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Beyond the tailpipe: Evaluating the shift from Vehicular to Volatile Chemical Products (VCPs) Emission in Indian Megacities (2016 – 2026)

A Dissertation submitted in the partial
fulfilment of the requirement for the
Award of the Degree of

MASTER OF SCIENCE

In

Chemistry

Submitted by

Anshu Yadav

(24/MSCCHE/25)

Under the supervision of

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JUNE 2026

DELHI TECHNOLOGICAL UNIVERSITY

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CANDIDATE'S DECLARATION

I, Anshu Yadav(24/MSSCHE/25) student of MSc. (Chemistry) hereby declare that the project Dissertation titles "**Beyond the Tailpipe: Evaluating the shift from Vehicular to Volatile Chemical Products (VCPs) emission in Indian megacities (2016-2026)**" which is submitted by us to the Department of Applied Chemistry, Delhi Technological University, Delhi in the partial fulfilment of the requirement for the award of the degree of Master of Science, is original and not copied from any source without proper citation. This work has not previously formed the basis for the award of any Degree, Diploma, Associateship, Fellowship or other similar title or recognition.

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CERTIFICATE

I/We hereby certify that the project Dissertation titled **"Beyond the Tailpipe: Evaluating the shift from Vehicular to Volatile Chemical Product (VCP) emissions in Indian megacities (2016-2026)**" which is submitted by **Anshu Yadav(24/MSCCHE/25)** , Department of Applied Chemistry, Delhi Technological University, Delhi in partial fulfilment of the requirements for the award of the Master of Science, is a record of the project work carried out by the student under my supervision. To the best of my/our knowledge this work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere.

Place: Delhi

Date: June 2026

PROF. ANIL KUMAR
(Head of Department)

DR. ARCHANA RANI
(Supervisor)

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Anshu Yadav

(24/MSCCHE/25)

ABSTRACT

The rising concentration of air pollutants in the megacities of India has been attributed largely to pollution from vehicles. This has been greatly altered over the years from 2016 to 2026, mostly due to research on the sources of Volatile Organic Compounds (VOCs). This work has put emphasis on the fact that Vehicular emissions are not the biggest VOC source, and Volatile Chemical Products (VCPs) also contribute to it significantly especially in the major cities of India like Delhi.

11 VCPs are a range of consumer products such as paints and coatings, pesticides, personal care products, printing inks, adhesives, cleaning Products. Recent studies have stated that VCPs can emit high levels of VOCs to the air. In few developed cities it has been noticed that VCPs make up almost half of VOC emission from fossil fuel sources. India is a rapidly urbanizing country so
29 these emissions are increasingly significant for the air Quality management in India. Vehicles are one of the major anthropogenic sources of non- methane Volatile Organic Compounds (NMVOCs) accounting for approximately 31% of VOC emissions, but emissions from solvents and consumer products are growing and currently account for nearly 10% of VOC concentration in Delhi.

This work studies changes in Delhi's emission profiles after the implementation of certain policy
23 measures like transition of Delhi's public transport to Compressed Natural Gas (CNG), Bharat stage VI emission standards and the odd- even traffic scheme. All of these measures have reduced emissions from vehicles and focused attention on non- mobile sources. This is a great observation that was made during COVID- 19 lockdown. Despite 96% decrease in traffic emissions ozone levels were nearly same. This meant that VOCs from other sources were still
27 supplying drivers to chemical reactions in the atmosphere that lead to the formation of ozone.

The evidence generally indicates that non – traffic sources are increasingly contributing to urban air pollution and thus there is need to increase the attention given to VCP emissions. This work has also recognized certain other issues that need attention. These include deficiency in comprehensive VCP emission inventories for India, limited understanding on the impact of VCP on the outdoor air Quality in cities like Delhi, Mumbai, Kolkata and Chennai and the lack of representation of VCP emissions in Chemical Transport models. These gaps will be significant in

developing better tools to control air Quality and to achieve goals of the National Clean Air Programme (NCAP) in India

Keywords: Volatile Chemical Products (VCPs), Vehicular Emissions, Indian megacities, Delhi Air Quality, VOC source Apportionment, Secondary Organic Aerosol, Ozone formation, non – exhaust emissions, Urban Air Pollution, Emission Inventory

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LIST OF ABBREVIATIONS

PM: Particulate Matter

WHO: World Health Organization

CPCB: Central Pollution Control Board

IMD: Indian Meteorological Department

VOC: Volatile Organic Compounds

VCPs: Volatile Chemical Products

SOA: Secondary Organic Aerosol

NCAP: National Clean Air Programme

49 **BS IV:** Bharat Stage IV

BS VI: Bharat Stage VI

US: United States

41 **NMVOCs:** Non- Methane Volatile Organic Compounds

CNG: Compressed Natural Gas

SPM: Suspended Particulate Matter

GIS: Geographic Information System

BTEX: Benzene, Toluene, Ethylbenzene, Xylene

20 **PTR – TOF – MS:** Proton – Transfer – Reaction Time - of -flight Mass spectroscopy

ppbv: parts per billion by volume

LPG: Liquefied Petroleum Gas

I/SVOCs: Intermediate – Volatility and Semi – Volatile Organic Compounds

NOS: Nitrooxy- organosulfates

PCPs: Personal Care Products

cVMS: cyclic – Volatile Methyl Siloxanes

I/VOCs: Intermediate Volatile Organic Compounds

PCBTF: Parachlorobenzotrifluoride

SIFT- MS: Selected Ion – Flow – Tube Mass Spectroscopy

UK: United Kingdom

CMAQ Model: Community Multiscale Air Quality Model

OVOCs: Oxygenated Volatile Organic Compounds

EPA: Environmental Protection Agency

51 **CTM:** Chemical Transport Model

WRF – Chem: Weather Research and Forecasting - Chem

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CHAPTER 1

INTRODUCTION

1.1 Urban Air Pollution in Indian Megacities

The environmental and public health concern have become more significant in the period of 2016-2026 due to increasing Air Pollution in Indian Megacities. The concentration of Particulate matter (PM), ozone (O_3) and Nitrogen oxides (NOx)frequently reached to levels that exceed national and WHO guidelines in the Indian Megacities due to various factors like rapid urbanization, rising energy and transport demand [1][2]. According to a 2025-2026 statistical analysis the annual average of PM2.5 across major Indian urban areas range from about 29-46µg/m³ in many southern cities to 82- 123µg/m³ in the Indo Gangetic plain urban centers with Delhi recording mean 24 -hour PM2.5 near 112 µg/m³ [1].

Within this national context, megacities are distinguished by both their persistently high baseline pollution levels and their frequent episodic extremes. A study was done over Delhi, Mumbai, Kolkata and Chennai in the period 2025-2026 using CPCB and IMD data for 2018-2022 which gives a data that PM2.5 and PM10 average up to 108 µg/m³ and 215µg/m3 respectively with values reaching above 344µg/m³ and 536µg/m³ for monthly maxima of PM2.5 and PM10 respectively in Delhi on extreme event days [2]. High Pollution episodes are mostly seen in winters due to stable atmospheric conditions and less mixing depths whereas higher ventilation and monsoon rainfall decrease concentration through wet deposition and dispersion [1][2]

High PM burden arises due to different sources which can be vehicular exhaust, construction and road- dust resuspension, Industrial Emissions, Biomass and waste Burning and Secondary Aerosol formation from VOCs and NOx [1][2]. The urban air pollution in Indian megacities is high due to various regions including local emissions, regional climatology and improper policy implementations between 2016 and 2026.

