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REVIEW

Atmospheric Non-Methane Hydrocarbons over Indian Region: From Initial Measurements to Latest Results

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ABSTRACT

Increased non-methane hydrocarbons (NMHCs) emissions brought on by urbanisation, industrialisation, and a warming planet have significantly modulated regional atmospheric photochemistry, ground-level ozone formation, oxidant levels, and secondary organic aerosol production. India, being a country with fast-paced changes with excessive and variable emissions like in the Indo-Gangetic Plains, a comprehensive understanding of the temporal and spatial evolution of NMHCs over this region is crucial to decipher contributing sources and quantify their impacts. In this context, we have evaluated peer-reviewed observational studies employing established analytical techniques on the detection of NMHCs over the Indian subcontinent, classified into major geographical realms (West, North, IGP, East, South, and Central). The study accesses measurement techniques, concentration levels, spatio-temporal variability, NMHC ratios and inter-relationships among species over multiple Indian locations representing diverse topographical, meteorological, and urbanization regimes. The reviewed research consistently shows that major urban regions like Delhi, Mumbai, Hyderabad, and Kanpur experience significantly higher NMHC levels in comparison to background and rural locations like Mount Abu, Nainital and Ajmer. Background regions also exhibit an increase under burgeoning emissions. Increasing contributions to the atmospheric NMHCs from the solvent usage sector has been observed in urbanized locations. The study emphasises how improvements in NMHC measurement methods—from conventional canister samplers to contemporary real-time devices like PTR-ToF-MS have improved evaluations of air quality. This review, based on over 15 study locations over India, underscores the need for expanded and sustained NMHC monitoring networks, adoption of cleaner fuels, and stricter emission control

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strategies to effectively mitigate NMHC-driven air quality degradation in India.

Keywords: Hydrocarbons; Atmospheric NMHCs; Sources; Effects; Measurements

1. Introduction

Hydrocarbons (HCs) are hydrogen and carbon-based organic molecules that are found in fossil fuels including natural gas, coal, and crude oil. HCs, which are used to produce most of the world's energy, are also highly flammable [1]. A few examples include gasoline, jet fuel, propane, kerosene, and diesel. Natural gas primarily consists of methane, ethane, propane, and butane. HCs are classified into two groups: aromatic (ringed planar structures like benzene) and aliphatic (straight chain structures like propane). HCs produced through the chemical breakdown of oils or fats were referred to as aliphatic (from the Greek aleiphar, "fat") which include alkanes (saturated), alkenes and alkynes (unsaturated). Alkenes, also known as olefins (from the Greek olefiant, "oil-forming"), contain double bonds, while alkynes have triple bonds. Aromatic HCs have cyclic structures, often with pleasant odours, and include compounds like benzene and toluene. The term "benzenoids" refers to aromatic compounds with a benzene ring, while "non-benzenoids" refers to compounds without a benzene ring [1].

Non-methane hydrocarbons (NMHCs) are a class of aliphatic, aromatic, and alkyl compounds that are both naturally occurring and anthropogenically emitted. They typically have low molecular weights and comprise carbon atoms C_2 to C_{12} and hydrogen [2]. Among these, low molecular weight C_2 to C_5 compounds are classified as light NMHCs. Methane, despite its high emissions, is excluded from this group because of its weaker reactivity with OH radicals compared to NMHCs, and its direct link to climate change [3]. The term VOCs, which stands for "volatile organic compounds", is used to describe organic compounds that evaporate when exposed to air at room temperature. Carbon, hydrogen, and oxygen make up oxygenated VOCs, which are generated by automobile exhaust and atmospheric chemical processes. SVOCs, which are also known as "Semi-volatile organic compounds," are a type of VOC with the boiling points ranging from 260 °C to 400 °C. They are gradually synthesized from the underlying material and can be classified as gaseous, particulates that are airborne, and dust. Phthalates and flame-retardant chemicals (FRs) are the most common SVOCs found in indoor environments [4]. The term NMVOCs, which stands for "non-methane volatile organic compounds" encompasses a wide range of chemical substances, each of which has its own distinct chemical characteristics and, by extension, impacts on the formation of ozone (O_3) and secondary organic aerosols (SOA) [5]. An essential part of VOCs that may be utilised to calculate their levels is NMHC.

Research on NMHCs is crucial for addressing key environmental and health issues. One of the primary reasons for investigating NMHCs is their significant influence on air quality. These compounds contribute to the formation of ground-level O_3 and SOA, which are major pollutants associated with smog and haze. Ground-level O_3, in particular, is a harmful substance that can cause respiratory issues, aggravate asthma, and reduce lung function, which has serious public health implications and impacts plant health, consequently impacting agriculture and GDP of a nation [6]. Furthermore, SOA, which are formed through chemical oxidation of NMHCs in the atmosphere particularly biogenic VOCs [7], can contribute to the deterioration of air quality and visibility. By understanding the sources and concentrations of NMHCs, researchers can gain better insights into how to control and reduce these pollutants vis a vis NOx levels. Beyond air quality concerns, NMHCs are also important in the context of climate change. Research on NMHCs helps to understand their atmospheric lifetimes, reactivity, and interactions with other pollutants, which in turn can enhance climate models and predictions. Many of these compounds are toxic and have been linked to a variety of health problems, including respiratory diseases, cardiovascular issues, and even cancer. For example, large amounts (~40 t) of methyl isocyanate leakage during the Bhopal Gas Tragedy (1984) led to thousands of deaths in a short span of time. This incident led to enactment of Environment (Protection) Act (1986) under Article 253 of the Indian Constitution, promulgating enhanced research on environment and air quality over India. Long-term exposure to elevated levels of NMHCs can lead to chronic health conditions, especially in urban areas with high levels of vehicular and industrial emissions. By studying the sources and concentrations of these compounds, researchers can identify the specific risks they pose to public health, particularly vulnerable populations such as children, the elderly, and individuals with pre-existing health conditions.

The purpose of this review article is to assess the characteristics, sources, and impacts of NMHCs in India and its evolution over time during the last three decades. India, with its rapidly growing urban centres, industrial clusters, and agricultural sector, presents a unique case for studying the behaviour of NMHCs in diverse environments and emission regimes. By investigating the distribution of these compounds, from highly industrialized cities like Delhi and Mumbai to more rural sites in Ajmer and Gadanki and remote areas like Nainital and Mount Abu (Mt. Abu), this study seeks to provide a comprehensive understanding of their spatio-temporal variations. As India has developed in the last three decades both economically as well with respect to industrial production, so has the funding increased to conduct air quality research in the country. In this context, the measurement systems for NMHC have evolved from simple canister collections to sophisticated online analysis. As such, there has been a treasure of data related to NMHC over time and it needed to be compiled to present a holistic insight into the evolving sources, concentrations, and environmental impacts of NMHCs in India. The review is an attempt to provide essential data to support the development of air quality management strategies, regulatory policies, and public health initiatives aimed at reducing the harmful effects of NMHCs.

Previous reviews have provided important insights into the role of non-methane hydrocarbons (NMHCs) and VOCs in atmospheric chemistry, source characteristics, and environmental impacts from both global and India-specific perspectives[8–10]. Existing studies have addressed aspects such as the contribution of NMHCs to ozone and secondary organic aerosol (SOA) formation, health risks, and regulatory gaps, often with a focus on selected compounds, specific regions, or limited time periods. However, a consolidated synthesis capturing the long-term evolution of NMHC measurements across diverse Indian environments, together with a systematic assessment of methodological advancements and ratio-based source apportionment, remains limited.

In this context, the present review provides a comprehensive and updated synthesis of atmospheric NMHC measurements in India, focusing on the evolution of measurement techniques and concentrations over the past three decades. It emphasizes the critical role of NMHCs in atmospheric chemistry, their contributions to O_3 and SOA formation, and their broader environmental and health impacts. The review focuses on the Indian subcontinent's unique geographical and meteorological conditions, such as the Indo-Gangetic Plain (IGP), which are characterized by high and heterogeneous emission patterns. This regional focus is particularly relevant given the interplay of urbanization, industrialization, and natural factors in shaping air quality across India. Starting from early measurement approaches such as gas chromatography–flame ionization detection (GC-FID) in the 1990s to advanced techniques including Proton Transfer Reaction–Time-of-Flight Mass Spectrometry (PTR-ToF-MS) in recent years, the review highlights how technological advancements have enabled more precise and comprehensive analyses of NMHCs. This historical perspective not only contextualizes the current state of NMHC research but also identifies limitations of earlier methods. The review further synthesizes the application of NMHC ratios as indicators for source apportionment, providing a granular framework for distinguishing emissions from natural, vehicular, industrial, and biomass-burning sources across urban, rural, and high-altitude regions of India. The analysis also underscores the importance of interactions between anthropogenic and biogenic emissions, particularly within diverse ecosystems such as the Western Ghats and the Himalayan region, and highlights the need for targeted mitigation strategies, including cleaner fuel transitions, improved emission standards, and enhanced public awareness.

Literature Search and Review Methodology

The present review is based on a comprehensive survey of peer-reviewed literature reporting atmospheric NMHC measurements over India. Relevant studies were identified using major bibliographic databases, including Google Scholar. Since Google Scholar offers thorough coverage of interdisciplinary atmospheric scientific literature, including regional journals and older works that might not be regularly indexed in subscription-based databases, it was chosen as the main resource. Both NMHC-specific research and more general VOC-related literature pertinent to atmospheric chemistry over India were included in the search criteria that were chosen. Search terms included combinations of "non-methane hydrocarbons", "NMHCs", "volatile organic compounds", "VOCs", "atmospheric NMHCs in India", and "ambient air NMHCs over India". Studies were included if they reported ambient atmospheric NMHCs conducted over Indian locations representing diverse topographical, meteorological, and urbanization regimes, including urban agglomerations, semi-urban regions, rural sites, coastal locations, and high-altitude/background environments. Only peer-reviewed observational studies employing established analytical techniques were considered. Studies not relevant to the Indian region, indoor studies, were also excluded. The review covers studies published from the mid-1990s to 2023, corresponding to the period during which NMHC measurements have been reported over India.

This review paper is organized as follows: first, the sources and sinks of NMHCs in the atmosphere (Section 2), including sources (Section 2.1): natural (Section 2.1.1) and human-made (Section 2.2.2) are discussed followed by removal processes (Section 2.2), their environmental impacts (Section 3.1) and their effects on human health (Section 3.2). Next, we review studies on NMHCs over the Indian region (Section 4) and examine how they have changed over the years [(Western India: Section 4.1), (Northern India and IGP: Section 4.2), (Eastern India: Section 4.3), (Central India: Section 4.4), (Southern India: Section 4.5)]. We also explore the sampling techniques for NMHCs (Section 5.1), measurement methods for NMHCs (Section 5.2) and how NMHC ratios can indicate their sources (Section 6). Finally, we conclude the study (Section 7) and suggest directions for future research (Section 7.1).

2. Sources and Sinks of NMHCs in the Atmosphere

2.1. Sources of NMHCs in the Atmosphere

NMHCs are released to the Earth's atmosphere through biogenic and human-induced sources. Gasoline, also known as petrol, for instance, is a mixture of aromatic hydrocarbons and alkanes, alkenes, and naphthenes. A plethora of hydrocarbons come from animal fats, plants (for example, pine oil, essential oils), and natural gas. Different activities producing different atmospheric NMHCs, categorised into anthropogenic and natural sources, are summarized in **Supplementary Materials Table S1**.

The HCs listed in **Table S1** are classified into anthropogenic and natural sources, with detailed information about their chemical formulae, activities, and associated references. This classification highlights the diverse origins and roles of HCs in the environment, emphasizing their significance in air pollution, industrial activities, and natural processes. The anthropogenic and natural sources in **Table S1** are further divided into major and minor contributors according to their contribution to total NMHC emissions. Transportation emissions, industrial processes including refineries and petrochemical sectors, and the burning of fossil fuels are the main anthropogenic sources. Fuel evaporation, solvent use, and combustion processes, including coal, are in general minor contributors. Industrial operations, fuel combustion, and solvent use are the main sources of pollutants like benzene, toluene, and xylene. Olefins like ethylene and propene are associated with the burning of biomass and the petrochemical industry. Ship emissions are a minor source of olefins like butene, hexene, and pentene, which are mostly released by fuel refineries and automobile exhaust. Methane combustion and vehicle emissions are the primary sources of ethylene and acetylene. Diesel combustion is the primary source of C_{11}–C_{14} aliphatic species.

Significant sources of VOCs include natural gas and the combustion of fuels, including petrol, diesel, wood, and trash. VOCs with high vapour pressure and poor water solubility include benzene, toluene, and formaldehyde. During storage and usage, a variety of industrial and domestic items, such as paints, varnishes, fuels, adhesives, and cleaning supplies, release VOCs, which can have both short-term and long-term negative health effects. VOC emissions comprise a range of chemicals such as chlorinated, oxygenated, nitrogenous, and aromatic hydrocarbons, as well as solvents like acetone and chloroform. They are also caused by tobacco smoke, cosmetics, and industrial processes. Isoprene and terpenes are created by plants during photosynthesis, while butane and benzene are predominantly created by the combustion of fossil fuels (including emissions from automobiles) and other industrial activities [11].

