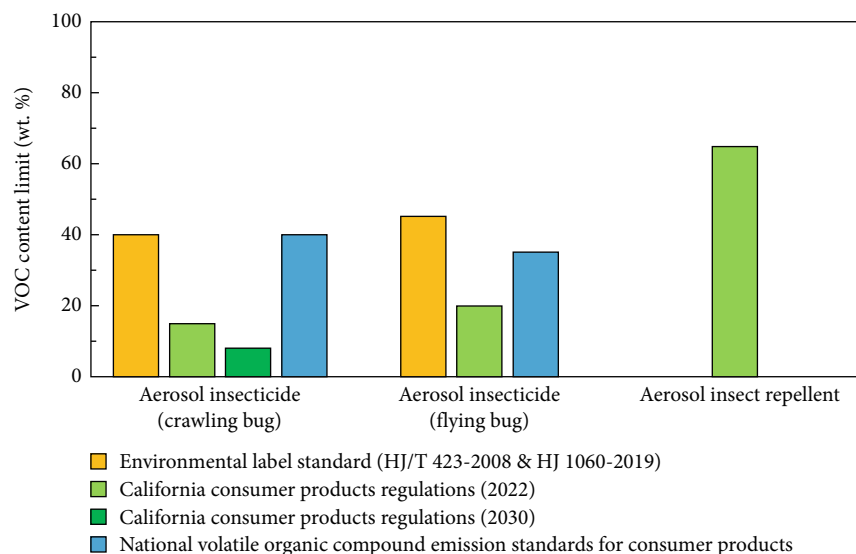


FIGURE 7: VOC content limits for insecticides and insect repellent in Mainland China and United States.

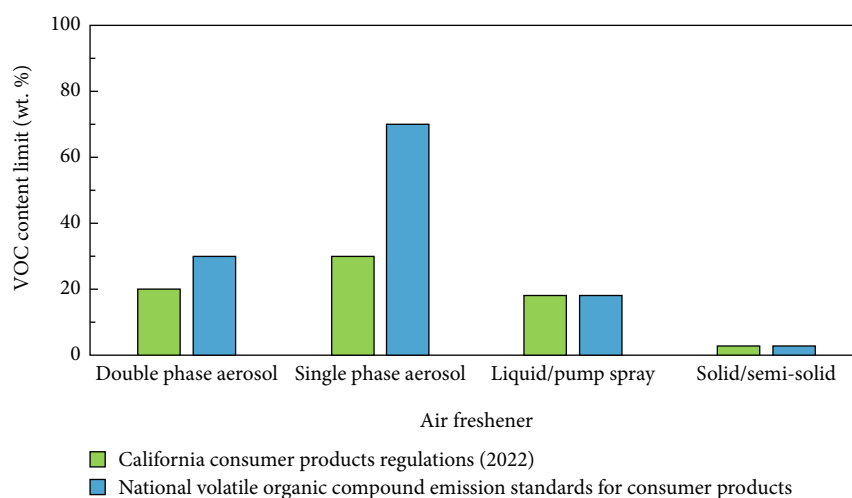


FIGURE 8: VOC content limits for selected air fresheners in the United States.

China's regulatory framework extends its purview to include much of the downstream segment, particularly sellers.

However, the emergence of online shopping platforms has blurred the traditional distinctions of importers. Both end-users and retailers can transcend their roles to importer, especially when procuring products for any purpose. Online platforms, when stockpiling products for resale, can also function as importers. This phenomenon complicates enforcement efforts, necessitating heightened vigilance and increased resources to ensure compliance.

In terms of regulatory effectiveness, preidentification efforts depend on a sufficiently robust sampling frequency to detect any widespread noncompliance. Thus, a representative sample size is essential for justifying reliable spot about noncompliance in a large volume of product to ensure the accurate and timely identification of true positives. Particularly when noncompliant products are identified, it is essential to ascertain whether the noncompliance indicates

a systemic design flaw or merely reflects a product variation. The representativeness of sampling results is thus crucial, as it directly influences regulatory decisions and actions. Compounding these challenges is the product categorization, which complicates the applicable VOC content limits; different product categories may have varying VOC content limits, creating legal ambiguities that impede consistent enforcement efforts. The sheer volume of goods traded globally further complicates the regulatory landscape, imposing significant obstacles on authorities tasked with monitoring compliance across a diverse array of products.