1.2 The Tailpipe -Centric paradigm in India

Vehicular emissions have always been held responsible for ambient PM and gaseous pollutants in Indian megacities. They have dominated the air quality planning and policy formulation for so long [3]. According to an emission study the on- road vehicles have dominated the PM2.5

hotspots over the Indian urban – rural landscape thus has been a significant source of urban air pollution [4]. Urban Air Pollution control policies have focused highly on emissions due to vehicles. India has heavily relied on transport - oriented measures like controlling traffic and implementing vehicle standards which states that it has treated the tailpipe emissions as a central theme for urban air pollution [3]

Recent systematic evidence maps of urban – level interventions to reduce traffic -related emissions show that Indian cities mainly implement policies at reforming vehicle fleets and improving fuel quality, including a rapid shift towards cleaner fuels and more stringent emission standards [4].Scholarly reviews on air pollution have stated tailpipe emissions as the main source of CO, Nox, VOCs and PM and have neglected the role of other non -tailpipe and sectoral sources in public – health narratives [5].Analyses of pollutant emissions from road vehicles in the megacity of Kolkata similarly identify motorized transport as the primary driver of ambient - air quality degradation, thereby justifying the focus of regulatory efforts on tailpipe exhaust and related traffic – management measures [6].

This tailpipe centric framing is further entrenched by policy documents and implementation strategies that prioritize vehicle – based control technologies such as catalytic converters and that treat emission reductions as a problem of engine and fuel – reform rather than that of broader urban – chemical sources [7].Reviews of urban air pollution control policies also observe that India 's transport oriented strategy is rooted in long – standing planning traditions that regard motor vehicles as the main symbol of environmental degradation in rapidly expanding cities. [3]. As a result, decision makers and the public alike continue to associate urban air quality almost exclusively with tailpipe emissions, even though high - resolution studies demonstrate that non- exhaust and non- traffic sources collectively contribute substantial shares of PM2.5 and gaseous precursors [4].

1.3 Emerging Global recognition of VCPs

In the past decade certain scientific works have considered volatile Chemical Products as a significant source of urban Volatile Chemical Compounds (VOCs) in industrialized cities. A landmark study has stated that the use of Volatile Chemical Products – including pesticides,

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printing inks, coatings, adhesives, cleaning agents and personal care products – now account for nearly half of fossil fuel VOC emissions in industrialized cities. These findings have concluded that VCPs are no longer a minor source of urban VOCs rather they significantly contribute to the urban VOCs in developed countries.

This work has also concluded that the outdoor and indoor air quality is in correspondence with the VCP emissions thus both are influenced by these products. Initially human exposure to carbonaceous aerosols and petrochemically derived particulate matter was dominated by tailpipe emissions but now it is dominated by VCPs. VCPs leads to the generation of Secondary Organic Aerosols (SOAs) but the current US regulations on VCPs are just focusing on ozone formation and air toxics generation. Thus, there are issues in the current source profiling of VCPs [8]

Some observational studies have shown that VCP emissions have contributed to about 78% of Anthropogenic VOCs and 22% was contributed by mobile sources at certain urban centres of US cities. Studies have concluded that 50-80% of the reactivity, emissions and SOA formation potential of anthropogenic VOC s is contributed by VCPs. Thus play a major degrading role in US air quality [9]

Certain studies have shown that VCPs contribute largely to ozone formation and a data was observed that the anthropogenic VOCs contribute to about half of the total VOCs and the one – third of anthropogenic VOCs is contributed by VCPs [10]

1.4 Why 2016 – 2026 is a critical decade

As tailpipe emissions fall, peer – reviewed studies collectively indicate a global scientific consensus that the relative contribution of VCPs to urban air quality problems is increasing and this trend must be addressed in both policy making as well as research. During the period 2016-2026 there have been a transition from unregulated vehicles and industrial activity to emission control and urban air quality governance. A 2025 peer reviewed assessment of air quality during the period of implementation of the National Clean Air Programme observed that there are small improvements in the air quality which are somehow cancelled by increasing no. of vehicles and other factors thus the goal of 20-40% reduction has not been accomplished yet. The trend in few years before 2026 will play significant role in long term planning [11]

An analysis of the Annual PM2.5 trends in 5 Indian megacities over the years 2014-2020 showed significant yet small decline which means there are effects of policy implementation but yet concentrations remain far beyond health – based standards [12].

At the same time evaluations of Bharat Stage mitigation measures have concluded that there have been a reduction in on road vehicular emissions with CO, NMVOC, OC and BC reducing by 7-20% in 2021 as compared to 2017 after transitioning from BS IV to BS VI[13].Certain Studies have emphasized that the source of urban VOC s can be paints ,coatings and Industrial Solvents which are VCPs and are rising due to rising construction and manufacturing [14].

The total VOC concentration accounts of a lot of VOC sources rather than only tailpipe emissions. These sources can be Anthropogenic as well as natural VOC sources which also include VCPs [15]. If the emissions from Volatile Chemical Products (VCPs) are not explicitly targeted they may lead to secondary pollution regime dominated by ozone and secondary organic aerosol precursors [10].

1.5 Objectives

This work is structured to address questions such as –

(1) How have vehicle emission inventories in Indian Megacities evolved over the period 2016 – 2026 with changes in policies and Technology?
(2) It addresses the question of knowledge about VCP emissions in India compared to the global scenario.
(3) It talks about the atmospheric chemical Transformations that link VCPs to secondary Organic Aerosol Production.
(4) It provides us evidence which tells about VCP dominance in India and the barriers it faces in recognition.
(5) It talks about the policy, regulatory and research directions that are needed to consider VCP emissions as a growing challenge for India.

CHAPTER 2

LITERATURE REVIEW

2.1 Background and conceptual framework

2.1.1 Defining Volatile Chemical Products and their role in urban VOC budgets

Volatile Chemical Products are items that contain Volatile Organic Compounds as significant ingredients or solvents covering household cleaning agents, personal care products (lotions, hair sprays, perfumes and deodorants), printing inks, adhesives, Architectural coatings (sealants, varnishes, paints), Pesticides and Industrial process solvents [16]. VCPs can be differentiated from combustion sources by the process of VOC emissions, Combustion sources undergo thermal oxidation to produce VOC whereas VCPs produce VOC by evaporation of product constituents during usage, storage and disposal which makes them different in speciation, emission timings and indoor – outdoor dynamics from tailpipe emissions. Seltzer et al (2020) positioned VCPs as a major source of anthropogenic reactive organic carbon in the US. To model these emissions across the US a VCP y model was developed. VCP organic emissions were estimated to be 9.5 kg per person per year [16]

VCP derived VOCs have higher atmospheric reactivity than that produced from equivalent mass of combustible sources. VCPs often constitute of oxygenated compounds, aromatic solvents and terpenoids that has higher secondary organic aerosol formation as well as higher OH reactivity [17]. Khare and Gentner (2017) found out that VCPs contribute to less mass concentration of VOCs than combustion sources but they have produced higher amount of SOA precursors and ozone precursors in Los Angeles owing to their favorable volatility and reactivity distributions. This reactivity argument is significant for understanding the disproportionate atmospheric impact of VCPs relative to their mass contribution to emission inventories [17].

2.1.2 Global Evidence for the VCP Transition

The foundational research for the dominance of VCPs in urban VOC budgets was done in the US. Per vehicle VOC emissions have reduced in US due to application of stringent vehicle emission standards while the VCP emissions have remained constant or increased due the growing population. Mc Donald et al (2018) used a detailed mass balance method including the chemical product sales information, ingredient specific VOC content data and ambient air from

Los Angeles to analyze emission sources. Their study shows that the Volatile Chemical Products (VCPs) contribute nearly 50% of petrochemical VOC emissions even though there was a public perception that on road transportation is the primary emission source [8].

Coggon et al (2021) noticed a monoterpene flux of fragranced VCPs from 14.7 to 24.4 kg per day per km^2 in New York city. He stated that VCP emissions scale with population density rather than kilometers travelled by vehicle. VCP emissions are widespread in US and European cities [10]. Gkatzelis et al (2021) Out of the total Anthropogenic VOCs 42 to 78% is contributed by VCP based emissions [9].