2.1.1. Natural Sources of NMHCs

Emissions from different plant species, soil microorganisms, and oceanic phytoplankton constitute natural sources of hydrocarbons. It can be anticipated that 900 to 1115 TgC of the biogenic VOCs (BVOCs) are released each year globally [12]. Isoprene, monoterpene, and sesquiterpenes are the most common biogenic NMHCs produced by vegetation. Oceanic emissions and microbial production are two additional sources of biogenic NMHCs. Approximately 160 Tg BVOCs released into the atmosphere annually are monoterpenes, which are generated from vegetation [12,13]. Emissions of myrcene make up between 2% and 10% of all biogenic monoterpene emissions [12]. Several studies [14–17] suggest that in rural and wooded settings, plant-released VOCs, especially monoterpenes and isoprene, can be more relevant than the human-induced VOCs, which are transported in by contaminated air masses from nearby industrial and urban regions [12]. Isoprene is mostly emitted by deciduous trees; hence, across wooded areas, isoprene mixing ratios can reach several ppbv [18,19]. Coniferous species, including Abies alba, oak trees, and deciduous trees, are the main sources of isoprene. Its emission is also influenced by heterotrophic bacteria and soil microbes [20], phytoplankton from the ocean [21], and aquatic plants [22]. *Quercus ilex*, *Pinus pinea*, and other coniferous trees, as well as the emissions from leaves and soil in red pine forests, are the main sources of monoterpenes. *Abies alba, Pinus roxburghii, Pinus wallichiana, Cedrus deodara,* and *Cupressus torulosa* are the primary producers of several monoterpenes, like α-pinene. Deciduous trees, cannabis, and biomass burning are minor sources.

Other prominent monoterpenes, which can be found in oak and pine trees as well as herbs like parsley and rosemary, are β-pinene, sabinene, myrcene, β-phellandrene, limonene, camphene, and terpinene. Furthermore, *Peucedanum cervaria* and *Rosmarinus officinalis* are the major emitters of cineole. Apart from monoterpenes, methane oxidation is the main source of formaldehyde, with biogenic emissions contributing next. *Peucedanum cervaria* emits sesquiterpenes, including β-caryophyllene, α-humulene, germacrene D, and germacrene B. Broad-leaf trees and coniferous plants produce a considerable amount of terpenes, semi-terpenes, sesquiterpenes, and diterpenes, which are important components of atmospheric chemistry. It has already been established that isoprene emission peaks at the maximum intensity of light in saturated photosynthesis, rises with temperature up to a certain point, and then rapidly falls. Isoprene emissions peaked during the wet season and were at their lowest throughout the wintertime. α-pinene appears to emit at a rate that is independent of light and rises exponentially with temperature [23]. In order to account for all emission levels, *Nerium indicum* and *Bougainvilea spectabilis* have been offered as barriers, while *Alstonia scholaris, Acacia Arabica, Azadirachta indica*, as well as 7 additional species were considered for planting as trees [23]. Higher molecular weight hydrocarbon species are more reactive in the O_3-producing process [8].

Spring and summer are peak times for BVOC emissions because of increased solar insolation, warmer temperatures, increased foliar density and leaf area index. Peak O_3 episodes occur in rural regions throughout the summer because of this feature and the high reactivity of BVOCs [24–26]. Major NMHC species contributing to biogenic emissions in the atmosphere include isoprene and α-pinene [27]. Among biogenic sources, plants are the primary emitters of isoprene, monoterpene, and sesquiterpene [2,28]. Atkinson [29] claims that, globally, BVOCs from biological sources are over 10 times larger than those from human activity. The main natural sources of atmospheric NMHCs have also been discussed in **Table S1**. Air quality, climate control, and biological interactions are all impacted by these biogenic HCs, which are also crucial to the creation of atmospheric aerosols and contribute significantly to OH reactivity [7].

2.1.2. Anthropogenic Sources of NMHCs

NMHC measurements in large cities represent a broad spectrum of anthropogenic emissions from diverse activities in varied geographic regions [23]. NMHCs are major pollutants in urban areas, typically well characterised with origin from vehicle exhaust emissions, fuel vaporization, solvent usage, industrial operations, LPG gas leaks, and natural gas emissions [30–32], their relative relevance can vary by region [32,33]. In cities, the development of tall structures that obstruct airflow, traffic jams, high levels of mobility, and the existence of industrial hubs lead to accumulation of VOCs [23]. The main anthropogenic sources of atmospheric NMHCs have also been listed in **Table S1**.

The nature of the fuel and its combustion stages influence the different types of emissions. The combustion process, particularly partial combustion from diesel and petrol engines, biomass burning, and coal combustion for heating and cooking, releases NMHCs. Factors such as automobile age/type, speed, fuel type, and the flow rate affect NMHC levels in the atmosphere [34]. Approximately, 17 to 27 TgC/year of NMHC emissions are emitted into the environment as a result of solvent use in industries and consumer products such coatings, paints, adhesives, and varnishes[8,35]. Mobile sources emit a variety of NMHCs such as ethylene, i-pentane, ethane, acetylene, propane, 1,3-butadiene, i-butane, pentane, propylene, n-hexane, cis-2-pentene, benzene, and toluene[8,35,36]. Less than one percent of NMHCs[8] are thought to enter the environment as a consequence of landfilling. Additionally, VOCs, including oxygenated molecules like formaldehyde and esters, are released into the atmosphere[37], adding to NMHC burden and OH production[38]. Acetylene is frequently produced during combustion, while several human and natural processes emit ethylene. Ethane was the second predominant organic trace gas in the troposphere and primarily released during the extraction, processing, and use of fossil fuels, as well as from biofuels, biomass burning, and paddy fields that use organic fertilizers[39,40]. HCHO is created both naturally by people, animals, and plants[41,42], and artificially through combustion processes, industries, building materials, and consumer items[43]. Oxidation of VOCs is a significant contributor to HCHO, with methane producing up to 60% in isolated areas[38,44–47]. Apart from outdoor atmosphere, household chemicals, solvents, essential oils, and insecticides can add to hydrocarbons from indoor activities[48–51]. As a solvent base, HCs are also used in several toxic chemicals, including metallurgy, pesticides, and carburettor cleanser (methanol). Different poisoning syndromes can be caused by each of these substances[1].

2.2. Sinks of VOCs

VOCs are naturally oxidised by atmospheric oxidants like O_3, nitrogen oxides, halogens, and predominantly OH radicals, which also initiates their removal from the atmosphere or transformation into other forms like SOAs. By and large, oxidative degradation of VOCs in the atmosphere constitutes their largest natural, chemical sink. Adsorption, absorption, thermal oxidation, catalytic combustion, and other measures are employed to reduce the emission of VOCs[52,53]. Among all available techniques, catalytic combustion has been found to be the most effective at removing VOCs due to its low power requirements, ability to prevent the production of NOx, and high efficiency[54].

Li et al. explored soil's role as a sink for atmospheric VOCs, showing that most VOCs undergo net deposition on sterilized soil through physicochemical processes like surface interactions and heterogeneous oxidation. Soil and soil-derived dust can act as a VOC sink under certain conditions, but the sink strength varies based on environmental factors and molecular properties. Additionally, the emission of formic acid also implies that some VOCs can be converted and released back into the atmosphere. Therefore, depending on the particular VOC and how it interacts with soil surfaces, soil can function as both a source and a sink[55].

A study by Hodzic et al. in 2013 examined how dry deposition functions as a VOC sink and how it affects the development of SOA in the Mexico City plume. Less than 5% of SOA is removed within the Mexico city's boundary layer and roughly 15% downwind by dry deposition, making it an ineffective sink. It competes with gas-particle partitioning, which reduces the deposition of longer-chain species by partitioning them into SOA, while only VOCs with $< C_{12}$ are efficiently eliminated[56].

Grøntoft et al. in 2014 identified key sink processes for removing VOCs from museum environments. Surface deposition on materials like glass and canvas helps reduce airborne VOC concentrations, with acetic acid showing strong adsorption. Activated carbon cloths effectively scavenge volatile organic acids, making them useful for maintaining low pollution levels. The efficiency of VOC elimination depends on how well surface deposition, regulated ventilation, and absorbent material utilisation are balanced. Therefore, maintaining ideal ventilation and replacing activated carbon filters on a regular basis are important aspects of enclosure management in museums[57].

3. Impact of NMHC on the Environment and Human Health

3.1. Impact of NMHC on the Environment

Photochemical haze, acid deposition, and greenhouse gases all result from chemical reactions in the atmosphere, and NMHCs play an important part in these processes[58]. In the presence of sunlight, the NMVOCs combine with the nitrogen oxides to form a hazardous ground-level O_3 and smog layer, which has negative impacts on the human health (especially the eyes, lungs, and skin problems), the environment, and plants. The effect of NMHCs on the climate may comprehensively be characterized through their ability to support oxidation and degradation of chemical products in the atmosphere.

BVOCs, as well as many species of anthropogenic VOCs (AVOCs), also have the additional function of producing 2^{nd}-generation particulates in the atmosphere, which in turn alter the radiative balance of the planet. Many types of plants contribute to acid rain by emitting VOCs, especially the terpenes. Highly reactive isoprene in the atmosphere has a high photochemical O_3 production potential value. Slum inhabitants in Indian cities burn biomass for heat during the winter, including wood waste along with other organic waste, which further contributes to the atmosphere's load of VOCs[59]. In contrast, metropolitan cities like Delhi have higher mixing heights during the summer, as well as an unstable environment and the potential for numerous *andhi* (locally known as sandstorm) events, which can dilute strong emissions[60].

Atmospheric total nonmethane hydrocarbons (TNMHCs) are an index for showing the combined load of measured NMHCs in an atmosphere and have a direct relevance global warming because they participate in O_3 photochemistry and lead to the generation of organic aerosols[61]. Formation of both SOA and tropospheric O_3 are influenced by TNMHCs, making them an important class of VOCs[62–64]. Due to their high reactivity with atmospheric oxidants such as hydroxyl radicals (OH) and O_3, TNMHCs act as crucial precursors for photochemical smog through PAN. Several model studies[65,66] have shown that changes in anthropogenic emission levels of NMHCs, NOx, and CO have a significant impact on surface-level concentrations of O_3, especially peak values, in semi-rural and rural regions. Despite their critical role in atmospheric chemistry, research on NMHC interactions in the tropical regions remains limited. According to Saito et al.[67], the ratio of organic molecules such as NMHC and NOx shows how VOCs affect the site's ability to produce O_3.

In addition, the atmospheric impact of NMHCs is strongly governed by their OH reactivity and ozone formation potential (OFP). Although NMHCs are primarily removed from the atmosphere through oxidation by OH radicals, their influence on atmospheric chemistry depends critically on their chemical composition and reactivity. Across India, regional differences in NMHC mixtures lead to distinct photochemical regimes and ozone formation efficiencies. The IGP and other densely populated northern regions are characterized by high abundances of reactive alkenes, aromatics, and oxygenated VOCs, resulting in enhanced OH reactivity and elevated OFP, often operating under VOC-sensitive or transitional O_3 production regimes. In contrast, background, coastal, forested, and high-altitude regions exhibit differing NMHC profiles, including higher contributions from alkanes or biogenic VOCs, which tend to show lower overall OH reactivity but greater sensitivity to meteorological conditions and regional transport. These compositional differences also influence secondary organic aerosol formation efficiencies, directly linking speciated NMHC measurements to regional air-quality impacts, oxidative capacity, and climate-relevant atmospheric processes over India.

3.2. Impacts of the NMHC on Human Health

Several NMVOC species are hazardous compounds that can directly harm human health[68]. Some VOCs, such as terpenes emitted from plants, are naturally occurring and harmless, whereas others, like those released from forest fires, can contribute to air pollution and have significant environmental and health impacts. Short-term exposure can cause headaches and nausea, while long-term exposure may lead to respiratory issues and lung function decline[69].

VOCs comprise a diverse spectrum of chemicals, some of which may have both immediate and long-lasting harmful health effects. Several VOC concentrations were found continuously greater in indoors (up to a tenfold higher) than outdoor environments, as they emit from a wide range of household and industrial products, including paints, pharmaceuticals, refrigerants, cleaning agents, construction materials, adhesives, and office equipment. Additionally, certain VOCs, such as halocarbons and perfluorinated compounds, act as potent greenhouse gases, contributing to climate change and environmental degradation.

The central nervous system and other organs may be harmed as a result of breathing in VOCs, which may also irritate the eyes, nose, and throat and produce breathing problems and nausea. Cancer may be brought on by certain carcinogenic VOCs like benzene, formaldehyde, vinyl chloride, 1,3-butadiene, trichloroethylene, perchloroethylene, etc.[70]. Perchloroethylene (or tetrachloroethylene, used in dry cleaning) is a strong substance of VOCs, as are benzene, formaldehyde, toluene, styrene, xylene, and tetrachloroethylene. There have been reports of skin irritation, eye irritation, sensitization, consequences for the central nervous system, carcinogenicity, and effects to the liver and kidneys in both people and experimental animals [70]. Based on the findings of these researches, regulatory authorities determine the maximum allowable concentrations of each VOC for human exposure.