With respect to pollution control and remediation, the discovery of noncompliant VOC products is uncertain. During such a discovery, environmental damage may commence, particularly for products that remain in use by consumers or regulated entities. The current regulatory frameworks, such as those of the United States and the EU, typically impose penalties intended to deter noncompliance

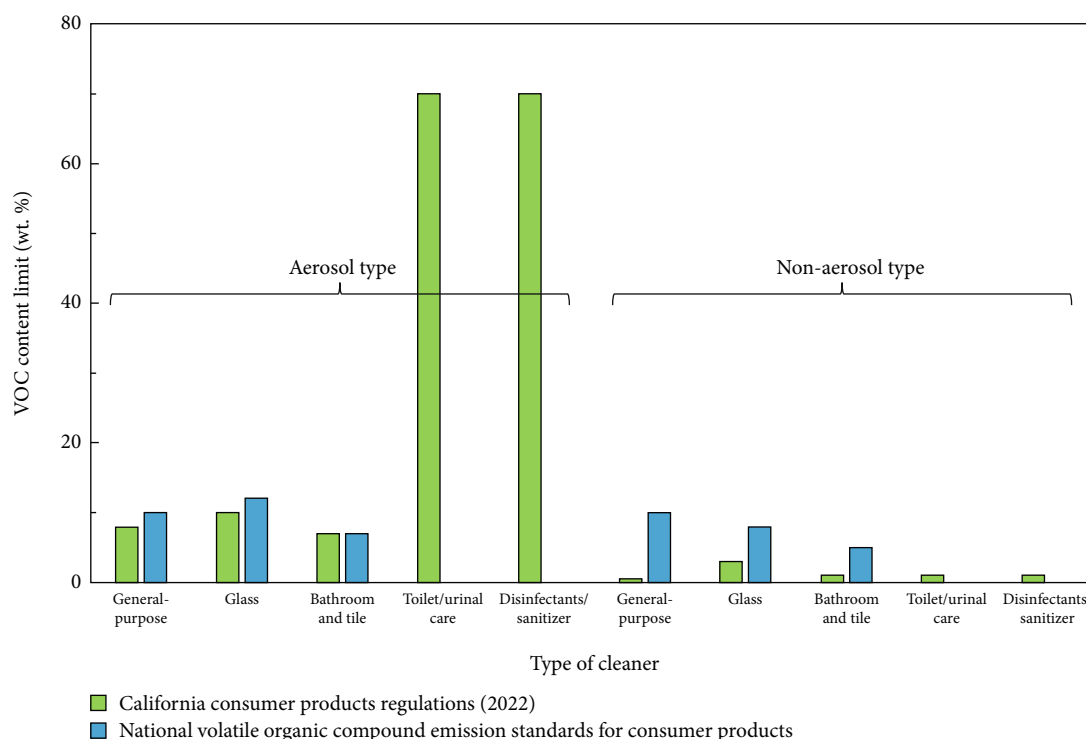


FIGURE 9: VOC content limits for cleaning products in the United States.

rather than enforcing confiscation of noncompliant goods. This implies that ongoing pollution resulting from the continued use of the noncompliant products may not be adequately addressed. While financial penalties for VOC exceedance may deter certain violations, they do not sufficiently incentivize manufacturers to significantly reduce VOC content during the production and design phases. Even when enforcement actions are initiated, delays between detection and remediation can exacerbate environmental harm, raising profound questions regarding the overall efficacy of the existing regulatory frameworks.