Development of global emission inventory is evident of the VCP transition. The first global inventory of anthropogenic full volatility organic emission was developed by Huang et al (2023) which stated that VCPs, on road transportation and domestic combustion are three important contributors to the global organic emissions. The importance of each category of organic emission depends on the regulatory maturity and level of development of a country or region under consideration [18]

2.1.3 Indian Megacities: Unique contextual factors

In American and US cities VCP dominance have been taken into consideration [8]. In India policies still focus on tailpipe emissions, Bharat Stage emission Standards have also been applied to reduce vehicular emissions [19]. We found out that two wheelers contribute to more CO and hydrocarbon emissions per km travelled as compared to four wheelers.[20]. An early emission inventory was provided by Gurjar et al (2004) which positioned transport as the dominant source of CO, Nox and NMVOC emissions providing a basis on which further air pollution trends would be assessed [21]. There was significant increase in vehicular emissions in Delhi during the period 2000-2010 as noted by sindhwani and Goyal (2014) and two wheelers were found out to be the ones producing the most emission, [22]

During the post monsoon season the VOC concentration is mainly governed by biomass burning which is due to combustion of agricultural residues in the neighboring states of Delhi and due to solid fuel use in the city [23].Stewart et al (2020) observed 29 fuel types in residential area of Delhi and measured emission factors of 192 non-methane VOC compounds representing different emission profiles produced by crop residue , cow dung cake , fuelwood ,charcoal ,municipal solid waste , sawdust which makes the source attribution complex [24]

2.2 Vehicular Emission Dynamics in Indian Megacities :2016 – 2026

2.2.1 Historical Trajectory and Policy Interventions

A lot of policy experiments have been done over Delhi to reduce Vehicular Emissions one of it was Supreme Court's order to convert Delhi's public Transport fleet to CNG in the early 2000s [25]. Significant reductions in the CO, Nox and SO_2 concentrations have been observed since the conversion to CNG but the Suspended Particulate matter (SPM) was found to be still above permissible limits which reflects the complexity of multi -source pollution management which would be needed in further years. [26]. This initial success in lowering combustion related gaseous pollutants provided a model for technology riven vehicle emission control strategies, which also highlighting the limitations of focusing on single pollution source.

Nagpure et al (2016) systematically quantified Delhi 's Vehicular emission inventory and established important baseline estimates. This study projected that emissions from private vehicles in Delhi could increase by 2 to 18 times by 2020, with two wheelers emerging as the primary source of carbon monoxide emissions, while private cars were found to contribute disproportionately to CO_2 and other combustion related pollutants [27]. In a megacity environment the vehicular emission follows a heterogeneous distribution pattern which was explained by Kumar and Mishra (2017) by location of specific hotspots which act as center of peak vehicle toxic emission at ITO Bridge, ISBT flyover and Nizamuddin Bridge in Delhi [28]

50 Bharat stage emission standards were deployed in India to reduce vehicular emissions since 2000, The BS VI being the latest have been implemented nationwide since 2020 [29]. RTEII high resolution road transport emission inventory was developed by Hakkim et al (2021) at 0.1°× 0.1° resolution. He covered 74 speciated NMVOC along with Nox, CO, CH_4, CO_2 and PM2.5 and noticed that Nox and CO emissions were overestimated while nitromethane was barely considered an emission species. He identified acetaldehyde. toluene and isopentane as the top 3 NMVOC emissions from road transport.[30] The development of this inventory highlighted significant improvements in the accuracy of emission assessments, while emphasizing the ongoing challenges and uncertainties in quantifying speciated VOC emissions across mixed vehicle fleets.

2.2.2 Emission Inventory Development and uncertainties

High resolution spatial emission inventory is an important tool for understanding the geographical distribution of vehicular emissions contributions to urban air quality in Indian Megacities. Biswal et al (2023) applied COPERT emission functions to the advance traffic flow and speed data for 127 vehicle categories, for estimating the multi pollutant hourly gridded on road traffic emissions in Delhi by applying a bottom-up methodology. From this study it became clear that total VOC emissions were dominated by petrol vehicles and it established the value of high resolution temporal data for analyzing diurnal emission patterns corresponding to photochemical modelling [31] By representing traffic emissions at the road segment scale , this work provides a significantly finer spatial resolution , facilitating chemical transport model simulations that are qualitatively superior to those based on city level aggregated emission inventories.

High resolution emission gridding was extended to CO_2 and other pollutants by Mittakola et al (2025) from road traffic across various cities of India, which gives a data that proves spatial heterogeneity of the urban transport emissions at scales in correspondence to surrounding level exposure assessment [32]. Mangaraj et al (2022) developed a high-resolution emission inventory for Kolkata. This study also stated that the Anthropogenic inventory of Kolkata is also dominated by VOC emissions from vehicles. [33]

A GIS based emission inventory was developed by Swarnkar and Gurjar (2023) that considered NMVOCs from biomass burning and heavy metals from road transport. Zinc and copper from road transport which mainly arose from tyre and break wear, NMVOC from fuelwood combustion and dung cake were among the categories with highest emission rates [34]. This established the co- existence of exhaust and non – exhaust emission streams in the Delhi Megacity. These all studies reveals that spatial and temporal resolution is improving and it covers lot more species, also there is a growing recognition for non- exhaust emission pathways that shifts the global attention from tailpipe to Anthropogenic VOC emissions.

2.2.3 The COVID -19 lockdown as a natural Experiment

A natural experiment was provided by the COVID -19 lockdown implemented in India from March 2020 which almost eliminated the vehicular emission as transportation was halted during this period and significantly reduced emission from other sources. It was observed by

Manchanda et al (2020) that there was a decrease in vehicular emission contributions by 96% but it was observed during he later lockdown phases that the low volatility organic aerosols and ozone level increased by 95%. Vehicular emission was reduced but there was an increase in secondary pollutant formation proving that there were ozone and secondary organic aerosol precursors from non – vehicular sources [35]

During the lockdown phase of COVID-19 in India Pakkattil et al (2021) conducted a study over 6 megacities of India using TROPOspheric monitoring Instrument and variations in BTEX (Benzene, Toluene, ethylbenzene and xylene) and HCHO concentrations were observed. The transportation was halted during this period thus tailpipe emissions were all time low. The concentration of BTEX was found to be decreased by about 80% when compared to the pre lockdown period but the concentration of HCHO remained more or less similar. Reduction in BTEX concentration also reduced its ozone formation potential but still the concentration of ozone increased which suggested formation of ozone through means other than road transport [36]

2.2.4 Non – Exhaust Vehicular Emissions

Nagpure et al (2016) demonstrated that road dust, tyre wear and brake wear are the source of non-exhaust emissions and that contributed to 66-86% of the PM10 in 2002 in Delhi [27].According to Singh et al (2019) the total concentration of PM10 in Delhi was found to be 31.5Gg/year and 86% of it was contributed by non-exhaust sources and 79% was contributed by dust resuspension [37]. At national scale there was an assessment done on India's ten states with highest vehicle population and it was found that PM emissions from road dust resuspension was higher than that produced by tyre wear and break wear. Light Duty vehicles came out to be the biggest contributors of PM [38]. Source apportionment of the PM emissions in Agra gave a data that 82% of PM10 and 68% of PM2.5 concentration are contributed by road dust emissions. Implementation of new policies are making fuels cleaner thus tailpipe emissions are reducing and non-exhaust emissions are currently dominating the PM emissions [39].

2.3 VOC source Characterization in Indian Megacities: Measurement Campaigns and source Apportionment

2.3.1 Ambient VOC measurement Infrastructure and Methods

The identification of VOC sources in Delhi has become much more accurate with the application of Proton -transfer – reaction time- of -flight mass spectroscopy (PTR-TOF-MS) as an advance technique that allow continuous, real-time monitoring of a wide variety of VOCs without extensive sample preparation. In a study conducted between January to March 2018, Wang et al (2020) deployed PTR -TOF-MS instruments at both urban and suburban locations across New Delhi to investigate VOC behavior. Their observations showed that VOC concentrations were sufficiently high with particularly elevated levels during the night. Distinct differences between daytime and nighttime concentrations were linked to weaker atmospheric dispersion after sunset and the persistence of emission sources throughout the night. By applying positive matrix factorization (PMF) the researchers were able to distinguish the major sources of VOCs, identifying road traffic and solid – fuel burning as the dominant contributors to Delhi's atmospheric VOC burden [40].