Humans may be exposed to NMHCs by a number of routes, including ingestion, inhalation, and dermal absorption [71], with ingestion and inhalation being the most common. Numerous studies have established the negative consequences of breathing HCs on human health since it is such a prevalent route of exposure. Prolonged exposure to extremely low concentrations of the aromatic NMHCs like as benzene, is associated with an elevated risk of leukaemia [72]. Aliphatic hydrocarbon exposure, like propane and butane, has been linked to several deaths, according to several studies [73].

Exposure to xylene can lead to inflammation of the nose, eyes, and throat, breathing difficulties, lung function damage, and nervous system damage; benzene can cause acute and chronic nonlymphocytic leukaemia, prolonged lymphocytic leukaemia, anaemia, and other blood disorders [74,75]. Benzene and 1,3-butadiene are also very dangerous and carcinogenic to humans [75,76]. Hexane, propylene, and ethylene are other NMHCs whose negative effects on human health have been documented [77]. Some NMHCs, like aromatic species, are carcinogenic on their own, and they play an important role in the formation of PM and O_3 [78].

Toxicity and carcinogenicity: Benzene and polynuclear hydrocarbons with more than two benzene rings fused together are toxic and thought to have the ability to cause cancer. The Environmental Protection Agency, of the United States (US-EPA) has recognized 188 hazardous air pollutants (HAPs), many of which are VOCs. HAPs [23] refer to carcinogenic pollutants and other substances with proven or strongly suspected adverse health and environmental consequences. Although HCs are found naturally, their conversion into energy sources through non-natural processes poses a threat to humans [23].

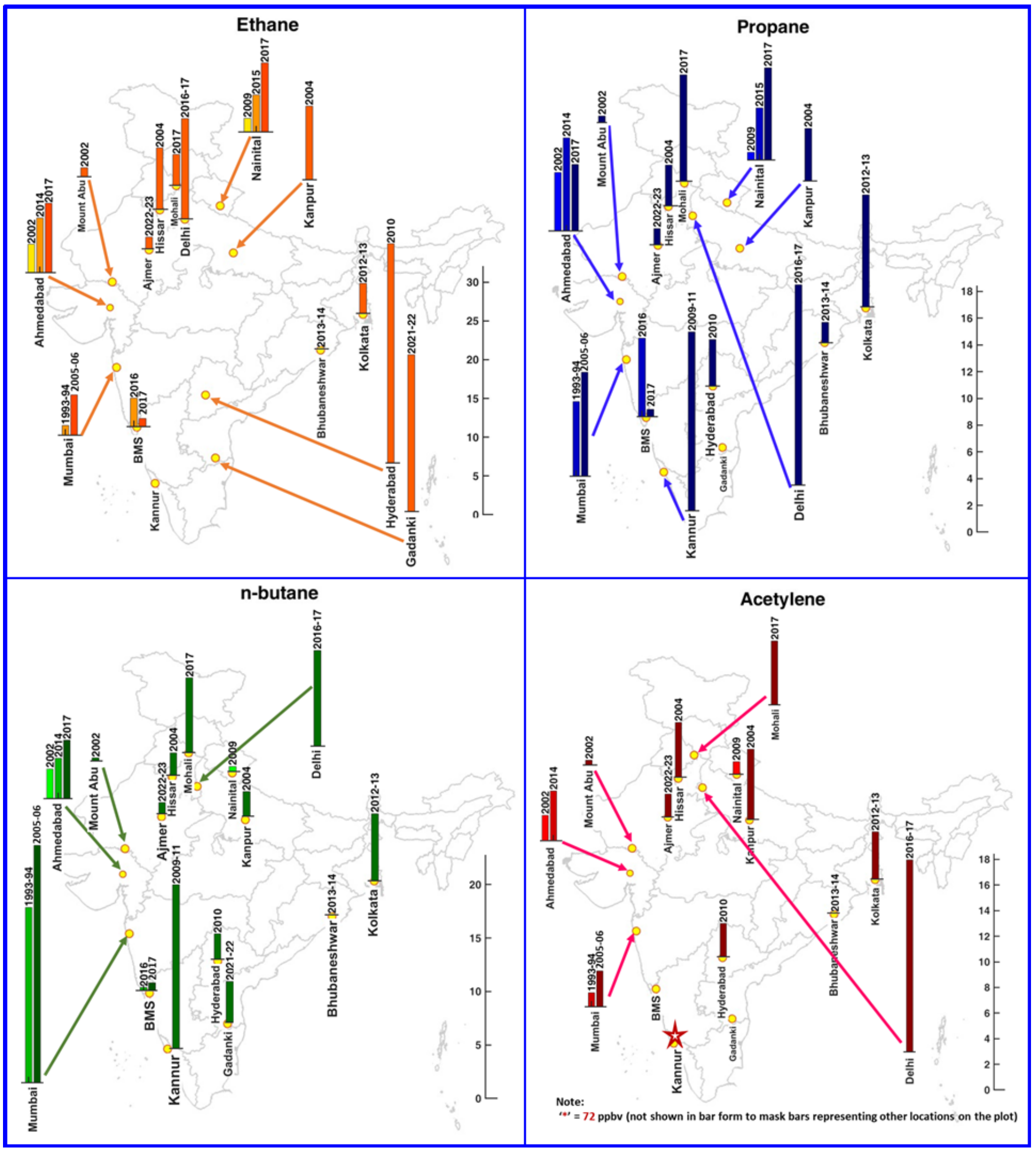
4. Study of Non-Methane Hydrocarbons Established over Indian Region

India is the seventh-largest country in the world area-wise, covering a geographical area of 3,287,263 km^2, with 90.44% land and 9.56% water. India's varied topography and diverse geographical features, such as the towering Himalayan mountains in the north, the Thar Desert in the west, the Indo-Gangetic Plains stretching from north to north-east, the Western ghats in the west coast and the peninsular region surrounded by the Arabian Sea and the Bay of Bengal provide routes and barriers to the transport of pollutants, heat and moisture. This leads to varied meteorological conditions across different regions, which, in turn, influence air quality [23,79].

The climate in India is largely characterized by three distinct seasons: winter, summer, and the monsoon. During winter (December to February), cooler temperatures and stable atmospheric conditions cause pollutants to accumulate, especially in urban areas, creating issues like smog and haze. In contrast, the summer season (March to June) is marked by higher temperatures, which allows pollutants to disperse more easily. The monsoon season (July to September) brings heavy rains, which help cleanse the air both due to an increase in oxidants as well as washout to reduce pollution levels temporarily.

A number of key cities and regions across India representing various topographical and meteorological conditions, as well as potential urban agglomerations, have been studied to provide insight into the diversity of air quality across multiple environmental regimes [80,81]. In contrast to polluted cities like Delhi and Kanpur, high-altitude sites like Nainital and Mount Abu (Mt. Abu), represent a cleaner environment providing an ideal location for studying background atmospheric conditions, and sometimes free tropospheric conditions [82]. In more rural or less-industrialized areas, such as Kannur, Hissar (North India), Gadanki (South India) and Ajmer (West India), air quality is typically better, as these regions are less affected by the extensive pollution seen in urban centres and provide important comparisons for studying the natural background levels of air pollutants as well as secondary pollution [16,33].

Studies conducted in India on the monitoring and source identification of NMHCs date back to the middle of 1990s. **Figure 1** presents a contextual analysis of the spatial and temporal distribution of NMHCs across India, including ethane, propane, n-butane, and acetylene [18,34,61,83–87] by incorporating the years of observation and historical data [88–92]. In India, for ethane, the highest and lowest mixing ratios are observed over Hyderabad and Bhubaneswar, respectively, two urban regions separated by 1000 km in eastern-central India, one representing industrial emissions, another representing traditional culture. High altitude sites like Nainital show moderate ethane rather than the lowest due to the effects of transported biomass burning plumes.



Note:
'*' = 72 ppbv (not shown in bar form to mask bars representing other locations on the plot)

Figure 1. Geographical distribution of selected non-methane hydrocarbons at different locations over India for the different observational periods.

Note: '*' = 72 ppbv (not shown in bar form to mask bars representing other locations on the plot).

In **Figure 1**, yellow circles represent the location in uniform symbol size, not representative of concentration. Vertical bars represent the reported mixing ratios (ppbv) of individual NMHC species at each location, with the corresponding year(s) of observation indicated adjacent to the bars. Separate panels show distributions for ethane, propane, n-butane, and acetylene. For acetylene, the exceptionally high concentration observed at Kannur (72 ppbv) is indicated by a star symbol and is not shown as a bar in order to avoid scale distortion and masking of bars at other locations.

Source: All data are compiled from published studies cited in References[18,34,61,83–87]. Additional datasets are taken from related published literature[88–92].

Multi-year measurements, such as in Kanpur, highlight historical emission trends, with increasing concentrations also seen in cities like Mumbai, underscoring the role of urbanization in driving emissions. In the case of propane, Delhi exhibits the highest levels, particularly in 2016–2017, due to emissions from LPG use, vehicular traffic, and industrial activities. In contrast, Mt. Abu shows the lowest concentrations, consistent with its remote location and minimal anthropogenic influence. Historical data, such as of Ahmedabad in 2002, reveal consistent spatio-temporal heterogeneity. For n-butane, the highest concentration is recorded in Mumbai during the 1993–1994 and 2005–2006, attributed to vehicular exhaust and industrial emissions. Bhubaneswar, with its lower urban density, reports the minimum levels. Ahmedabad shows rising concentrations, reflecting the growing impact of petrochemicals. Acetylene concentrations, with exceptionally high values of 72 ppbv observed over Kannur in 2010, are attributed to local biomass or waste burning. Mt. Abu exhibits the lowest levels, again reflecting its clean and remote environment.

Historical datasets from cities like Mumbai highlight early pollution hotspots, which continued to remain significant in more recent years. Overall, the spatial patterns reveal urban and industrial hotspots like Mumbai, Delhi, Hyderabad and Kanpur, where high NMHC concentrations are observed consistently across multiple years. In contrast, less industrialized locations like Bhubaneswar and background locations like Mt. Abu and exhibit relatively low concentrations, serving as baselines for comparison. The temporal trends indicate rising levels of NMHCs in urban sites over the years, driven by increased industrialization, vehicular emissions, and biomass burning. However, data gaps for some locations (e.g., ethane for Kannur, propane and acetylene for Gadanki) highlight the need for a planned and consistent monitoring to better understand regional variations and trends. The analysis emphasizes the diverse emission sources requiring region-specific mitigation strategies.

To present a further simplified picture, we categorise the NMHCs measurements over India first by region (Western India, Northern India, and IGP, Eastern India, Central India, and Southern India) and then by time to get a holistic view of the NMHCs in terms of concentration measurement over the Indian region.

The relative concentration levels are derived from spatial distributions and annual variations reported in the reviewed studies, as shown in **Table 1**. Dominant NMHCs represent compounds consistently reported at higher relative abundance within each region type. Emission characteristics are indicative and based on a synthesis of the literature.

Table 1. Comparative summary of NMHC characteristics over different type of regions in India.

Region Type (Urban/Rural)	Representative Locations	Dominant NMHCs	Relative Concentration Levels	Major Sources	Key References
Large Urban agglomerates	Delhi (IGP), Mumbai (West), Kolkata (East), Hyderabad (Central)	Ethane, propane, benzene, toluene, n-butane, Acetylene	High (frequent elevated annual means and peaks)	Strong influence of vehicular emissions, biomass burning, LPG usage, & solvent evaporation	Pandit et al. [34] Jain et al. [86] Kumar et al. [87] Dhara and Dutta [93]
Cities/metropolis and Towns (Urban)	Ahmedabad (West), Kanpur (IGP), Lucknow (IGP), Hissar (IGP)	Propane, n-butane, acetylene	Moderate–high	Mixed vehicular, residential, and industrial emissions	Sahu et al. [83] Lal et al. [84,85] Sahu and Lal [94]
Coastal cities	Kannur (South), Bhubaneswar (East)	Ethane, propane	Low–moderate	Marine influence with regional background and local urban contributions	Nishanth et al. and Panda et al. [61,90]
Semi-urban/industrial	Mohali (North)	Ethane, Propane, n-butane	Moderate	Combination of industrial activities, regional transport, and local emissions	Kumar et al. [87]
Rural/Peri-urban	Ajmer (West)	Ethane, propane	Low-moderate	Regional transport with limited local anthropogenic influence	–
Rural	Gadanki (South)	Ethane, propane	Low	Background atmospheric composition with minimal local sources	Sindhu et al. [91]
Background/High altitude	Nainital (North), Mount Abu (West), BMS (Western Ghat)	Ethane, propane	Low (relatively stable)	Long-range transport and background sources	Sarangi et al. and Ajayakumar et al. [88,92]

4.1. Study of NMHCs Established over Western India

The first study of C_2–C_5 NMHCs over the Indian subcontinent was done by Lal et al. in the city of Ahmedabad [95]. With over 2 million registered motor vehicles growing at 10% annually, Ahmedabad is divided into residential areas in the west and industrial zones in the east. It experiences a hot, semi-arid climate with around 750 mm of rainfall during the monsoon (June–August). May is the hottest month, with average temperatures of ~41.5 °C. Winds are typically stronger and westerly in both pre-monsoon and monsoon, with a reversal to northeasterly winds in late September and October. Major industries, including textiles, dyeing, and casting, are located in the eastern part of the city.