Compared to traditional regulatory frameworks, ecolabels offer a market-driven alternative to traditional regulatory frameworks, effectively influencing consumer choices and promoting a shift from downstream users to upstream manufacturers. Notably, 60% of consumers report selecting products for their lower environmental impact, with 38% frequently or occasionally purchase products bearing the EU ecolabel. Among the over 100,000 products awarded the label, 36% are paints and coatings, and approximately 8% are hard-surface cleaning products [103]. Integrating ecolabeling initiatives into existing regulatory frameworks could further enhance compliance and encourage manufacturers to prioritize the development of sustainable products, thereby contributing to more effective pollution control and remediation efforts.

4.2. Polluter-Pay Regulatory Frameworks. Current regulatory frameworks in Mainland China, the EU, and the United States provide economic incentives designed to encourage the adoption of low-VOC products; however, the polluter-

pays principle, while theoretically sound, presents several significant challenges within these frameworks.

One major concern is the potential for regulatory capture, where industries are often consulted before regulations are enacted, resulting in the plausible setting of compromised standards that prioritize economic interests over environmental protection. For instance, as detailed in Table 2, the VOC limits established in Mainland China are relatively permissive, implying the permission of the continued production, importation, sale, and use of SB architectural coatings—practices largely absent from regulations in the EU and the United States. However, Mainland China imposes a consumption tax on coating products with VOC content exceeding 420 g/L to increase the costs associated with SB products and reduce their profit margins to diminish their market competitiveness, diminishing the incentive to transition to low-VOC alternatives as well.

Moreover, the reliance on fees for exceedance can foster a “license to pollute” mentality, wherein manufacturers perceive compliance costs as an acceptable business expense rather than a fundamental obligation to mitigate environmental harm. In the United States, the alternative compliance provision permits regulated entities to pay fees for exceeding VOC limits, effectively monetizing compliance and potentially weakening the imperative for stringent VOC content control. This creates an environment where manufacturers may prioritize products with specific VOC content—often linked to performance metrics or consumer preferences—over adherence to VOC regulations, particularly when such products yield higher profit margins. Notably, Mainland China imposes a consumption tax on coating

TABLE 4: Mainland China's VOC content limits for cleaning products (GB 38508-2020)^a.

Product type (by composition)	Limit
Water-based cleaning agents	≤ 50 g/L
Semiwater-based cleaning agents	≤ 300 g/L
Organic solvent cleaning agents	≤ 900 g/L
Low-VOC cleaning agents	≤ 100 g/L

^aThe definitions of different types of cleaning agent are not specified in the standard. Typically, water-based cleaning agents have a high mass portion of water (>60%) with less than 10% of organic solvent, semiwater-based cleaning agents may have over 50% of organic solvent, and organic solvent cleaning agents may have merely 4%–6% of water [74].

TABLE 5: EU's VOC content limits for cleaning products (EU 2017/1217).

Product type (by application)	Limit
All-purpose cleaners	≤ 30 g/L
Kitchen cleaners	≤ 60 g/L
Window cleaners ^a	≤ 100 g/L
Sanitary cleaners ^b	≤ 60 g/L

^aWindow cleaners refer to detergent intended for cleaning of windows, glass, and other highly polished surfaces.

^bSanitary cleaner refers to detergent products applied in laundry rooms, toilets, bathrooms, and shower.

products with VOC content exceeding 420 g/L, which may increase the costs associated with SB products and reduce their profit margins, thereby incentivizing manufacturers and importers to pursue low-VOC solutions. In 2016, following the implementation of the consumption tax in Mainland China, VOC emissions from architectural coatings increased by 8.9%, a decline from 11.2% in 2015 and 12.3% in 2014 [104], while the overall growth rate of architectural coatings rose from 4.2% in 2015 to 7.2% in 2016 [105], suggesting a potential influence of the consumption tax on VOC emissions. Notably, in 2016, water-based coatings comprised 4.89 million tonnes, accounting for 84% of total coating usage in Mainland China, whereas SB coatings constituted only 11%.