The dual site framework was further studied by Tripathi et al (2022) to evaluate the composition of VOCs at urban and sub -urban locations of New Delhi. According to this study methanol was found to be the most abundant compound with a mixing ratio of about 28ppbv. Other significant VOCs included acetaldehyde (7.7ppbv). acetone (10.6ppbv), isoprene (2.8ppbv) and monoterpenes (0.84ppbv). The study noticed variations in VOC profiles between two monitoring sites and found out that ambient VOC concentrations depend on local emission activities as well as secondary atmospheric chemical processes. The consistently high levels of methanol and acetaldehyde with relative toluene to benzene ratio when seen in comparison to traffic dominated environments indicated contributions from non -vehicular sources [41].

Jain et al (2022) used PTR-TOF-MS to measure VOCs in different seasons in Delhi and to identify locations where emissions are high. Their result showed that traffic emissions and secondary atmospheric formation each contributed to about 31% of NMVOCs while solid – fuel combustion contributed to roughly 28%. Solvent related activities contributed to a smaller percentage and rest was mainly from biogenic emissions during the summer and monsoon season. One of the main findings of the study was the identification of a different solvent- use source [42]. Although solvent related activities contributed to a smaller number of VOCs but its presence is indicative of VOC emissions from Volatile Chemical Products (VCPs) in Delhi. This study is important because it has provided another source of emissions as compared to the traditional source of emissions like traffic and combustion. Jain et al (2023) did a study in

Lucknow which is considered to be an Indo – Gangetic city, which provided an understanding of the VOC sources in North India [43].

This study investigated the chemical composition of VOCs at a location in Delhi and studied how their concentrations vary with seasons and time of the day. The analysis revealed that gasoline evaporation and solvent usage (27.1%) and biomass burning (26.7%) were the largest source of VOCs, followed by LPG- related emissions (16.7%), Vehicle exhaust (16.4%) and painting (5.11%). A particular important outcome of the study was the identification of painting and solvent use as a major contributor to Delhi's VOC levels, accounting for more than one – tenths of the total VOC burden. This was the first study to quantify the contribution of these sources at such a significant level in Delhi [44]. The findings highlight that emissions from solvent – based products are not negligible and can play an important role in sharing urban air quality, alongside more commonly recognized sources such as fuel use, traffic and biomass burning.

2.3.2 BTEX aromatics and their sources

46 Benzene, Toluene, Ethylbenzene and Xylene are commonly used as marker compounds to evaluate the impact of vehicle emissions on urban air quality. Kumar et al (2018) found that VOC concentrations in urban Delhi were considerably high than those observed in rural areas of sub - Tropical India, with road traffic identified as the primary source of these emissions. Among the measured compounds toluene and m/p xylene was found to contribute the most to ozone formation, highlighting their important role in the development of photochemical smog. The study also indicated that exposure to VOCs in the region could pose significant cancer risks. Aromatic hydrocarbons are present in abundance in Delhi's air most of which are carcinogenic and this highlights the need for effective VOC emissions control strategies to improve air quality and ensure good public health [45].

Gaur et al (2016) observed that the BTEX concentration at a site with high traffic in New Delhi were much higher during winter than summer and spring. This increase was mainly due to poor atmospheric mixing, high fuel combustion for heating, and slower petrochemical removal of pollutants under colder temperature and reduce sunlight. As a result of this study BTEX levels in winter were 2 to 3 times higher than in summers [46]. These findings show that even if the emissions from vehicles were consistent throughout the year but seasonal variations also influence the ambient VOC concentration. As the concentration of VOCs vary throughout the year, we need to do an all- year analysis of VOC concentrations.

Sahu et al (2020) did a study on aromatic VOC at a semi – urban site of western India and found out the vehicular exhaust was the major source of BTEX compounds. Even though other sources such as biomass burning, Industrial operations, fuel evaporation and biogenic emissions also made contributions, incomplete combustion of agricultural residues released oxygenated and aromatic VOCs [47]. There are emissions from multiple sources in India which overlap with each other which make identification of VOC sources very difficult. Thus, establishing the sources of VOCs require careful analysis and proper source apportionment techniques

2.3.3 Biomass Burning and Solid fuel Combustion as VOC sources

Awasthi et al (2024) did a study to identify the major sources of VOC and PM2.5 during post monsoon season of 2022 in Delhi. The results of this study showed that Particulate matter was mainly contributed by biomass burning and VOC emissions and secondary pollutants were mainly contributed by industrial activities and vehicle traffic. These findings illustrate the complex nature of Delhi's air quality, where different pollutants are influenced by different emission sources. In other words, the source responsible for PM2.5 levels are not necessarily the same as those driving VOC concentrations. This highlights the importance of developing pollutant specific control strategies to effectively improve air quality in the city [48]

Mishra et al (2024) provided new insights into Delhi's VOC pollution by measuring Chlorine, sulfur and Nitrogen containing compounds during both clean and heavy polluted periods using a high-resolution PTR-TOF-MS instrument. The study revealed that VOC concentration in Delhi was considerably higher than those reported for many megacities in developed countries. During pollution episodes the elevated VOC levels were mainly linked to biomass burning and poor atmospheric ventilation, which restricted the dispersion of pollutants and allowed them to accumulate in the atmosphere [49]. The study is particularly important as it focused on reactive VOC species containing halogens and other heteroatoms, which play a significant role in atmospheric chemistry. These compounds are commonly found in Volatile Chemical Products (VCPs) including fragrances, preservatives, and pharmaceutical ingredients. As a result, these findings provide valuable information for understanding how VCP – related emissions may influence air quality and secondary pollutant formation in Delhi's urban environment.

Stewart et al (2020) measured comprehensive VOC emission factors from 29 domestic fuel types used in Delhi, demonstrating that biomass – burning fuels produce quantitatively distinct emission profiles rich in oxygenated VOCs, including methanol, acetic acid, and furan derivatives alongside the aromatic hydrocarbons, more commonly associated with fossil fuel combustion[24].Stewart et al (2021) complemented this analysis with measurements of intermediate – volatility and semi volatile organic compound (I/SVOC) emissions from domestic fuels finding that cow dung cake and municipal solid burning were significant sources of these high -molecular -weight precursors, which are important for secondary aerosol formation but are typically excluded from conventional VOC emission inventories [50].The I/SVOC emissions from domestic combustion represent a parallel non – exhaust stream to VCPs that must be considered alongside consumer product emissions in any comprehensive accounting of non-VOC sources in Indian cities.

2.3.4 Secondary and Biogenic VOC emissions

Yadav et al examined that how non – methane Volatile Organic Compounds (NMVOCs) influence air quality in Delhi by assessing their contribution to ozone formation, Oh reactivity, secondary organic aerosol formation. The study found that NMVOCs played a major role in all three processes. This study also suggested that there should be focus on the most chemically reactive species rather than focusing on the reducing the total VOC concentrations [51].

Bryant et al studied the both biogenic and anthropogenic sources of isoprene and monoterpenes and their contribution to Secondary Organic Aerosol (SOA) formation. The study identified high levels of nitrooxy – organosulfates (NOS) in night time, these compounds indicate interactions between naturally emitted VOCs and anthropogenic pollutants. These observations revealed a previously underrecognized pathway of SOA formation in Delhi's polluted atmosphere [52]. The finding suggests that emissions from city's urban vegetation can react with high concentrations of Nox and oxidants, creating conditions that favor efficient aerosol production. Such interactions resemble the processes involved in SOA formation from monoterpenes released by fragranced VCPs [10].