Sahu and Lal attributed large seasonal and diurnal fluctuations in C_2–C_5 NMHCs, prominently during the winter, to the changes in the air mass transport patterns, the convective boundary layer's height, and the concentration levels of OH radicals [94]. Ethane, along with propane, was linked to both leakage of natural gas and pollutants from the emissions of LPG. Compared to burning biomass and biofuel, vehicle exhaust has a major influence on CO, propene, ethane, and acetylene. In order to demonstrate site-to-site variation and identify regional sources of these chemicals, Sahu et al. monitored atmospheric concentrations of toluene and benzene between March and May 2015 at multiple urban sites in the Indian city of Ahmedabad [96]. They found significant site-to-site variations, with toluene levels constantly higher than benzene levels; inner road concentrations were significantly greater compared to outer road concentrations. Eastern Ahmedabad sites (industrial) had higher levels of pollutants than the western residential region. Greater toluene/benzene ratios in the east, particularly close to industrial parks, suggested non-traffic pollution origins' contribution (e.g., landfill, industry, etc.). Overall, the study brought attention to the significant spatio-temporal variation of aromatic VOCs in urban environments. Due to the "weekend effect," VOC concentrations were much lower on Sundays and higher on Saturdays as compared to weekdays. Although both VOCs were mostly released via vehicle exhaust, greater toluene/benzene ratios suggested that industrial, along with non-vehicular sources, indicated the effects of photochemical ageing. Daytime data showed decreased VOC concentrations and a toluene/benzene ratio roughly equal to 2.

Sahu et al. observed that VOC levels were lower under stronger breezes, indicating a ventilation effect [97]. Significant correlations between VOC night-time mixing ratios and benzene were discovered, indicating significant seasonality and non-anthropogenic source contributions.

Methanol and toluene were found to be the most prevalent OVOCs and primary VOCs, respectively, in Ahmedabad during winter of 2014 [83]. The toluene/benzene ratio was found to be higher during the transport from the IGP than that from the Thar Desert, and the isoprene/benzene ratio was found to be higher in the IGP region than in the Thar Desert. The concentration of aromatic VOCs followed the volume of traffic, but the proportions of isoprene to benzene and acetaldehyde to benzene fluctuated with the weather, pointing to biological and photochemical influences. During periods of high traffic, such as marathon and cyclothon events, high VOC concentrations have been recorded. Contrary to norms, the isoprene/benzene ratio reflected that human activity was responsible for large isoprene emissions. Acetaldehyde, acetone, and isoprene anthropogenic contributions exhibited considerable diurnal dependence, with greater values at night and in the early morning. Peaks in diurnal VOC trends were observed during rush hours, while afternoon levels were lowest Sahu and Saxena [98]. A high percentage of organic VOCs (OVOCs) (70–80%) was observed, with the predominant VOC being methanol.

The VOC composition and emission ratios of the Pirana landfill at Ahmedabad were investigated [99]. Within 800 m of the landfill, greater NMVOC concentrations were found, with residential areas as the main receptors. Alkane and aromatic chemicals were the principal contributors to NMVOC relative abundances, which did not show a considerable change with distance. Greater amounts of biogenic emissions came from nearby sites. About 75% of the overall propylene-equivalent concentration was comprised of m + p-xylenes, trans-2-butene, propylene/ethylene, and cis-2-butene. The propylene-equivalent concentration, a metric used to evaluate the contributions of different NMVOCs to O_3 formation, highlights the need to address both NOx levels and the Ozone Forming Potential (OFP) of VOCs for effective O_3 control. Propylene-equivalent concentration is a metric used to compare the ozone-forming potential of different NMVOCs. Since various NMVOCs have different reactivities in atmospheric chemistry, this method standardizes their contributions by expressing them relative to propylene (C_3H_6), which is commonly used as a reference compound.

The propylene-equivalent concentration of a given VOC is calculated using the formula:

$$Propylene - EquivalentConcentration$$
$$= \sum \left(VOCconcentration \times \frac{OHreactionratecoefficientofVOC}{OHreactionratecoefficientofpropylene} \right)$$

where:

- The *OH reaction rate coefficient* represents how fast the VOC reacts with hydroxyl radicals (OH) in the atmosphere.
- Propylene is used as the benchmark because it has a well-known reaction rate with OH radicals.

In February 2004, Lal et al.[95] studied the concentrations of O_3, methane, CO, and light NMHCs in the atmosphere at 8 rural sites in the country's central region. They found significant growth rates in O_3 forenoon concentrations (91–143 ppbv), while NMHCs and CO were of lower concentration than in Ahmedabad but slightly higher than nearby Indian maritime regions. The elevated O_3 levels at midday raise concerns for human health and agricultural productivity, exceeding specified criteria and potentially harming crops.

Mt. Abu's Guru Shikhar (24.6°N, 72.7°E, 1680 m) is a remote, high-altitude site in the Aravalli range in Western India, providing clean background air due to minimal human activity. It is 200 km from Ahmedabad and 250 km from the Arabian Sea. The site experiences marine air masses during the summer monsoon (May–September) and continental air masses in winter and spring, with a transitional mix during September–October. These unique meteorological conditions make it ideal for studying seasonal air mass dynamics and background atmospheric composition. Sahu and Lal observed that long-lived species at Mount Abu exhibited seasonal variations that were driven by wind patterns and OH radical reactivity[100]. Mt. Abu exhibited 3–9 times lower annual mean C_2–C_4 NMHC mixing ratios than Ahmedabad. The yearly mean mixing ratios for the NMHC species were as follows: ethane (1.22 ± 0.58), propane (0.46 ± 0.20), ethene (0.34 ± 0.24), propene (0.17 ± 0.14), acetylene (0.41 ± 0.43), and i-butane (0.21 ± 0.18). At Mt. Abu, ethane predominated (39%) while propane predominated in Ahmedabad (23.5%). The main source of propylene equivalent concentrations was alkenes. Nitrogen oxides were crucial precursors in the photochemical production of O_3.

The historical Udaipur city (24.58°N, 73.68°E, 598 m ASL) in western India, surrounded by Aravalli hills, forests, and lakes, serves as an important air quality monitoring site. The site is influenced by local emissions from traffic, residential activities, industrial estates (7–8 km away), agricultural residue burning, municipal waste treatment, and biofuel usage. Seasonal air mass transport from the Indo-Gangetic Plain, Thar Desert, and Arabian Sea further affects the region. The pre-monsoon season shows high planetary boundary layer heights (PBL-H) due to strong surface heating, while winter shows low PBL-H due to temperature inversions. Wind patterns vary seasonally, with NE winds in winter, SW winds during the monsoon, and NW winds post-monsoon. In Udaipur city in India, Yadav et al. described diurnal and seasonal variations of NMVOCs and trace gases throughout 2015[101]. The study found the main sources of emissions, with industry producing the most NMVOCs (about 40%), followed by vehicle emissions at around 19%, with vehicle exhaust predominating the geographic distribution of combustion products. Seasonal trends, driven by regional meteorology, emission trends, far-reaching transport, OH reactivity, as well as planetary boundary layer height, revealed greater levels throughout the wintertime to pre-monsoon but lower values for the monsoon season.

Mumbai, located on India's west coast at 47°N, 73°E, has a tropical savanna climate. Mumbai receives about 2078 mm of rainfall annually, with 34% of the total rainfall occurring in July. Mumbai is a hub for trade, commerce, and industry, hosting various industries such as thermal power plants, fertilizer plants, oil refineries, and chemical units. The increased use of personal and commercial vehicles, including two-wheelers and three-wheelers, strains the city's road network. Major emission sources in Mumbai include diesel and gasoline vehicles, natural gas combustion engines, fuel evaporation from vehicles, surface coatings, petrochemical industries, dry cleaning processes, printing presses, and LPG usage in homes and hotels. Rao et al. found that C_2–C_5 HCs were being emitted into the atmosphere from the exhaust of petroleum-powered vehicles in the Deonar neighbourhood of Bombay from March 1993 to May 1994[102]. They evaluated that isobutane accounted for just 1.2% of the total C_2 to C_5, whereas automobile exhaust accounted for 10%. While C_2 to C_5 hydrocarbons are significantly more prevalent in refineries, C_6 to C_{10} hydrocarbon concentrations were higher than those for C_2 to C_5 at industrial sites[102].

Srivastava et al.[103] investigated diverse emission regimes (residential, commercial, industrial, traffic intersection, and gas stations) in Mumbai (2005) and attributed emissions from mobile and maritime sources to significantly high levels of VOCs found there. VOCs from mobile sources, including benzene, toluene, xylenes, naphthalene, and ethylbenzene, were widely diffused in the urban environment of Mumbai. Chlorinated VOCs, including methylene chloride, carbon tetrachloride, and chloroform, were discovered to be uniformly distributed among emissions that can be attributed to maritime origins.

Pandit et al. employed the technique of principal component analysis (PCA) to determine the origins of NMHCs in the air over Mumbai city from February 2005 to January 2006, and determined 17 different light NMHCs and found that their concentration levels were greater in wintertime and lower in summertime[34]. Using factor analysis, they identified five possible contributors to NMHC emissions: polymer manufacturing industries (8%), paint solvent (11%), petrochemical industries (15%), refinery operation (21%), vehicular emission (33%), and unknown (12%).

On a broader perspective, NMHC measurements across western India reveal a clear contrast between highly urbanized and industrialized environments and regional background sites. Urban regions such as Ahmedabad and Mumbai consistently exhibit elevated NMHC levels driven by vehicular emissions, industrial activities, fuel evaporation, and landfill sources, with aromatic compounds and alkenes contributing significantly to OFP. In contrast, high-altitude and semi-rural locations such as Mt. Abu display substantially lower NMHC concentrations, reflecting minimal local emissions and a stronger influence of regional transport and atmospheric processing. Seasonal variability across the region is strongly modulated by meteorological factors, particularly boundary-layer dynamics and wind patterns, leading to enhanced concentrations during winter and pre-monsoon periods and lower levels during the monsoon season. While western India is relatively well studied in urban settings, long-term continuous measurements and improved spatial coverage over semi-arid and rural regions remain limited.

4.2. Study of NMHCs Established over Northern India and Indo-Gangetic Plain Regions of India

Hissar is a semi-urban, primarily agriculture-based industrial town located about 160 km northwest of Delhi, with a population of around 1.2 million. Lal et al. compared light HCs at Hissar to those from Ahmedabad[84]. Observations showed that measurements at Hissar were not significantly influenced by emissions from major roads or industrial zones but exhibited higher O_3 concentrations. The CO/NOx slope was comparable to rural Chinese sites; both China and India have higher CO emissions than NOx emissions, which could propel surface O_3 concentrations in the future. The data at Hissar were impacted by emissions from neighboring biomass burning sources, offering crucial information for budget forecasts and model validation. Although the total NMHCs were highest in Ahmedabad and lowest in Hissar, the total amount of propylene-equivalent was largest in Hissar and smallest in Ahmedabad.

Light NMHCs (C_2 to C_5) were measured by Lal et al. in the year 2004 at the Indian Institute of Technology (IIT) campus in the northern part of Kanpur, a major industrial city in Uttar Pradesh with a population of around 3.1 million[85]. A power plant is situated to the southwest, while industries related to textiles, leather, metals, and chemicals are located about 10–15 km to the south and southeast. Both the measurement site and the industrial areas were upwind from the main city centre. Photochemistry of O_3 was estimated through its propylene equivalents. Based on correlations across several species, combustion of biomass, biofuels, and fossil fuels was found to be the main source of NMHC emissions in the region. Propene as well as ethene were responsible for between 72% and 77% of the light NMHCs found in Hissar and Kanpur, in contrast to only 47% at Ahmedabad in Western India.

New Delhi, India's capital and one of the largest megacities globally, faces pollution from traffic, industries, power plants, and biomass burning. Emissions from diesel engines account for 26–54% of VOCs. However, benzene is reported to be comparably less in Delhi, demonstrating the growing influence of petroleum as well as the switch to CNG

(Compressed Natural Gas)[104]. Padhy and Varshney found that the urban environment of Delhi has very high levels of TNMVOC, with concentrations ranging from 1.3 to 32.5 ppmv[59]. leading to elevated ground-level O_3 concentrations. A study by Stewart et al. during pre-monsoon as well as the post-monsoon of 2018 evaluated the prevalent NMVOCs and found that petrol and diesel were the main emitters[105]. Following the monsoon, local emissions and stable meteorological conditions contributed to extremely high night-time NMVOC levels. An emission inventory from 1993 to 2016 was also developed as part of the study, and it showed that burning cow dung significantly increased residential NMVOC emissions.

Stewart et al. found that after the monsoons, NMHC concentrations were highest at night[106]. With the exception of isoprene, all NMHCs had strong diurnal patterns and extremely high mixing ratios from 35 to 1485 ppbv. Reactive monoterpene concentrations were also found to be high at night.