However, the effectiveness of these mechanisms can be undermined when the financial burden of exceedance fees is successfully passed on to consumers. This dynamic is particularly concerning when end-users are willing to pay a premium for high-VOC products, often under the misconception that such products offer superior performance without regard to health implications. Such scenarios diminish manufacturers' motivation to reformulate their products in compliance with regulatory standards and inhibit momentum toward environmental compliance among importers and distributors in product trade.

4.3. LRTAP. The effectiveness of VOC control measures in one region can be significantly undermined by pollution originating from elsewhere, as the characteristics of air pollution are influenced by the use of products that may not be locally manufactured or sold. Insufficiently robust regula-

tory and enforcement frameworks can lead to the phenomenon of LRTAP, where pollutants traverse national borders, complicating local efforts to manage air quality effectively.

The Convention on LRTAP serves as the primary international framework for cooperation aimed at limiting, gradually reducing, and preventing air pollution [106]. This convention encompasses 51 parties including EU member states and the United States. Since its signing in 1979, the LRTAP Convention has been supplemented by eight specific protocols, including the Gothenburg Protocol.

The Gothenburg Protocol, adopted in 1999, addresses the interconnected issues of acidification, eutrophication, and ground-level O₃ under the auspices of the LRTAP Convention. A primary objective of the protocol is to establish emission regulations on a regional basis within Europe, protecting ecosystems from transboundary pollution through the implementation of emission reduction ceilings. These ceilings, which were to be achieved by 2010, pertain to four key pollutants: sulfur dioxide (SO₂), NO_x, ammonia (NH₃), and VOCs. The protocol was revised in 2012 to set new emission reduction ceilings for different parties, with the EU committing to reduce VOC emissions by 28% by 2020 and beyond [107]. However, despite the framework's implementation and subsequent assessments indicating some progress in emission reductions, annual average O₃ concentrations have remained constant and even showed an increasing trend in urban areas [108]. In 2014, regional collaboration within Mainland China, which involved Beijing, Tianjin, eight cities in Hebei, and six cities in Shandong, demonstrated the effect of strong regional efforts for reductions in NO₂ (23%), 10 VOC species (40%), SOA (37%), and O₃ (9%) during the Asia-Pacific Economic Cooperation (APEC) summit, contributing to the phenomenon known as "APEC Blue" [109–111]. International frameworks such as APEC and the United Nations Environment Assembly (UNEA) play a crucial role in addressing air pollution. In 2024, the UNEA adopted a resolution promoting regional cooperation to improve global air quality, specifically targeting PM and O₃ and their precursors. This resolution recognizes the existing LRTAP framework and emphasizes collaborative measures, including data sharing and joint initiatives [112].

While international frameworks like the LRTAP Convention and the Gothenburg Protocol provide valuable mechanisms for addressing transboundary air pollution, current VOC control measures appear insufficient, particularly as O₃ levels show no signs of decline in urban settings [8, 10, 11]. Moreover, these frameworks do not comprehensively engage major emitting countries, thereby limiting their overall effectiveness. This situation underscores the necessity for ongoing international cooperation and a commitment to stricter emission standards. The complexities of LRTAP and global O₃ pollution necessitate a coordinated global response, which should include the active participation of all significant emitting parties. Enhanced collaboration and the development of more stringent, enforceable international regulations are imperative to effectively mitigate the impacts of transboundary air pollution and protect public health and environmental integrity across borders.