Further insight into Delhi's atmospheric chemistry was provided by Nelson at al who observed extremely nighttime nitric oxide concentrations during severe post monsoon pollution events. Average NO levels were around 200 ppbV and occasionally reached near 700 ppbV. These unusually high Nox concentrations suppressed much of the nighttime oxidation chemistry that would normally occur. As a result, ozone and secondary aerosol production were delayed until after sunrise, when sunlight triggered rapid photochemical reactions involving the accumulated VOCs and Nox, leading to enhanced secondary pollutant formation [53]

2.4 VOLATILE CHEMICAL PRODUCTS: GLOBAL SCIENCE AND INDIA RELEVANCE

2.4.1 VCP emission category and Atmospheric relevance

Volatile Chemical Products (VCPs) comprise a wide range of consumer and commercial product whose emissions vary considerably in chemical composition , emission patterns, indoor – outdoor distribution, and atmospheric reactivity, Among these personal Care Products (PCPs) – such as perfumes, deodorants, haircare products , body lotions, and cosmetics – have received significant attention because of their widespread use, substantial per capita emissions, and characteristic release of compounds such as cyclic volatile methyl siloxanes (cVMS) [16].Coggon et al showed that emissions of decamethylcyclopentasiloxane (D5),a common ingredient in personal care products, followed a clear daily cycle in North American cities. Emissions peaked between 6:00 and 7:00 AM, corresponding to morning grooming activities, and were found to be comparable in magnitude to benzene emissions from road Traffic [54]

Another important VCP category in architectural coatings, which exhibit emissions characteristics that differ markedly from those of personal care products. While PCPs are routinely used by large populations throughout the year, paints and coatings are applied intermittently during, construction, maintenance, and renovation activities, resulting in localized emissions events that can last from several hours to several days[16].Tanzer- Gruener et al measured emissions of intermediate – and volatile organic compounds (I/VOCs) from both water- based and oil- based paints and found that oil- based products generated a disproportionately large share of organic vapor emissions and Secondary Organic aerosol (SOA) formation potential, despite representing a smaller fraction of overall paint sales[55]. Similarly, stockwell et al identified para – chlorobenzenetriflurode (PCBTF) and Texanol as useful tracer compounds for solvent- based and water- based coatings, respectively. Together, these compounds accounted for roughly 10% of VOC ingredients used in coatings and proved effective for tracking coating – related emissions in ambient air [56]

A major advance in VCP research has been the identification of tracer compounds that allow these emissions to be quantified directly in the atmosphere. Gkatzelis et al found that ethanol and fragrance – related monoterpenes were among the most abundant and chemically reactive VOCs associated with VCP use in urban environments. Their study also showed that concentrations of these tracers were more strongly related to population density than to traffic activity, supporting inventory- based predictions that VCP emissions scale closely with human activity and product consumption [57].

Further methodological progress was demonstrated by Wagner et al who used a mobile inventory equipped with selected – ion – flow- tube mass spectroscopy (SIFT- MS) to measure VCP emissions and other atmospheric trace gases in urban settings. Their work highlighted the potential of mobile monitoring platforms for capturing the spatial variability of VCP emissions and provides a valuable framework that could be adapted for future studies in Indian megacities [58].

2.4.2 VCP emission Inventories: methods and approaches

Creating an accurate emission inventories for Volatile Chemical Products (VCPs) requires a different methodology from that used for combustion – related sources. Unlike vehicle or fuel-combustion emissions, which can be estimated from fuel consumption and combustion characteristics, VCP emissions are influenced by product sales, consumer usage patterns, chemical formulations, and the evaporation rates of individual ingredients. To address these complexities, seltzer et al developed the VCPy framework, a comprehensive modelling system for estimating VCP emissions in the United States. This study estimated the spatial and temporal emissions by combining product sales information, detailed ingredient data and evaporation models [16]. Even though this is a very good approach but its application in India will require considerations that there are differences in product formulations, consumer behavior and regulatory reporting practices.

The challenge of developing VCP inventories outside the United States were highlighted by Asif et al, who developed Anthropogenic VOC emission estimates for Canada. Their study emphasized the difficulties associated with obtaining reliable information on product sales and chemical compositions, particularly in regions where such data are not systematically collected or reported [59]. Similar Challenges exist in India, where limited VOC content reporting requirements, incomplete product sales databases, and a lack of India-specific emission factors make it difficult to develop a bottom- up VCP inventory comparable to those available for North American Cities.

The significance of VCP emissions is further illustrated by Askari and Chan, who estimated that VCPs were responsible for approximately 290 kilotons of gaseous organic emissions in Canada, with more than 60% of these emissions occurring indoors [60]. Their findings demonstrate that VCPs can be an important source of atmospheric organic compounds even in countries where per capita use of consumer chemical products is relatively low.

Insights from China also highlights the growing importance of VCP – related emissions. Mo et al developed a mass- balance – based inventory of NMVOC emissions from solvent use between 2000 and 2017 and found that emissions increased rapidly during the period of economic expansion from 2000 to 2014. However, this growth stabilized when the products with high VOC emissions were targeted and personal care products were identified as source of emissions [61]. This experience is evident that VCP emissions increase along with economic growth and rising consumer demand and can be very well managed through regulatory measures. In India consumer markets and urban populations are expanding rapidly, thus understanding and tracking VCP emissions will be very important. The scale, composition and future trajectory of these
42 emissions will be shaped by local economic conditions, consumer preferences, and regulatory frameworks that are different from those in China and North America.

2.4.3 Indoor VCP emissions and Outdoor Air Quality Implications

A large part of VCP emissions more than emission from combustion and industrial emission source occur indoors or in residential, commercial or institutional buildings which is about 60% for Canadian cities. These emissions then transmit to outdoor air through ventilation and infiltration. The indoor to outdoor transfer efficiency depends on several factors like air exchange rates, patterns of ventilations and physiochemical properties of the compound emitted [60].

38 A study was done by Norris et al (2022) where he measured the VOC concentrations inside and outside of 26 homes in Ahmedabad and Gandhinagar, Gujarat and he came to the conclusion that VOC concentrations were higher inside as compared to outside due to plastics, coking, consumer products, Siloxanes and Vehicles. This was the first Indian study which considered the indoor –

outdoor transmission of VOCs and also considered VOC emissions from consumer products and thought about its possible negative impacts on human health as well as noted that VOCs emitted inside can degrade outdoor air quality. It also showed that VOC emissions from siloxanes are present in the Indian Environment which is the marker of Personal Care Products [62]. Thus, this study proved that emissions from VCPs are significant in India too.

Speciation Profiles and Emission rates of non -aerosol personal products in UK were done by Yeoman et al (2020). He estimated annual per – person VOC emissions for every product in common use and identified shower gels and liquid foundations as the biggest contributor of VOC emissions [63]. This work was done in Uk but it can provide methodologies by which we can estimate the PCP emissions by applying these methodologies to Indian Product formulations. For an India specific estimations differences in product formulation should be kept in mind as well as the usage frequency and climatic conditions too. India being a country which has high temperature the emissions from PCPs will be faster leading to higher emission values.

2.4.4 VCP contributions to ozone and SOA formation

The atmospheric Chemical significance of VCP emissions is not only restricted to VOC
45 emissions in the environment but also its ozone formation potential and secondary organic
28 aerosol formation potential is of great significance. A study by Coggon et al (2021) suggested that 50% of the ozone emissions from VCPs come from monoterpenes and related compounds in New York City. Thus, VCP emissions affect the urban air quality to a large extent. In cities where pollution from combustion is substantially reduced VCP emissions acts a driver for photochemical pollutant formation [10]

According to a study by Zhang et al (2025) ozone formation in the troposphere occurs due to photochemical reaction of Nox, OH radicals and peroxy radicals (Ro_2). The process is sensitive for VOC and Nox limited regime. The VOCs present in the air are oxidized by OH radicals and thus peroxy radical is formed by this process. The peroxy radical formed in this process further reacts with NO and form Nitrogen dioxide and alkoxy radicals (OR). Photolysis of NO_2 occurs
5 which yields atomic oxygen and it reacts with molecular oxygen to form ozone.

$$VOC + OH \longrightarrow RO_2$$

$$RO_2 + NO \longrightarrow RO + NO_2$$

$NO_2 + h\upsilon \longrightarrow NO + O$

$O + O_2 \longrightarrow O_3$

When the ozone production is Nox limiting that is concentration of Nox is lowe than concentration of VOC , when Nox is increased ozone formation increases.In VOC limited regime presence of VOC lowes ozone formation thus when VOC is available ozone decreases [64].