In Delhi, Wang et al. simultaneously measured VOCs at urban (Indian Institute of Technology, Delhi (IITD)) and suburban (Manav Rachna International University, Haryana) sites. At each location, they found a six-factor PMF solution (2 traffic, 2 solid fuel combustion, as well as 2 secondary factors); human-induced factors were significant contributors, with traffic dominating the emissions, followed by secondary formation[81]. The analysis of naturally occurring indicators revealed that the effects of biogenic emissions were quite minimal. Very high VOC concentrations were found with anthropogenic VOCs predominating at night and secondary VOCs present during the day. At IITD, pollutants from traffic were the predominant source of NMHCs, with burning solid fuel combustions making an impact at night. The main secondary sources of oxygenated VOCs during the day were VOC transformations in the troposphere. Aromatic compounds were dominant, indicating both primary emission and secondary VOC generation.

The emission factors (EFs) for 23 NMVOC species were compared from household fuel combustion cycles in Delhi[107]. EFs of NMVOCs throughout the combustion stage were 88% greater than the complete combustion cycle for fuel wood and crop residue, but only 33% greater for animal dung cake and 73% higher than coal[107]. Ethane, propene, propane, 1-butene, and 1-pentene were most abundantly produced by *Azadirachta indica* during the burning phases (Flaming Stage and Complete Burning Cycle). Acetylene and o-xylene mean EFs varied considerably amongst fuel wood species. The EFs of crop residue species differed considerably. The highest fuel consumption rate was found in Delhi's north-west (32% of the city's total), where 92% of the domestic fuel was used for cooking, 7% for water heating, 1% for room heating, and 0.5% for insect repellents. Cholestanol and coprostanol were identified as trace elements for pollutants from combustion of animal dung cakes, and terphenyls were identified as markers for burning municipal solid trash[108]. Phenolic, along with furanic chemicals, were abundant in the gaseous emissions from samples of home solid-fuel burning in Delhi. Industrial and biomass burning sources, weather changes, and everyday car emissions were responsible for VOCs in Delhi[109]. Stronger winds lowered the levels of VOC, and during calmer wind periods, the VOC levels were found to be higher due to the ventilation effect. Suburban areas exhibited increased OVOCs and BVOCs. VOC levels were impacted by biomass burning during the Holi festival; acetonitrile divergence from CO indicated additional chemical as well as industrial impacts. At the urban site, anthropogenic sources were responsible for 60–73% of OVOCs and 82% of isoprene, whereas at the suburban site, anthropogenic sources were responsible for between 40–70% of OVOCs and 43% of isoprene. The suburban site also showed a larger daytime contribution from biogenic/secondary origins for OVOCs, isoprene, and monoterpenes compared to the urban site.

Analysis of seasonal sources of NMVOCs in the year 2022 in Delhi indicated that one-third of all sources result from traffic pollution and solid fuel combustion[86]. Winter and post-monsoon NMVOC levels were impacted by biomass burning in adjacent states, but summer and monsoon NMVOC levels were decreased by high wind speed and dilution.

Over the Indian region, 52 NMHCs (1 alkyne, 10 alkenes, 16 aromatics, and 25 alkanes) were measured in addition to CO at IISER Mohali and IGI Airport, Delhi, between December 2016 and January 2017[87]. Emission sources were analysed for their impact on NMHC concentrations using fingerprints from chemical sources as well as inter-NMHC molar emission level ratios. These sources included vehicles, petrol evaporative emissions, biomass, and incineration of waste. NMHCs' source profiling through PCA in Delhi's metropolitan area revealed natural gas emissions (10%), flare emissions (13%), refineries and gas station operations (14%), polymer manufacturing industries (19%), vehicle exhaust (23%), secondary manufacturing procedures (body soaps, paints, and metal fabricators and processing, 8%) were found to be the primary contributors to NMHC emissions in Delhi's urban environment while 13% remained unidentified[36].

Mohali, located 300 km north of Delhi, has a mixed land use, with agricultural land predominating in the northwest and urban and industrial sources more common in the south to southeast. Studies have discussed the site's seasonal meteorological conditions and the episodic agricultural residue burning activity, especially in the post-monsoon season[110,111]. In Mohali and Chandigarh, a thorough NMHC fingerprinting of emissions was performed from diverse sources, including burning paddy stubble, garbage, fuel evaporative emissions, and idle exhaust emissions of cars (LPG, CNG, diesel, and petrol)[112]. For each source, practical chemical tracers were selected, like propane used in LPG and emissions from evaporation, and acetylene produced from biomass burning. While alkene and aromatic chemicals were more common in fire emissions, alkanes predominate in gasoline evaporative emissions. Compared to LPG and CNG exhaust, diesel vehicle exhaust had a higher alkene and aromatic concentration. Diesel engine exhaust emissions had a lower aromatic content than gasoline vehicle exhaust emissions. Due to a higher percentage of cars running on petrol in India's on-road vehicle fleet, gasoline exhaust pollutants predominated ambient traffic pollution.

Studies in Mohali indicated that the biogenic sources, in particular isoprene, play a significant role in O_3 generation throughout the year, with the exception of the winter[111]. Burning crops increases VOC emissions and, combined with NOx emissions lead to high O_3 episodes (over 80 ppb) that last longer than eight hours. More than 38% of the O_3 produced year-round, from both anthropogenic and biogenic sources, comes from isoprene and acetaldehyde. Through reservoir species with a longer lifetime, for example, peroxyacetyl nitrate (PAN), isoprene, and acetaldehyde can also have an impact on downwind areas and the free troposphere. India's urban and rural areas are both impacted by the aerosol pollution brought on by agroforestry, a major regional source of biogenic VOCs. Increased O_3 mixing ratios are also observed in photochemically aged urban emissions plumes in rural downwind areas, which exacerbates air quality problems.

Measurements in Lucknow during December 2020 until May 2021 revealed that NMVOCs significantly affect the O_3 along with secondary organic aerosol generation[113]. The three most common NMVOCs were acetaldehyde, acetone, and acetic acid. Five different sources were identified as major contributors to NMVOCs, including vehicle traffic, VOCs, SVOCs, and two variables related to solid fuel combustion. Warmer months revealed the impact of photochemical activity and local transport, while wintertime NMVOC concentrations were greater due to the presence of solid fuel combustion along with stagnant conditions due to low mixed height. Controlling NMVOC emissions and secondary pollutants could be achieved by regulating benzene, toluene, xylene, phenol, furans, and oxygenates.

Like Mt. Abu in western India, Nainital serves as a high-altitude background site for North India. Winds in Nainital are predominantly westerly/north-westerly in winter and shift to south-westerly during June–July, connecting to IGP[82]. Sarangi et al. found that the overall concentration of NMHCs, including ethane and acetylene, was much lower during the summer and monsoon months, with peaks observed in late autumn and winter[88]. Annual ppbv estimates were also calculated for ethane (1.8 ± 1.0), propane (0.6 ± 0.8), ethene (0.7 ± 0.9), propene (0.6 ± 0.7), n-butane (0.5 ± 0.6), i-butane (0.6 ± 0.7), i-pentane (0.5 ± 0.6), and acetylene (1.0 ± 0.8) in Nainital. Hydrocarbon levels increased in Pantnagar and Haldwani (lower altitude compared to Nainital) throughout the winter. While the yearly methane cycle at Mt. Abu was different from that at Nainital, it was consistent with cycles seen at other high-altitude locations like Jungfraujoch and Mauna Loa. Ethane, propane, and other light NMHCs exhibited somewhat higher variability and magnitude at Nainital. Due to different breakdown rates for propane and acetylene in relation to CO, higher slopes were recorded in the wintertime and lower slopes in the summertime.

Light NMHCs measured over four years (2017–2020) at Nainital were compared with an IGP site (Haldwani) and higher NMHC levels were found at the IGP site. It was dominated by propane from LPG and fossil fuel combustion, while ethane from biomass burning prevailed at the mountain site[114]. Seasonal and diurnal patterns showed anthropogenic influence at the mountain site, especially in spring. The IGP site exhibited 4–6 times higher hydroxyl radical reactivity, O_3 formation potential (OFP), and secondary organic aerosol formation potential (SOAFP), driven by propylene, ethylene, and n-butane. Their findings highlighted the significant impact of IGP emissions on the Himalayas and the need for targeted emission control measures.

Higher BTEX levels were found at the IGP site (Haldwani), dominated by local emissions, while transport and boundary layer processes influenced the mountain site, with xylene (60–65%) being the most abundant at both sites[115]. Seasonal and diurnal patterns revealed elevated BTEX in spring and autumn at the mountain site and in winter at the IGP site. Health risk assessments highlighted benzene's dominant role in lifetime cancer risk (LCR) at both sites, exceeding the probable risk limit. Surface O_3 observations in the Himalayan Doon Valley (Dehradun, 700 m), revealed urban-type diurnal patterns with spring as the peak season (49.2 ± 24.8 ppbv in May), influenced by biomass burning[116]. A photochemical box model identified NOx-sensitive O_3 production and high contributions from aromatics to O_3 formation.

Emissions of trace gases during forest fires across the Southern Himalayan range revealed that ten common hydrocarbons, including aliphatic (ethane, ethene, propane, and propene), oxygenated (formaldehyde, acetaldehyde, acetone, and methanol), and aromatic (toluene, benzene), contributed to 91.63% of all around NMVOCs[89]. The average overall OFP of NMVOCs over the research period was calculated to be 299.7 $mg/m^2/day$. Propane was found to be among the most prevalent NMHC chemicals in crop residue burning pollutants[112].

Distribution of VOCs throughout IGP and NER (North East Region) revealed that reactive species like ethene and propene contribute less than propane and ethane[117]. Higher concentrations of HCHO and CHOCHO suggest greater emissions and photochemical reactions processing in these regions, which in turn affects temperature and local tropospheric chemistry.

Collectively, NMHC studies across northern India and the IGP reveal some of the highest and most variable concentrations reported over the Indian subcontinent, reflecting intense anthropogenic activity combined with unfavourable meteorological conditions. Urban and semi-urban sites such as Delhi, Kanpur, Mohali, and Lucknow are consistently dominated by vehicular emissions, solid-fuel combustion, and biomass burning, while background and high-altitude locations such as Nainital exhibit lower concentrations but clear signatures of regional transport from the IGP. Pronounced seasonal enhancements during winter and post-monsoon periods are driven by shallow boundary layers, stagnant conditions, and large-scale agricultural residue burning in upwind regions. Source apportionment and ratio-based analyses consistently highlight the strong contribution of alkenes, aromatics, and oxygenated VOCs to ozone and SOA formation, underscoring the critical role of IGP emissions in influencing both regional air quality and downwind Himalayan environments. Despite extensive short-term campaigns, long-term continuous NMHC observations over this region remain limited.

4.3. Study of NMHCs Established over Eastern India

Kolkata is a megacity in Eastern India with a population of 15.7 million and features key industrial and port areas, including Haldia refinery and power plants. Kolkata has about 0.45 million motor vehicles, mostly taxis (45%) and auto-rickshaws (28%), which run on diesel or CNG. Public transport is more widely used than private vehicles.

Petrol filling stations located on the roadside of major roads with high traffic density were found to be significant NMHC emitters)[118]. Exhaust from light-duty diesel and gasoline vehicles around petrol pumps—the majority of which lacked catalytic converters—contributed 10.3 ± 5.2% and 6.5 ± 6.4% of VOCs, respectively[118].

Mallik et al., for the first time in India, applied the PCA to investigate the source profiles of NMHCs in Jadavpur University's green campus in Salt Lake from March 2012 to February 2013[119]. They observed that boundary layer effects were implied by wintertime early morning enhancements in numerous NMHCs. Kolkata's ethene to CO ratio, which reflects the effects of local biofuel combustion, was found to be equivalent to those of other Indian cities. High concentrations of propane and butane further demonstrate the dominance of LPG and petrochemicals in the studied area. Bhubaneswar, a rapidly growing city in Eastern India with a population of 1.2 million, is surrounded by industrial townships within a 150 km radius. Panda et al. observed that during the winter months (December 2013 to February 2014) when pollution was widespread, Bhubaneswar had greater NMHC levels than the entire Bay of Bengal but lower levels than other Indian urban regions[90]. Propane and butane were linked to LPG emissions, while vehicle emissions and solvent use were significant sources of ethane and ethylene. Due to solvent evaporation, diurnal observations revealed greater n-pentane and i-pentane. Propane was a major contributor to O_3 formation. Relative humidity decreased the concentration of total non-methane hydrocarbons (TNMHC). The sources of CO and TNMHC concentrations were comparable.

Overall, NMHC observations over eastern India indicate moderate to high concentrations in urban environments influenced by a combination of vehicular emissions, LPG usage, landfills, industrial activities, and solvent evaporation. Cities such as Kolkata and Bhubaneswar show clear signatures of anthropogenic dominance, with propane and butane associated with LPG emissions and ethane and ethylene linked to traffic and solvent-related sources. Seasonal enhancements during winter reflect boundary-layer suppression and stagnant conditions, while meteorological factors such as relative humidity play an important role in modulating NMHC levels. Compared to heavily polluted regions such as the IGP, eastern Indian cities generally exhibit lower NMHC concentrations, yet their proximity to industrial clusters and coastal meteorology underscores the need for sustained monitoring to capture evolving emission patterns.