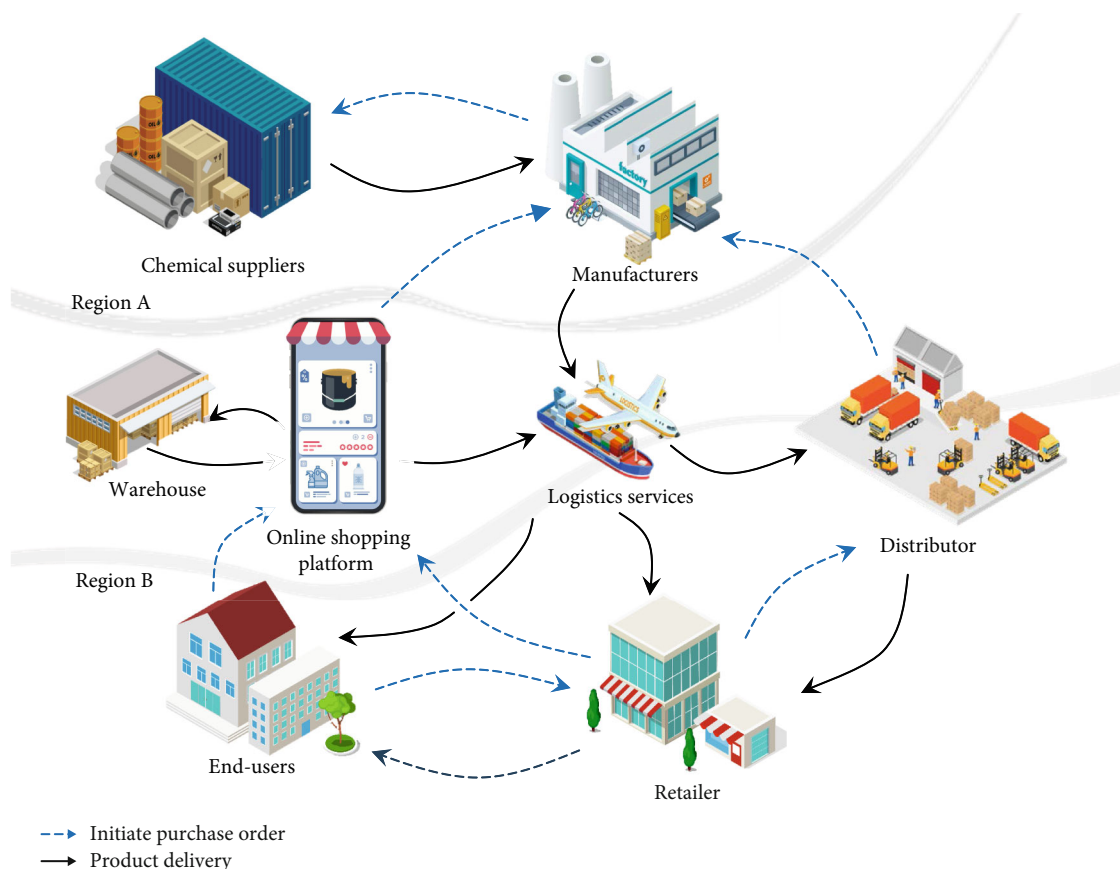


FIGURE 10: Typical chain routes for product purchase and delivery.

4.4. Future Directions. To effectively address the shortcomings in the existing regulatory frameworks, there is significant potential for enhancing VOC emission controls across various jurisdictions. Strengthening these frameworks is essential not only to impose more stringent restrictions on VOC emissions but also to incentivize the development and use of low-VOC products. One viable approach is the implementation of “blanket bans” on specific high-VOC products, particularly where viable alternatives are readily available in the market. The example of Shenzhen, China, which has successfully banned the sale and use of SB coatings, serves as a compelling precedent for more rigorous regulatory actions.

In addition to punitive measures designed to deter non-compliance, regulatory authorities should actively analyze market dynamics and provide financial support to manufacturers for upgrading production facilities and adopting cleaner technologies. Such initiatives would facilitate the reduction of VOC content in products and minimize emissions during use, thereby fostering a transition to more sustainable manufacturing practices. This dual-strategy approach—combining stringent regulatory measures with supportive financial mechanisms—aligns with the polluter-pays principle and promotes innovation and sustainability within the manufacturing sector.

Future research should focus on identifying effective methodologies for encouraging manufacturers to reformu-

late their products to lower VOC content. Investigating the barriers and incentives that influence product design and formulation can provide valuable insights for policymakers. Furthermore, empowering consumers to make informed choices regarding VOC content in products is critical. Research into consumer behavior and preferences can help develop educational initiatives that promote the adoption of environmentally friendly options, which will drive manufacturers to increase their efforts in developing low-VOC products.