36 Pennington et al (2021) used Community Multiscale Air Quality Model (CMAQ model) to understand the formation of Soa from VCP emissions. It also stated that VCP emissions are higher in areas with high population density [65].

Aircraft based measurements were used by Nault et al (2021) which concluded that SOA from anthropogenic VOCs which also include VCP precursor contribute significantly to air mortality and can impact health of individuals negatively. Thus attention is needed for its regulation as combustion based emissions have reduced focus should be on these emissions [66].

Seltzer et al (2021) combined VCP specific modules into Chemical Transport models in the US CMAQ model. This is evident of the critical capability gap of Indian Air quality modelling system which doesn't give required importance to VCPs as a pollutant [67].

Travis et al recognized that the photochemical models for simulating ozone production can be improved by enhancing VCP emission representation and production of NOx.This highlights the fact thart current models doesn't accurately take into consideration ozone formation from VCPs and including it will be a great step to understand ozone production[68].Yarwood and Tuite (2024) studied the representation of the VCP ozone formation chemistry in Carbon Bond Chemical mechanism which provided updated kinetic parameters and chemical apthways for improving the accuracy of the models which are used for simulating ozone formation.This methodology will be extremey useful for studying the ozone formation from VCPs in India[69].

2.5 OZONE AND SECONDARY ORGANIC AEROSOL FORMATION : THE ATMOSPHERIC CHEMISTRY NEXUS

2.5.1 Ozone Chemistry and VOC sensitivity in Delhi

Several factors govern the ground level ozone formation in Delhiwhich can be VOC precurosr availability, Nox concentration, degree of atmospheric oxidation capacity and photolysis frequency. As it stated that reduced particulate matter during COVID -19 lockdown period increased the solar radiation which increased ozone production in Delhi, thus photolysis frequency is a significant governing factor [70]. Nelson et al (2021) did a study on sensitivity of in situ ozone production in Delhi. He used a chemical box model to measure the VOCs , radical species and Nox during october 2018. The ozone production in Delhi is very much sensitive to VOC concentration which also include reractive aromatics and oxygenated species. It is not Nox limited which is commom for areas with cleaner urban environment [71].

The VOC limited nature of ozone production in Delhi brings light to the fact that VCP emissions should be included in emission inventories of Delhi and India. As VCP derived monotepenes , oxygenated solvents and fragnances will lead to ozone production without any change in Nox concentrations as they give rise to VOCs.It was found that if VOC are reduced along with reductions in Nox and PM ozone production can be significantly reduced.The identification of Delhi as a VOC limited ozone production environment is of great atmospheric importance as emissions from VCPs is significantly higher in Delhi as compared to other cities [71].

Gupta et al (2022) analyzed the impact of different air pollution mitigation methods on the air quality using the WRF chem Chemical Transport Model.This paper established that implementation of BSVI in ransportation , transition from coal to natural gas in generation of power and usage of LPG as a domestic fuel improved air quality and reduced PM10 and ozone [72]. This study didn't considered VCPs as a potential target for air pollution mitigation which is evident of the gap in Indian emission inventories. The absence of VCPs from the Indian Emission inventories signifies ignorance of a very large contributor of Air Pollution.

2.5.2 Secondary Organic Aerosol formation and VCP precursors

43 Th oxidation of various VOCs and IVOCs emitted from various sources play a major role in Secondary Organic Aerosol (SOA) formation over Delhi. These compounds react in the gas phase, with already existing particles [52]. Shukla et al reported that in summer in Delhi, the majority of the organic aerosol mass consisted of secondary oxidized aerosols, even in the absence of high emissions from primary sources like biomass burning [73]. They conclude the VOC precursors from vehicles, biomass burning and even from Volatile Chemical Products (VCPs) have a profound influence on ambient SOA levels.

17 In addition, Jain et al (2017) studied the chemical composition of PM2.5 at a site located in urban environment of Delhi, through applying various receptor modeling methods, provided

further evidence of the importance of secondary aerosol formation. The major sources of PM identified in the study were secondary aerosols, vehicular emissions, soil and road dust, biomass burning, fossil fuel combustion and industrial activities [74]. Well -defined secondary aerosol factors indicate that Delhi's atmosphere is highly affected by extensive photochemical processing of the primary emissions, as is expected given the high concentrations of VOCs and Nox. The diesel vehicles, traffic -related exhaust, and evaporative emissions were found as the critical sources of VOCs for Delhi in earlier study by Srivastava et al (2025) which also gave an idea of evolution of VOCs sources in the city in the past [75].

VCP related compounds can also provide contribution to the formation of SOA apart from the traditional emission sources. For the case of benzyl alcohol, a solvent and ingredient for fragrances often used in the consumer products. Jaoui et al (2023) studied the photooxidation to determine the formation of products that were highly oxygenated and hydroxy nitroaromatics [76]. A number of these products were determined to have strong light absorbing properties, which suggests that they could have a significant impact on the optical properties of aerosols. The results show that atmospheric oxidation of VCP emissions can result in a broad spectrum of complex chemical products which have implications for the broader effects on the atmosphere beyond the formation of conventional ozone and SOA, on public health and climate.

2.5.3 Radical Chemistry and Atmospheric Oxidation Chemistry

The atmospheric oxidation budget in Indian Megacities is affected by shift from vehicular to Volatile Chemical Product emissions which alter radical initiation, propagation and termination steps. Delhi follows VOC limited regime for ozone production thus production rate of local ozone depends on availability of VOCs and not Nox. Reducing the concentration of Nox will increase the ozone level [71]. Under high Nox concentration, the hydroxyl radical OH reacts with NO_2 to produce HNO_3 and the VOCs drive a reaction

$$RO_2 + NO \longrightarrow NO_2 + RO$$

This reaction amplifies the ozone formation. During the post monsoon period in Delhi the Nox concentration is at all time high level which quench nocturnal oxidants like NO_3, O_3 and OH by proceeding with reactions like –

$$NO + O_3 \longrightarrow NO_2 + O_2$$

$$NO + NO_3 \longrightarrow 2NO_2$$

These reactions lead to a peak of ozone from noon to mid – afternoon. This peak of ozone leads to early day photo oxidation [53].

Chemically diverse VOC species are introduced by VCPs that affect radical cycling directly. Highest sensitivity to ozone production is possessed by monoaromatic compounds but when we half their concentration the morning ozone reduces by 15.6% followed by reduction of monoterpenes and alkenes by 13.1% and 12.9% respectively [71]. Traditionally sources of monoterpenes and isoprenes is considered biogenic but they showed strong correlations with CO in Delhi during night which is indicative of its anthropogenic sources such as fragranced VCPs. Organosulfates ($ROSO_3^-$) and nitrooxy- organosulfates are formed by oxidation of these in presence of high SO_2 and Nox. 6.6% of organic aerosol which is oxidized is contributed by organosulfates and nitrooxy- organosulfates during post monsoon season in Delhi [52].

VOCs containing reactive chorine, sulfur and nitrogen (e.g. methanethiol, dichlorobenzenes, C6 amides) which are present in Delhi have introduced alternate radical initiation pathways like-

$$Cl\cdot + VOC \longrightarrow R\cdot + HCl$$

Here VOCs are oxidized by Cl· faster as compared to OH on per molecule basis [49]. Thus, the radical chemistry in Indian megacities is not only dependent on Nox – hydrocarbon photochemistry but also on Halogenated and oxygenated VCP – derived species.

2.6 EMERGING EVIDENCE FOR VCP EMISSIONS IN THE INDIAN CONTEXT

2.6.1 Consumer Product Growth and VCP emission Potential

With increase in urbanization the use of Personal Care Products is increasing in India as well as the World. This increase is affecting the air Quality very negatively as PCPs are a major source of VOCs [8]. Evaluations of products in the Indian Market have suggested the presence of Cyclic Volatile methylsiloxanes (cVMS) and monoterpenes. The per capita emissions of siloxanes are estimated to be reaching as high as 1,950,000 µg/day when the product is used in routine [77]. This study is significant in understanding how PCPs are now affecting the urban Air Quality. Huang et al (2023) gave us an idea by which we can analyze the effect of GDP, urbanization and sector – specific consumption patterns on the VCP emissions [18].