4.4. Study of NMHCs Established over Central India

Nagpur in Central India has diverse sources of NMHCs. Power plants and industries contribute to ground-level NMHCs through local and regional dispersion, even if located over 10 km from monitoring sites. Seasonal variations influence NMHC emissions, with activities such as open burning, domestic heating or cooling, tourist influx, and festivities. Daily mean TNMHC concentration varied across various locations (Residential, Commercial, Traffic intersections, and Residential-commercial mix) and times of year, with winter having greater levels while summer having lowest due to improved dispersion[120]. Due to the explosion of firecrackers during the Diwali Festival, TNMHC concentrations peaked, weekdays had slightly greater (1.17 to 1.21 times) TNMHC levels than weekends due to the higher traffic and transportation.

Chandrapur district in Maharashtra is a major industrial region, known for coal mining, thermal power plants, and cement industries. The district's location in central India also exposes it to regional transport of pollutants, making it an important site for air quality studies. Gudadhe and Manik in 2024 evaluated NMHCs in the ambient air of Chandrapur district. NMHCs were included in the analysis of air quality trends due to the area's rapid industrialization, urbanization, and vehicular emissions. Although NMHC concentrations were found to be below National Ambient Air Quality Standards (NAAQS), their increasing levels indicate potential health risks to local residents. Effective mitigation measures, such as greenbelt development, large-scale tree plantations, and improved pollution control strategies, are essential to address the rising NMHC levels and ensure healthier air quality[121]. The concentrations of NMHCs were found to be within permissible limits around the Chandrapur Super Thermal Power Station (CSTPS).

Among the least studied regions, NMHC values over central India highlight the influence of mixed emission regimes characterized by industrial activity, power generation, vehicular traffic, and episodic combustion events. Urban centres such as Nagpur show clear seasonal variability, with elevated NMHC levels during winter and festival periods driven by reduced atmospheric dispersion and enhanced combustion-related activities. In contrast, industrial districts such as Chandrapur reflect the growing role of coal-based power generation and heavy industries, where NMHC levels, although generally within regulatory limits, show increasing trends linked to rapid industrialization and urban expansion. The combined evidence underscores the importance of region-specific mitigation approaches and continued monitoring in central India to assess long-term trends and emerging health risks.

4.5. Study of NMHCs Established over Southern India

NMVOCs in the heavily forested Western Ghats during the late monsoon seasons of 2016 and 2017 were studied to understand the chemical makeup and origin of light alkenes in biological systems[122]. These measurements were contrasted to an urban site in Udaipur (UDR), India, for the late monsoon season of 2015. The forest location was a Mahadev Temple, at Bhagwan Mahavir Sanctuary (BMS; 74.2526°E, 15.4390°N; 890 m amsl, 207 km^2), a protected area in the Western Ghats in Goa State. The Western Ghats is a long mountain range (~1600 km) running along the west coast of peninsular India, characterized by diverse tropical and subtropical forests. The site has a rich forest cover, with tropical wet evergreen (25%), tropical semi-evergreen (19%), and tropical moist deciduous forests (25%). The site is primarily influenced by biogenic emissions due to its dense forest cover and minimal anthropogenic activities, making it ideal for studying natural emissions and atmospheric processes. Ethane, propene, ethene, and isoprene dominated under clear skies at BMS and UDR [122]. Light alkene peaks were higher in sunny than in overcast weather. Propane contributed in a minor way only. BVOC concentration was greatest in the afternoon and least in the morning as well as in the evening. Ethane to propene, ethane to ethene, and ethane to propene all exhibited very different ratios over the BMS site as compared to the UDP site. Ethene and propene were the two primary contributors to NMVOCs, making about 30–54% and 12–21%, respectively, with isoprene contributing 10%. Tropical woods were shown to be the primary source of biogenic NMVOCs. Both the OFP and the propylene equivalent concentrations of isoprene and light alkenes were found to be greater compared to other NMVOCs at BMS.

Kannur is a tropical town in Southern India between the Western Ghats and the Arabian Sea. Key meteorological patterns include high wind speeds and rainfall during the monsoon and high temperatures in summer. The southwest monsoon, from June to August, brings 80% of the annual rainfall, while winter is marked by clear skies and lower humidity. The levels of TNMHCs were examined to trace indicators in Kannur's rural coastline regions [61], India, and determined that the lowest, maximum, and the mean concentrations of TNMHCs at the observational location were 13.84 ± 4.31, 25.45 ± 6.56, and 19.23 ± 5.56 ppbv, respectively. The negative cumulative effect of NOx on O_3 concentrations and the falling exponential correlation between the two indicated a possible VOC-sensitive site, suggesting that the quantity of biogenic VOCs played a substantial role in the synthesis of O_3 even at low concentrations of NO_2 [61].

The O_3-forming potential of VOCs and NMHCs emitted due to the burning of biomass over India was analysed using data from an international biomass emission data source encompassing the years 1997 to 2009 [123]. Additionally, in-situ light NMHC information gathered from CARIBIC observations during flights connecting Frankfurt and Chennai in 2008 revealed deforestation and burning of agricultural waste as the main sources of NMVOCs (80% for isoprene, 72% for toluene, and 59% for methyl alcohol, respectively). The yearly emissions were estimated for NMHCs from 100 to 470 Gg yr^{-1} and CH_3OH from 46 to 211 Gg yr^{-1}. Common long-lived species were acetylene, ethane, and propane; ethane had the greatest mean concentration (0.51 ppb). VOC/NOx ratio reflected photochemical O_3 formation sensitivity in the upper troposphere. A thorough investigation of the estimated total anthropogenic NMVOC emissions for the year 2010 in India, comprising a state-by-state inventory, found a total emission of 9.8 Tg [124]. Transportation (12%), solvent use (16%), and biomass combustion (60%) were the main contributors. Alkanes, alkenes/alkynes, aromatics, and carbonyls accounted up about 22%, 38%, 16%, and 15% of NMVOC emissions, respectively. Greater contributions from the solvent usage sector were seen in more urbanized states compared to more rural ones, indicating a rise in the consumption of products based on solvents.

Taken together, NMHC studies over southern India highlight the dominant role of biogenic emissions, particularly from forested ecosystems such as the Western Ghats, alongside contributions from biomass burning and regional anthropogenic activities. Forested and coastal environments exhibit NMHC compositions rich in light alkenes and isoprene, with strong diurnal and meteorological controls driven by solar radiation, temperature, and monsoonal dynamics. Coastal and rural sites such as Kannur further demonstrate VOC-sensitive ozone formation regimes, emphasizing the importance of biogenic VOCs even under low NOx conditions. Regional and national-scale analyses additionally indicate that biomass burning and solvent use substantially contribute to NMVOC emissions over southern India and beyond. These findings underscore the need for air-quality management strategies that account for biogenic–anthropogenic interactions and the influence of large-scale transport and seasonal meteorology across peninsular India.

5. NMHC Changes over India during Years 1993 to 2023

Figure 2 shows the evolution of NMHC measurements done at different locations in India with respect to their new measurement techniques for the last 30 years (1993 to 2023)[36,42,59–61,84–87]. It highlights the advancements of research on NMHCs in India through improvements in sampling methods and instruments[88–92,102,107,118,125]. The studies began in 1993 in Bombay, where simple tools like sample canisters were used to collect NMHCs for subsequent GC-FID analysis. In 1994, the research expanded to Delhi, and by 1995, Ahmedabad and Mt. Abu were included. Hypodermic syringes were introduced. Between 2002 and 2004, new locations like Hissar and Kanpur were added. Glass bottles were introduced to improve sample collection, allowing the study of additional gases such as pentanes and butenes. From 2009 to 2012, the research expanded further, including high-altitude places like Nainital. This period also introduced the study of oxygenated compounds like formaldehyde, acetaldehyde, and methanol, which play a role in smog formation. Borosil glass flasks were introduced in 2012 for better sample storage, enabling studies in Mohali and Kannur. Between 2013 and 2017, technology advanced significantly.

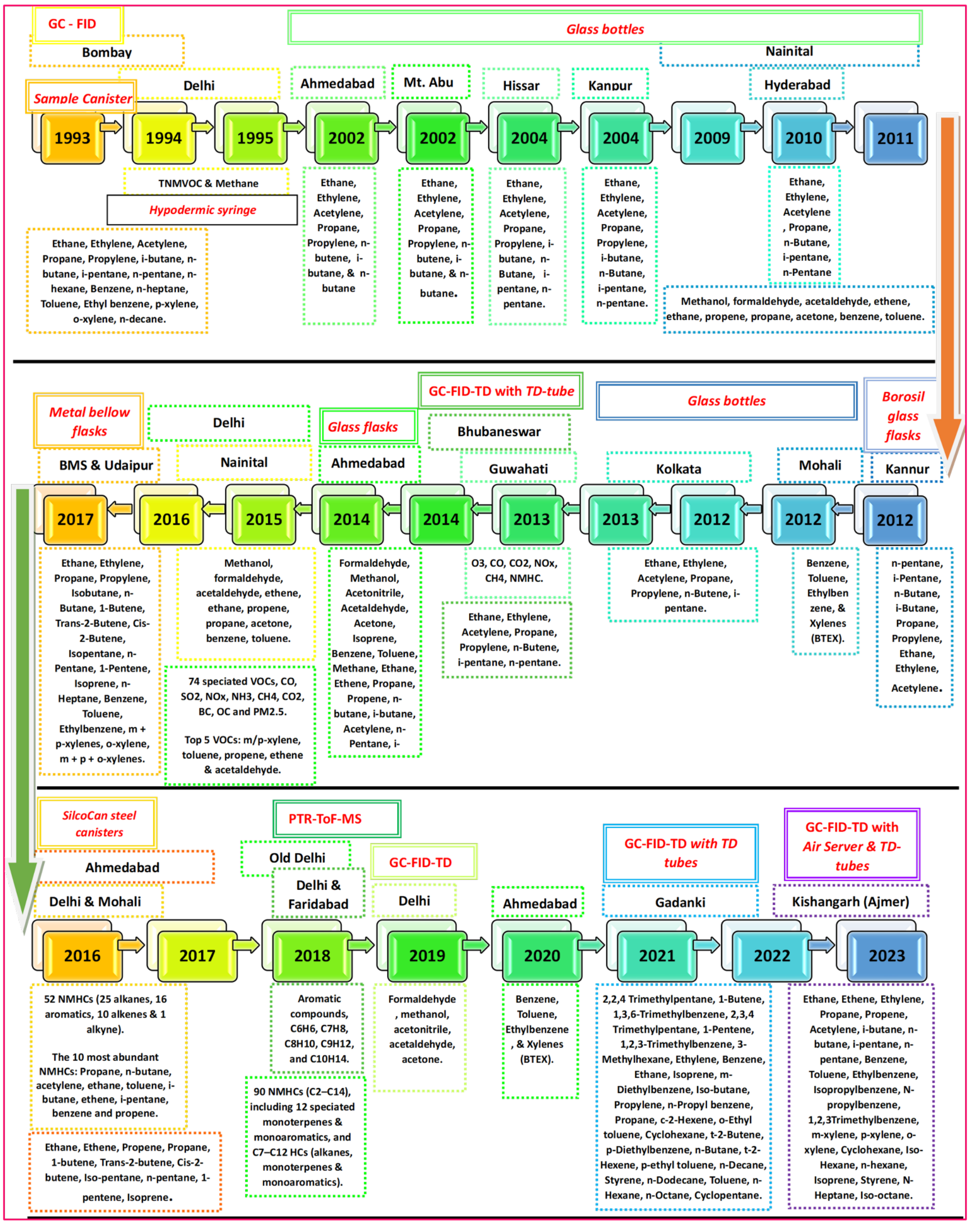


Figure 2. Timeline diagram (year-wise) of measurements of different hydrocarbons over India[36,42,59–61].

These measurements reflect the gradual expansion of observational coverage and methodological advances across India over multiple decades [84–87]. Later studies further incorporated advanced analytical techniques and extended spatial coverage [88–92,102,107,118,125].

New instruments, like GC-FID-TD, were used in Bhubaneswar and Guwahati to measure heavier NMHCs simultaneously with NOx, O_3, and CO, allowing O_3 chemistry studies. Advanced flasks were also used to collect samples in areas like Udaipur and Nainital to study oxygenated VOCs, including methanol, acetone, and acetonitrile. In 2016, stronger steel canisters were introduced in Ahmedabad and Mohali, making it easier to store NMHCs samples for longer periods. In 2017, cutting-edge instruments like PTR-ToF-MS were used in Delhi and Faridabad to measure a complex suite of VOCs, such as monoterpenes and aromatic compounds, in real time. This period also saw the study of 52 different VOCs, such as propane, acetylene, and isoprene, deciphering their role in atmospheric chemistry.

From 2019 onwards, NMHCs research became more advanced and focused. Monitoring expanded to locations like Gadanki in 2021 and Kishangarh (Ajmer district) in 2022. Instruments like GC-FID-TD with Air Server and TD Tubes allowed for precise measurements of harmful NMHCs, such as BTEX compounds (benzene, toluene, ethylbenzene, and xylenes), which are major urban air pollutants. Researchers also began studying more complex and reactive gases like cyclohexane and 1-pentene. Over the years, VOC studies grew from a single site to covering many locations across India, including urban, rural, and remote areas. Instruments improved from basic gas chromatography to highly advanced technologies like PTR-ToF-MS, which allowed for the study of a wide variety of NMHCs. The focus shifted from simple hydrocarbons to include oxygenated VOCs, BTEX, and reactive alkenes, providing deeper insights into air pollution.