Additionally, cross-border regulatory actions warrant greater attention, particularly given the transboundary nature of air pollution. Understanding the dynamics of how regulatory disparities impact air quality and public health can inform the development of more cohesive international standards. Collaborative research efforts among jurisdictions can facilitate the sharing of best practices and foster harmonization of VOC regulations.

5. Conclusions

The VOC regulation in products is a vital aspect of environmental law that necessitates a multifaceted approach to effectively mitigate their adverse effects on public health and the environment. The current frameworks, while providing a foundation for VOC control, reveal significant gaps that can undermine the efficacy of regulatory efforts. Key

challenges include the potential for regulatory capture, the monetization of compliance through alternative fee structures, and the leniency of permissible VOC limits that allow high-VOC products to persist in the market.

To enhance the effectiveness of VOC control measures, it is imperative to explore the establishment of stricter emission standards, implementation of comprehensive bans on specific high-VOC products, and provision of support for the transition to low-VOC alternatives through financial incentives and technological upgrades. Moreover, empowering consumers with information and choices will facilitate a market-driven demand for safer products. The transboundary nature of air pollution further underscores the need for international cooperation and harmonization of regulations to prevent cross-border pollution from undermining local efforts.

Future research should focus on identifying best practices, understanding market dynamics, and evaluating the effectiveness of proposed regulatory changes. Taking a cross-disciplinary lens from the economic and legal perspectives, similar to the recommendation of Lai et al. [113], further study is warranted to explore how to achieve an economic optimum with appropriate regulatory control. By adopting a robust, evidence-based approach that combines stringent regulations with supportive measures, policymakers can align economic incentives with environmental protection, ultimately fostering a cleaner and more sustainable manufacturing landscape.

In light of these considerations, it is clear that a proactive and integrative legal framework for VOC control is not only necessary but also urgent. Such a framework will not only protect public health and the environment but also ensure compliance with international obligations and promote innovation within the manufacturing sector. As we move forward, the commitment to improving regulatory structures and engaging in collaborative efforts will be essential for achieving meaningful progress in the fight against VOC emissions.

Data Availability Statement

Raw data is available on request from the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

C.K.L.: investigation, methodology, validation, writing original draft, visualization, project management. S.Y.T.L.: validation, writing (review and editing). J.H.K.L.: writing (review and editing).

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. (*Supporting Information*) Table S1: Harmful substances limits for interior floor coatings (GB/T 38468-2019). Table S2: Harmful substances limits for architectural wall coatings (GB/T 18582-2020). Table S3: Harmful substances limits for decorative coatings (GB/T 18582-2020). Table S4: VOC content limits for adhesive (GB 33372-2020). Table S5: VOC content limits for water-borne coating (GB/T 38597-2020). Table S6: VOC content limits for solvent-borne coating (GB/T 38597-2020). Table S7: VOC content limits for architectural coatings (DB11/1983-2022). Table S8: VOC content limits for architectural adhesives (DB11/1983-2022). Table S9: Maximum VOC content limits for paints and varnishes (Directive 2004/42/CE). Table S10: VOC limits for outdoor paints and varnishes (Commission Decisions 2009/543/EC). Table S11: VOC limits for indoor paints and varnishes (Commission Decisions 2009/544/EC). Table S12: VOC and SVOC content limits (Commission Decision 2014/312/EU). Table S13: VOC content limits for hard surface cleaning products (The Commission Decision 2017/1217). Table S14: VOC content limits for architectural coatings (40 CFR Part 59—National Volatile Organic Compound Emission Standards for Architectural Coatings). Table S15: VOC content limits for architectural coatings (40 CFR Part 59—National Volatile Organic Compound Emission Standards for Consumer Products). Table S16: VOC content limits for architectural coatings (Rule 1113). Table S17: VOC content limits for selected products. (THE CALIFORNIA CONSUMER PRODUCTS REGULATIONS). Table S18: Technical requirement for environmental labeling products—Aerosol insecticide (HJ/T 423-2008). Table S19: Technical requirement for environmental labeling products (HJ 1060-2019).

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