Evidences were provided by Beaudry et al (2025) that methanol and ethanol are not included in the current emission inventories of South Korea and China. The sources of these have been found to be cleaning products and products of consumer usage [78]. There has been a spike in surface disinfectants and sanitizers after the COVID 19 pandemic. The emissions of VOCs are very high from such products. Ethanol was the major VOC emitter from such products but there were VOC emissions from monoterpenes and monoterpenoids too [79]. These studies have suggested increased use of VCP usage over the world including India due to rapid urbanization, GDP as well as the COVID 19 pandemic. As the VCPs are increasing VOCs and factors degrading Air Quality are also increasing.

2.6.2 Paint and Coating Emissions in the Indian Context

Paint and coating emissions are a significant source of VOCs in the Indian Urban environment. Recent studies have demonstrated high VOCs from industries related to paints and coatings. A study done on unorganized paint manufacturing workers gave a data that the concentration of ethylbenzene, toluene and dichloromethane exceeded the threshold limit values of the American Conference of Government Industrial hygienists. This study stated that 52% of the workers working in these industries developed respiratory and pulmonary diseases in the long run [80].

Delhi's okhla Industrial area is surrounded by industries of paints, varnishes and motor vehicle serving stations. All of these affect the air Quality of Okhla. The concentration of toluene and benzene is highest in okhla due to presence of Industries related to paints and varnishes. Thus, these play a significant role in degrading air Quality. It was also found that in a newly renovated room in Mumbai, xylene and toluene concentrations were found to be very high which is indicative of emissions from paint indoors [81].

Solvent usage in painting and coating is found to produce Non -Methane Hydrocarbons in urban areas of India [82]. VOCs from paints and varnishes also possess ozone formation potential as m/p – xylene and toluene are mainly responsible for the formation of ozone and they are emitted in a high concentration by paints and varnishes [45].

2.6.3 Automobile Repair and Industrial VCP sources

Automobile Industry is also a significant source of VOC emissions. According to a study, industries using VOCs as raw material have emitted 45% of VOCs in the time period from 2022 to 2023 in the industrial areas. Ankleshwar in India is one of the biggest chemical zones in Asia which emit a large number of VOCs. It has over 2000 industries and among these the ones that emit high number of VOCs are textile, automobile, pharmaceuticals, refining and petrochemicals. Chemical, Coke production, organic chemical and pesticide industries [83].

Another important source of VOC emission is vehicle repair Industry. The sheet metal spray painting done in repairing automobiles emits VOCs in large concentration. The annual VOC per auto repairs store depends on the type of business ranging from 0.07t to 2.54t. The emission factor was found to be 254g/car for sheet metal spray painting and it was 237g/ car for machine repair process of the vehicle repair [84].

The major VOC species emitted during the automobile manufacturing are undecane, xylene, n-hexanal, acetone, n- butyl acetate and 1,2,4 trimethylbenzene which account for 68% of total VOCs. OVOCs and aromatics are the main contributors of VOCs in the automobile manufacturing Industry. Automotive manufacturing emissions for SUV car ranges from 0.23-1.66 kg/SUV car and the emissions produced by cleaning solvents is the biggest contributor of VOCs among the other contributors [85].

2.7 COMPARATIVE ANALYSIS: INDIAN MEGACITIES VERSUS GLOBAL BENCHMARK

2.7.1 Delhi in global context

Delhi as a megacity has always shown emissions from traffic and combustion related activities. studies have also shown the dominance of these factors over the urban air quality of Delhi and their contribution to VOCs, but the effect of solvent use in Industries which are a kind of VCP is coming in light. Thus, the VOC emissions in Delhi is becoming multi sourced including emission from traffic, solid fuel combustion, biomass burning, Industrial activities and solvent use [42]. Singh et al (2020) analyzed the air quality of 5 Indian megacities which are Delhi, Kolkata, Chennai, Mumbai and Hyderabad. It was found in this study that the PM2.5 concentration in all these cities exceeded the National ambient air quality standards and even their concentration was multi folds of the national standards with Delhi having the highest concentration of PM2.5 among all the cities [86].

An assessment was done by Hama et al (2020) which assessed ambient PM and trace gases in the region of Delhi NCR and it was found that PM2.5 and trace gases in this region were contributed by local sources and it is very difficult to study the regional pollution transport from concentration measurements only. The mentioned VOC mixture is more likely to be influenced by the local emission sources of the VOCs than by the transport from the air of the neighboring regions because of the predominance of local emissions over the city of Delhi [87]. This is why Delhi is the perfect region to pursue source attribution studies, and make it easier to identify and distinguish VOC source contributions, in particular from Volatile Chemical Products (VCPs).

The COVID 19 period of Delhi revealed that there are other non-traffic sources too which are responsible for VOC emissions During the lockdown period when the traffic was all time low and emissions from vehicles were nearly absent still ozone production was high [36] This suggests alternate sources of VOCs other than vehicles which also suggests emissions from VCPs too. Such patterns are also seen in other Asian megacities too. Beijing during the COVID 19 lockdown period was not able to reduce haze pollution and also ozone level was also continuously increasing [88].

2.7.2 Lessons from Regulatory Trajectories in Developed Nations

The work done by US and Europe in controlling emissions of VCPs can be viewed as a lesson for India as India needs to improve its air Quality. In the United States there is an implementation of California's Consumer Product Regulations and EPA's control techniques Guidelines since 1990s which have helped a lot in controlling the VOC emissions from Consumer products [17].

McDonald et al (2018) discovered that VCPs are a very important contributor of VOC emissions in many cities in US. The current regulations have been successful in controlling ozone forming compounds but total VOC emissions from all sources are not controlled that much [8].

The study by Pfannerstill et al (2023) gives further information about quantifying VOC emissions in the Los Angeles area by comparing it to available emission inventories and by doing airborne observations. They found out that the VCP emissions were higher in the studied area as compared to the data given by the emission inventories which means these inventories were underestimating VCP emissions [89]. These differences in emission estimations are in a place where regulations related to VCP emissions have implemented for long term suggests that there are issues in quantifying these sources accurately. Such differences can be very high in India as the emission inventories barely consider VCP as a source of VOC emission in India. It provides a basis for future studies to find new ways to include ambient information and emission inventories such as those done in Los Angeles. These strategies might help in controlling VCP emissions in Indian megacities.

2.7.3 Multiple Megacity Comparison within India

Delhi has received the most attention in VOC research more than any megacity in India although every megacity has a distinct VOC profile which needs to be studied. Mangaraj et al (2022) through its study found out that the anthropogenic inventory of Kolkata is dominated by VOC emissions from transport sector. Two and Three wheelers are the largest contributors because of their high number and large emission factors [33]. Sahu et al (2023) reported that the overall emissions of major air pollutants in Delhi have slightly increased in the past decade. The transport sector was the largest contributor of emissions, reflecting the increasingly large and important role of vehicles as an emission source in the city, as well as the emergence of new emission sources like emissions from construction activities [90].

Tewari and Jindal studied the air pollution scenario in Delhi in the past decade and sources like transport, industrial, power generation, domestic burning etc. were identified. They found that while severe pollution control measures have been taken, some have been more effective in reducing emissions than others, depending on the sector [91].

Source Category	**% Contribution to VOCs**	**Key Study**
Petrol four - wheelers	20%	Awasthi et al (2024) – Delhi [23]
Petrol Three – wheelers	14%	Awasthi et al (2024) - Delhi
CNG heavy duty Vehicles	15% PM 10, 11% PM2.5	Awasthi et al (2024) - Delhi
Volatile Chemical Products (VCPs)	11 – 50% (varies by city)	MC Donald et al (2018) , [8] Coggon et al (2021) [10]

VCP – fragranced Personal care	>50 % of VCP ozone contribution	Coggon et al (2021)
Industrial Emissions	12% (Delhi)	Awasthi et al (2024) - Delhi
Biomass Burning – Paddy Residue	6%	Awasthi et al (2024) - Delhi
Biomass Burning – Residential Cooking	10%	Awasthi et al (2024) - Delhi
Road Construction (Asphalt)	8%	Awasthi et al (2024) - Delhi

Table 1. Source of VOCs

CHAPTER 3

HEALTH IMPLICATIONS OF THE VCP TRANSITION

Besides forming secondary pollutant precursors VCPs pose serious threat for human health. Different sampling methodologies of VCP emissions from consumer products were studied by Haug et al (2022). He concluded that different analytical methods give different VOC profiles and to study its exposure on human inhalation we must be aware of all the compounds emitted during the product use [92]. Studying the impact of VCPs on human health in India is very complex because product formulation data is not available.