5.1. Sampling Techniques for NMHCs

In the early years of NMHC research in India, sample canisters were among the first tools employed to collect air samples. These stainless-steel canisters provided a reliable method for capturing and preserving air samples, enabling researchers to analyze only a few hydrocarbons, such as ethane, propane, benzene, and toluene. Over time, advancements led to the introduction of more durable steel canisters in 2016, which allowed for longer-term storage of samples without significant degradation. These improvements supported more extensive and precise measurements of NMHCs across various locations.

By the mid-1990s, hypodermic syringes were introduced as an alternative sampling method. These simple tools allowed researchers to collect additional compounds such as acetylene, propylene, and i-butane. While effective for short-term or small-scale studies, hypodermic syringes were limited by their storage capacity and susceptibility to contamination. In the early 2000s, glass bottles became the preferred method for sample collection due to their ability to improve sample stability. Later, borosilicate glass flasks were introduced for studies of oxygenated VOCs (OVOCs) such as formaldehyde, acetaldehyde, and methanol, which play a significant role in smog formation. These chemically inert flasks reduced sample loss and prevented chemical reactions during storage, ensuring higher accuracy in VOC analysis.

The adoption of thermal desorption (TD) tubes marked a significant advancement in sampling techniques. These tubes trap VOCs on adsorbent materials, which are then thermally desorbed and analyzed. TD tubes, coupled with advanced instruments, enabled high-sensitivity measurements of heavier hydrocarbons and pollutants like BTEX compounds. Their compatibility with automated systems and ability to handle trace-level compounds made them an invaluable tool in modern NMHC research.

5.2. Measurement Methods for NMHCs

The earliest analytical method used in NMHC studies was gas chromatography-flame ionization detection (GC-FID). This method, employed in India since 1993, separates hydrocarbons via gas chromatography and detects them using flame ionization. GC-FID was instrumental in identifying the commonly measured C_2–C_{10} hydrocarbons and remained a reliable technique for many years due to its specificity for hydrocarbons. However, its limitations became evident as research expanded to include more reactive compounds and oxygenated VOCs.

To enhance sensitivity and expand the range of measurable compounds, researchers began combining GC-FID with thermal desorption (GC-FID-TD). This technique allowed for precise measurement of trace-level hydrocarbons and OVOCs. Widely used between 2013 and 2017, GC-FID-TD enabled additional study of BTEX compounds, heavier hydrocarbons, and oxygenated VOCs in locations such as Bhubaneswar and Guwahati. Its ability to handle complex samples and provide detailed compositional analysis made it a cornerstone of NMHC research during this period.

In 2017, a significant leap in technology occurred with the introduction of proton transfer reaction-mass spectrometry (PTR-MS) and its more advanced time-of-flight variant (PTR-ToF-MS). These cutting-edge techniques provided real-time measurements of VOCs by ionizing them through proton transfer reactions and separating ions based on their mass-to-charge ratio. PTR-ToF-MS was particularly valuable for analysing complex and reactive VOCs such as monoterpenes, isoprene, and aromatic compounds. Its high sensitivity and real-time capabilities enabled researchers to study the dynamic behaviour of NMHCs and their role in atmospheric chemical reactions.

Over the last three decades, NMHC research in India has seen a remarkable evolution in both sampling techniques and measurement methods. The progression from basic tools like canisters and syringes to advanced instruments such as PTR-ToF-MS reflects the growing impact of this field. Sampling techniques improved with the introduction of glass flasks and TD tubes, enabling the collection of diverse and reactive compounds. These advancements have significantly enhanced the understanding of NMHCs, their sources, and their impact on air quality and atmospheric chemistry.

5.3. Temporal Evolution of NMHCs

Figure 3 presents a detailed analysis of the annual variation in the concentrations of selected NMHCs—Ethane, Propane, Acetylene, n-Butane, Benzene, and Toluene—across several Indian locations over the past three decades[36,61,84–87]. Supporting studies further document these long-term trends across different regions of India[88–90,102,125]. Despite the gaps, NMHCs like propane and butane show increasing values over the years, which suggests the influence of increasing urbanization and emissions from transportation and energy sectors. The spatial distribution of NMHC concentrations highlights that urban sites such as Delhi and Ahmedabad are significant contributors, with higher peaks compared to other locations. Delhi frequently displays elevated levels of most NMHCs, particularly Propane and Benzene, with major spikes observed around 2016 and 2018. Ahmedabad, represented in blue, also exhibits high concentrations, especially for ethane, benzene, and toluene during the same period. Other cities like Nainital, Kanpur, and Mohali show relatively fewer peaks, possibly due to their smaller industrial bases. The variability across locations highlights the role of urban and industrial activities in shaping NMHC levels in different regions. Each compound demonstrates unique patterns in its temporal and spatial variations, reflecting differences in emission sources. For instance, ethane concentrations show significant spikes in Ahmedabad and Delhi in recent years, likely due to biomass burning. Propane levels rose sharply in Delhi around 2018, potentially linked to increased use of LPG and industrial activities. Acetylene, a by-product of incomplete combustion, exhibited elevated levels in Ahmedabad and Delhi during the early 2000s and mid-2010s. Similarly, n-Butane shows sporadic peaks, with Delhi being a major contributor, indicating emissions from fuel evaporation and industrial sources. Benzene, a toxic and carcinogenic hydrocarbon, had high concentrations in Ahmedabad and Delhi during 2016–2017, pointing to vehicular emissions and solvent usage. Toluene, though less prominent, displays occasional peaks in urban areas. The irregularity in temporal data coverage across years and locations highlights the need for more systematic and consistent monitoring efforts. While **Figure 3** provides valuable insights into the changes in NMHC levels, the gaps in data limit the ability to fully understand their long-term trends. The results emphasize the influence of urbanization and industrialization on NMHC emissions, particularly in major cities like Delhi and Ahmedabad. Addressing these gaps and expanding monitoring networks would provide a more comprehensive understanding of NMHC sources.

Additional long-term datasets contributing to this analysis are reported in previous studies[88–90,102,125].

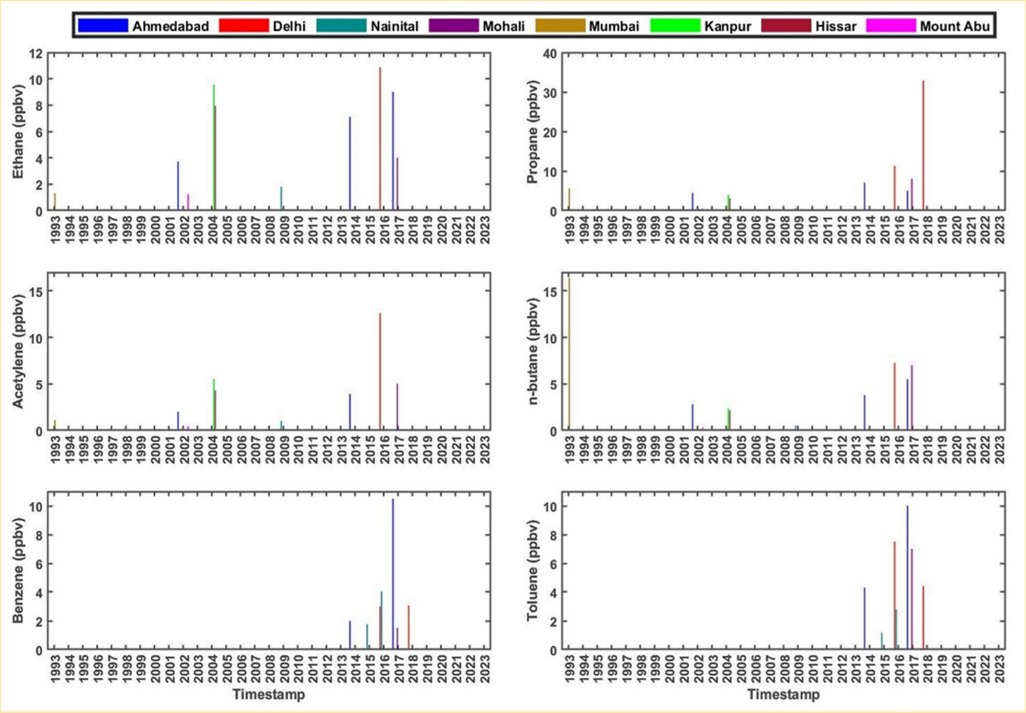


Figure 3. Annual variation of selected NMHCs over locations with higher data availability [36,61,84–87].

6. NMHC Ratios as Indicators of Sources

Relative variation of NMHCs constitutes an important indicator of their sources. One reason is that different sources of NMHCs have varied abundances of different species, leading to different emission ratios. The other reason is that each molecule has a different rate coefficient with oxidants like the OH radical, providing different atmospheric lifetimes while being transported from their source regions. Some literature-based indicators of source apportionment through ratio studies are provided in **Table S2** and **Figure 4**.

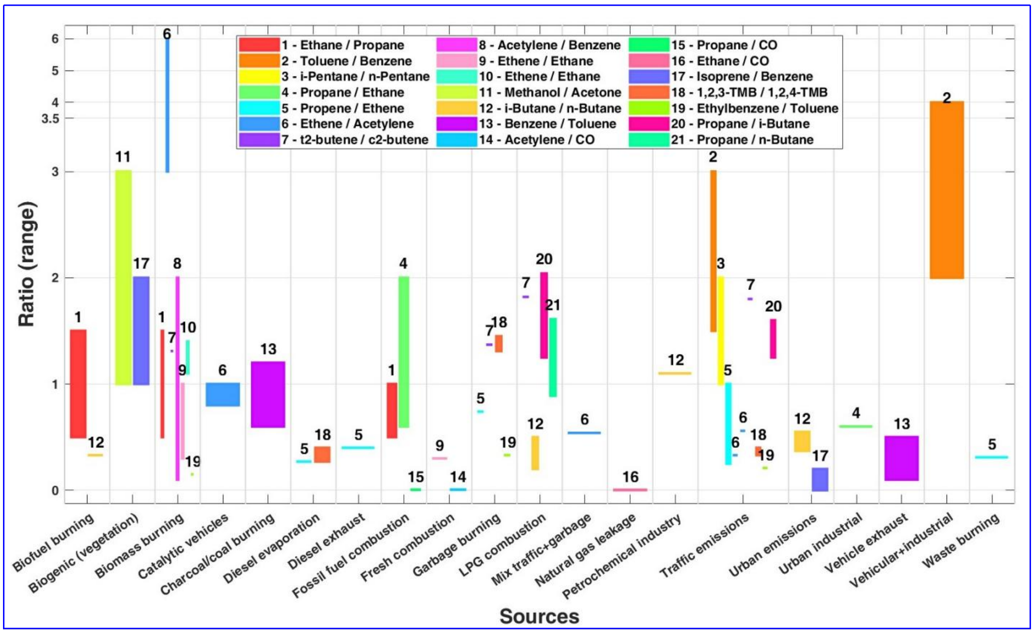


Figure 4. Different NMHCs ratios as indicators of different sources.

Source: As per **Table S2**.

The ratio of ethane to propane has been used extensively in studies of emission characteristics from a wide range of geographical areas [28,126]. The isoprene/benzene ratio showed that human activity can be responsible for large isoprene emissions [83]. The ratio of isoprene to C_6H_6 rose in warm weather (over 25 °C). Wind speed affected the dilution of VOCs from nearby sources. Greater toluene/benzene ratios were found in non-traffic pollution origins (e.g., landfill, industry, etc.) [96]. Using ΔVOCs/Δbenzene emission ratios, anthropogenic (vehicle exhaust) as well as other sources can be differentiated. Emissions originating from the Thar Desert along the IGP are recently reflected in the toluene/benzene ratio.

The significance of petrol and diesel emissions to NMHCs is shown by the presence of a significantly higher molar ratio of toluene to benzene in ambient samples [106]. A high i-pentane/n-pentane ratio indicates that traffic-related emissions have a significant impact [106]. Even after several days of transportation, the ratios of acetylene and benzene to NMHC and pentane isomers could serve as markers of biomass combustion [127–129]. Emissions from burning biomass could be identified using the NMHC to CO ratios [130]. A strong correlation is observed between anthropogenic emissions and the burning of biomass using n-butane and n-pentane markers. NMHC emission factors differ significantly depending on the type of fire (flaming, smouldering, etc.) and the fuel source [127,131]. The combustion fingerprints of crop residue biomass, waste burning, and other biomass (such as charcoal, cow dung, wood, and sawdust) are indicated by ethylene/acetylene ratios greater than 3 [106,112].

Ambient propene/ethene molar emission ratios in Delhi are 0.31 ± 0.05 ppb/ppb [87]. and traffic sources are indicated by 0.38 ± 0.10 ppb/ppb, diesel evaporative emissions (0.27 ± 0.11 ppb/ppb), and diesel vehicular exhaust emissions (0.40 ± 0.02 ppb/ppb). Furthermore, the variation in Delhi's ethene/acetylene mixing ratios (0.33 ± 0.04 ppb/ppb) suggests that sources other than traffic are significant for these chemicals in Delhi [87].