Billionnet et al (2011) concluded through its study that n – undecane and 1,2,4 – trimethylbenzene were the cause of 8.6% of asthma cases and ethylbenzene, trichloroethylene, m/p and o – xylene were the cause of 38.3% of rhinitis cases [93]. Noteworthy is that most of these VOCs are emitted from VCPs.

Nault et al (2021) stated that SOAs from VOCs mainly the ones derived from VCPs contributed to air mortality on world level. It also provided a health - based rationale for regulatory attention to VCP emissions that is far extended than ozone precursor control. This study basically gave the link between VCP emissions and its impact on public health [66]. The application of this global air mortality attribution will need the presence of VCP module in Indian Chemical Transport model which is unavailable currently. Brunet et al (2024) noticed a very high outdoor concentration of Volatile Methyl Siloxanes (VMS) in New York city which is due to personal care products. It has been found that VMS cause lung and liver damage, endocrine disruption and can be the reason of decreased fertility. Atmospheric oxidation of VMS can cause formation of secondary chemical products which also affect health [94].

CHAPTER 4

DISCUSSION

4.1 CRITICAL RESEARCH GAP AND FUTURE DIRECTIONS

4.1.1 India specific VCP emission inventory development

The most critical research gap is the absence of India – specific emission inventory which should possibly be including the local product formulations, usage pattern, building characteristics and climate conditions. Countries like North America and Europe possess VCP inventories that consider ingredient disclosure data, safety data sheets and product sale statistics compiled by regulatory agencies, India lacks such data infrastructure. The development of an India – specific VCP inventory would require a systematic survey of all the VOC contents present in VCP categories available in Indian Market. A survey should be done across different income, geographic and demographic groups to study the usage pattern data of consumers. Evaluation model should be developed which is adjusted according to climate as large parts of India experience high ambient temperature. Indoor – outdoor transfer modelling calibrated to Indian building type and ventilation practices should be done.

Askari and Chan (2025) explained the complexity of quantifying VOC emissions from residential buildings to ambient air. The study stated that the residential emissions of VCPs are detectable at building scale and it contribute to VOCs in the neighboring area [95]. In representative housing type of major Indian cities, a similar building scale emission assessment process can be carried out to gather real – world data on the movement of VCP emissions from the indoor to the outdoor space and to fill a critical knowledge gap to better understand the contribution of VCP to urban air pollution.

4.1.2 Tracer Compound identification and Monitoring

The identification of VCP tracer compounds in Indian megacity ambient air similar to that done by Gkatzelis et al (2020) in US cities is a prerequisite for evaluating VCP emission estimates [57]. The selection of appropriate tracer for VCP in Indian air must account for local product formulations which will be different from that of US and Europe in solvent selection, fragrance compound composition and in prevalence of certain product categories like hair oils and incense sticks. For identifying the VCP tracer compounds in India, we must measure the compounds which are identified as VCP tracer globally and are associated with personal care products, fragrances, coatings and cleaning products. This would provide a foundation for India specific VCP tracer validation.

Li et al (2024) showed that types of VOC emissions over the past few decades can significantly influence urban ozone formation. They monitored the chemistry of ozone in the city because over time, production changes and changing solvent use affected ambient VOCs, leading to measurable changes in ambient ozone chemistry over time in Birmingham, UK [96]. Ambient VOC monitoring data at least since 2005 in Delhi may be used to establish the VOC mixture which would have resulted from the changing VOC use patterns in the city over time. A similar long - term study could be carried out in Delhi and will give an idea about the impact of changing VOC use pattern over the years on the VOC mixture. This analysis would give historical context to the growing importance of VCP emissions, and would help to better understand the potential future changes in VOC source contributions.

4.1.3 Chemical Transport Model Integration

There is a need to integrate the VCP emissions into Indian Chemical Transport Model (CTM) particularly the CMAQ and WRF – chem configurations which is currently used for air quality modelling in India [97] [98]. Currently Indian CTM simulations follow emission inventories that include transportation, power generation, biomass burning, Industry categories as source but representation of VCP is absent. The contribution of VCP in the formation of ozone and SOAs is either absent from the model predictions or these are categorized under other source categories without proper chemical speciation. Seltzer et al (2021) developed a methodology to integrate VCP emissions into the CMAQ model which provides a template for Indian CTM development though adaptations to Indian scenario would require a lot of effort [67].

The family of chemical bond mechanisms known as carbon bond mechanisms are used widely in air quality models around the globe, and Yarwood and Tuite (2024) enhanced the representation of formation of VCP in these mechanisms [69]. Before the detailed India specific inventory is developed, these changes should be added to CB6 and other methods used in Indian CTMs to drive better prediction of ozone levels. The new mechanisms are more representative of the reaction of compounds of the fragrance or solvent, which are normally emitted by VCP to the atmosphere and are responsible for the formation of O3. Similarly, Dodero et al (2025) showed

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how a network of monitoring instruments can be used to monitor the spatial and temporal distribution of VCP emissions throughout the greater Houston area [99].Their work gives a good methodological guideline that can be followed in the Indian megacities and can enhance the understanding of the source of VCP, its time variation and contribution to air pollution in cities.

4.1.4 Socioeconomic and Consumption pattern Research

To understand the trajectory of VCP emissions in Indian megacities we need to study the socioeconomic analysis of VCP consumption pattern and their drivers. India has transitioned from Low VCP use traditional products to High VCP use commercial products due to growing urbanization and economy. To get inputs for long term emission development we need to focus on the market penetration of VCP high product categories and the potential for green chemistry product substitution.

According to a study by Huang et al (2023) the VCP contribution of a country to global organic emissions increases with the economic growth of the country and regulated combustion sources of that country [18]. This study has provided a link between the VCP transition and macroeconomic factors which can be directly applicable for projecting India’s emission trajectory.

CHAPTER 5

CONCLUSIONS

This review concludes that India's megacities face a new fight against air Pollution. Various measures such as enacting BS VI norms for vehicles, greater promotion of CNG vehicles and the slow introduction of Electric Vehicles have been taken over the last ten years to control VOC emissions from the transport sector. Traditional sources are becoming scarce and Volatile Chemical Products like personal care products, paints and coatings, adhesives, household cleaning products will be expected to account for a greater proportion of the urban VOC emissions. COVID 19 lockdown was one of the most important pieces of evidence of this change as the amount of traffic was reduced significantly, but ozone pollution remained a significant problem in the urban atmosphere, showing that non – vehicular VOC sources already have a significant role in the urban atmospheric chemistry.

Delhi is a critical problem where VOC availability plays a major role in determining the ozone levels, and VOC emission sensitivity is of utmost importance. But the need for research doesn't end in Delhi. These emission characteristics of VCP and the response of the ozone may differ across cities, like Mumbai, Chennai and Hyderabad, owing to industrial, commercial and consumer product usage.

Thankfully India doesn't need to face this challenge without any previous information. Learning from experiences in North American and European cities where VCP emissions are similar, or higher than those of vehicles is beneficial in drawing conclusions. The learning experience can help the country to deal with future challenges.

The Indian specific emission inventory, tracer- based source apportionment and VOC- content regulations for consumer and Industrial products should be prioritized to take the lead in the problem. Inclusion of these measures will address the VOCs before they become a significant source of VOCs in urban areas, which will lead to sustainable improvement in air quality and ozone depletion.

CHAPTER 6

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