Acetylene to CO and propane to ethane ratios have been utilised to determine if the pollution is newly released or has been carried from somewhere else [80,132]. Compared to CO, acetylene has a significantly shorter photochemical persistence (about two weeks) [133]. Consequently, the acetylene to CO ratio lowers as an air mass ages due to a faster fall in the acetylene mixing ratio. Therefore, a larger ratio (0.0056 ppbv/ppbv) suggests that the quantity of air is influenced by recent emissions, and a lower ratio denotes that the airmass has undergone significant atmospheric processing due to photochemical ageing [132,134,135]. The acetylene/CO slope for both of the IGP sites (Hissar and Kanpur) is found to be 0.007 ppbv/ppbv [85]. These ratios indicate that the emissions were fresh and local [85]. A higher acetylene to CO ratio (0.0056 ppbv/ppbv) indicates fresh emissions. Fossil fuels have been characterised using the propane to CO ratio [136]. For Hissar and Kanpur, the slope values are 0.005 and 0.006 ppbv/ppbv, respectively. These coincide with the combustion-related values for fossil fuels at both sites. In contrast, the projected values for Hissar and Kanpur are 1.34 and 1.11 ppbv/ppbv, respectively, if we take the slope values of ethane to propane. These show a greater contribution from the burning of biofuel, since the average values for burning biomass, biofuel, and fossil fuel are 8, 2.3, and 0.5, respectively [137,138]. For Hissar and Kanpur, the observed slope values of Δethene/Δethane are 1.4 and 1.1 ppbv/ppbv, respectively. According to Carmichael et al. [138], this shows that emissions from burning biomass or biofuels [85,138].

Acetylene showed a strong correlation ($r > 0.9$) with CO during the night in Delhi. Unburnt fuel may release acetylene and partially explain the observed ratios in Delhi, even if traffic is probably a key factor. Vehicles using older emission control technologies, such as catalytic converters, are more likely to have ethylene/acetylene molar emission ratios ≤ 1 [139,140]. According to data from Mohali and Delhi, a significant amount of the fleet in both cities still consisted of cars with outdated technology, as identified from these ratios. Trans-2-butene/cis-2-butene emission ratios showed contrasting signatures at both sites. In Mohali, mixed indications of trans 2-butene to cis-2-butene (1.64 ± 0.02 ppb/ppb), dominated by LPG evaporative emissions and traffic emissions were measured, while in Delhi, the ratio (1.23 ± 0.13 ppb/ppb) was found to be an indicative of a mixture of the pyrogenic (bio mass and burning of garbage) and emissions from diesel vehicular exhaust [87]. The term "photochemical clocks" refers to non-isomeric NHMC ratios, like ln([propane/ethane]) and ln([n-butane/ethane]), which can be used to analyse photochemical processes during transport [131]. O_3 production as a function of transit and seasonal photochemical processing can also be examined using the ln([propane/ethane]) ratio[129,141]. The ratios of ambient propene/ethene and ethene/acetylene in Mohali, which were 0.74 ± 0.05 ppb/ppb and 0.54 ± 0.03 ppb/ppb, respectively, indicated a combined impact from sources of traffic emissions and waste burning[87].

The strong positive correlation (r^2 value found 0.99) found between i-and n-butane implies that Nainital is also being impacted by natural gas leaks. An additional estimate of the CH_4 to C_2H_6 ratio in Nainital is 20 ppbv ppbv^{-1}. n-butane and propane showed a positive correlation, which supports the impact of LPG emissions[88]. Sahu and Lal[100] attributed the linear association between ethane-propene at Mt. Abu to emissions from marine sources and the combustion of fossil fuels[88]. Specifically, the ethene/ethane and propene/ethane ratios, which were much higher, indicate the presence of biogenic sources at the BMS site[123]. Since ethane's biogenic emissions are far lower than those of light alkenes, the result of the comparison is consistent.

7. Conclusions

This review paper is an amalgamation of NMHC measurements conducted to date over the Indian region. After a brief introduction of various NMHC-related terminologies, the manuscript delves into various sources of NMHCs available in the literature. It also summarises the impacts of NMHCs on our atmosphere (chemical processing), climate, environment, and the health of plants and human beings[142–146]. This is followed by a thorough analysis of NMHC measurements reported over the Indian region, divided into large geographical realms (West, North, IGP, East, South, and Central), followed by timeline evaluations of reported measurements as well as measurement techniques. The highlight of the paper is the analysis of NMHC ratios for source apportionment. Recent studies also demonstrate that ground-level O_3 over Indian regions is strongly governed by interactions between NMHC-related precursors and meteorological parameters such as humidity, pressure, and wind speed, highlighting the importance of integrated chemistry–meteorology frameworks in air-quality assessments[147].

There were no measurement reports of NMHCs available over Indian region before the 1980s. During November 1994 to June 1995, NMVOC concentrations ranged from 1.3 to 32.5 ppmv (high values), showing significant seasonal and temporal fluctuation in Delhi's ambient atmosphere[59]. The concentrations of C_6 to C_{10} HCs were found to be more than those for the C_2 to C_5 at the 2 industrial sites located at Thane region of Mumbai. Some of the individual hydrocarbons to acetylene ratios in the air were much greater than auto exhaust emission ratios over Mumbai[102], indicating a growing threat from industrial sources.

The overall concentration of NMHCs is, in general, much lower throughout the summer and monsoon months compared to winter and post-monsoon, requiring season-specific management strategies during different times of the year. This could mean more intensive monitoring during the later period, as well as stricter implementation of policy controls. In the Indian atmosphere, ethane concentrations were found to be higher over the southern states of India (Hyderabad and Gadanki[148]) and coastal locations (Bhubaneswar and Kannur), while propane shows a mixed regional distribution. Ethane shows a consistent increase over time over representative locations in both western India (Mt. Abu) and IGP (Nainital). In the IGP of India, the highest concentration of ethane was found in Delhi's atmosphere. Similarly, the propane concentration was found to be highest for Delhi, followed by Kannur, and least over Mount Abu in Rajasthan (West, high altitude). Although emitted mostly from traffic-related sources, butane levels are much higher than acetylene. Barring Kannur, n-butane was found to be maximum in the atmosphere of Mumbai (West, highly urbanised commercial capital of India), while acetylene is conspicuously high in India's capital, Delhi. Among the locations reviewed, smart cities like Ajmer (semi-urban, close to the desert) and Bhubaneswar (east coast) have comparatively lower levels of light HCs, as shown in **Figure 1**. Strong positive correlations (r^2 around 0.99) found between i-and n-butane implied that Nainital (North, high altitude) is also being impacted by natural gas leaks. An additional estimate of the methane to ethane ratio in Nainital is 20 ppbv ppbv^{-1}, while n-butane and propane showed a positive correlation, which supports the impact of LPG emissions[88].

Because of evaporation in the summer, emissions of butanes, acetylene, and propane from industrial and urban sources increase; however, near-surface levels are lowered by mixing into a convective boundary layer. Propane and butane are mostly by-products of refining fossil fuels, such as petroleum and natural gas. Ethane is released during the burning of biomass and biofuels, as well as during the combustion and explosion of fossil fuels[88]. The main cause of the elevated levels of ethene and propene in various locations is the burning of biomass. Overall, transportation and biomass burning are the two most important anthropogenic sources of NMHCs. In cities, NMHCs concentration levels are high due to more automobile exhaust. Alpha-pinene concentrations increase exponentially with temperature, and they are independent of sunlight. In India, around 60% of the NMHCs released is the result of combustion of biomass, which is the main contributor to atmospheric NMHCs, and among which the maximum concentration observed is of alkenes (~38%). Increasing contributions to the atmospheric NMHCs from the solvent usage sector have been observed in more urbanized states compared to more rural ones, indicating a rise in the consumption of products based on solvents. When using VOCs mixing ratios as markers, dependence on the wind direction and wind speed should be taken into account. For collecting the samples for VOCs, different techniques such as canisters, hypodermic syringes, glass bottles, borosil glass flasks, TD-tubes, glass flasks, metal bellow flasks, SilicoCan steel canisters, and TD-tubes have been used along with online sampling. For analysis of NMHCs, researchers use different types of techniques, such as GC-FID, GC-FID-TD, PTR-ToF-MS, and GC-GC-FID. Funding for NMHC measurements over less-represented locations like rural regions (affected by agriculture and biomass emissions) or desert regions (impacted by high temperature, dust, and soil as sinks) would be useful to develop policy perspectives with respect to human health and climate over such regions.

Based on the compiled observational record, approximate quantitative contrasts can be identified despite differences in study periods and methodologies. For example, propane concentrations in Delhi increased by approximately 30–50% between early-2000s and post-2016 observations, consistent with increased LPG usage and traffic activity. Urban–background gradients for long-lived NMHCs such as ethane typically exceed a factor of 3–5 when comparing megacities (e.g., Delhi, Mumbai) with high-altitude or background sites (e.g., Nainital and Mount Abu). These order-of-magnitude contrasts highlight the strong influence of localised urban emissions and regional transport on heterogeneous NMHC distributions over India.

7.1. Future Scope of the Study

From the Indian perspective, several groups have investigated the atmospheric non-methane hydrocarbons mostly over selected regions covering 13 of 28 states of India, viz. Ahmedabad (Gujarat), Kishangarh, Udaipur and Mount Abu (Rajasthan), Hissar (Haryana), Delhi (New Delhi), Mohali (Punjab) and Chandigarh, Nainital, Haldwani and Pantnagar (Uttarakhand), Kanpur and Lucknow (Uttar Pradesh), Bhubaneshwar (Odisha), Kolkata (West Bengal), Kannur (Kerala), Mumbai (Maharashtra), Gadanki (Andhra Pradesh), and Hyderabad (Telangana). While most of these are urban locations, a few background measurements, e.g., Mt. Abu and Nainital and non-urban measurements, e.g., Hissar, Pantnagar and Ajmer (Central University of Rajasthan area), are also available and provide useful references and contrasts to compare the measurements. Long-term measurements at non-urban locations are encouraged to arrive at better conclusions regarding NMHC origins with lower effects from highly mixed emissions. A consolidated summary of the regional distributions, study density, and temporal coverage of atmospheric NMHC measurements across India, compiled from the literature reviewed in this study, is provided in **Table S3**, clearly highlighting the spatial bias and under-represented regions in current observations.

For many other parts of India, which can be strong source regions, NMHCs have not been reported with respect to the air quality data. As NMHCs can indirectly modulate air quality by influencing oxidising capacity, there is a huge possibility and scope of establishing the air quality relationship with the hydrocarbons. Further, the study locations in India have long-term data of atmospheric composition, including VOCs, available with prestigious research institutes like the Indian Space Research Organisation (ISRO) and Council of Scientific and Industrial Research (CSIR) laboratories, but even these are not sufficient to represent the diversity in environmental and emission regimes over India. There are very few time-series which represent rural emissions. Similarly, desert, as well as forest environments, are under-represented. Possibility of measurements in the Thar desert (e.g., Jaisalmer, Jodhpur), petrochemical industries (e.g., Jamnagar), forest regions (e.g., western ghats, wildlife sanctuaries), rural atmospheres (different villages in northern, western, eastern, southern and north-eastern India), will help to constrain emission regimes in regional and global models as well as calibrate satellite sensors. For example, ethane measurements over such representative locations can help to segregate fossil fuel emissions and natural processes for important missions of Suomi-NPP (with CrIS instrument)[149]. There is an urgent need for NMHC data over such under-represented regions (the Thar Desert, NE India, rural interiors, vicinity of wetlands and lake ecosystems, landfills, etc.). Further, flux measurements, profiling through tower, balloon, and aircraft setups, and ship-borne measurements need to be conducted regularly.

There are robust techniques now available in India for the measurement of NMHCs, including GC-TD-FID (started in 2013); PTR-ToF-MS (started in 2018); and GC-TD with FID and Air Server, which has been available in the Central University of Rajasthan since 2022. This is a very convenient technique to measure the NMHCs online and offline with TD-tubes. With the help of a study based on this review paper, the sources of the NMHCs have been documented from various measurements over the Indian region, where there are very few measurements available. Compared to individual VOCs, their relative abundances (ratios) can provide a more robust estimation of sources. The compilation of the variation of NMHC ratios as source indicators in this review article can be used as an effective tool for devising mitigation policy frameworks.

7.2. Key Insights

- India's atmospheric NMHCs exhibit significant regional diversity, with concentrations consistently higher in large urban and industrialized areas than in rural, coastal, and high-altitude areas.
- In the majority of Indian regions, vehicular emissions and biomass burning are the main anthropogenic sources of NMHCs. In highly urbanized areas, industrial activities and solvent consumption have a growing impact.
- Because of air mixing and wet scavenging, NMHC behaviour is characterized by seasonal variability, with higher concentrations during winter and post-monsoon periods and lower levels throughout summer and monsoon seasons.
- Analysis of NMHC ratios published in the literature shows the usefulness of ratio-based methods for source apportionment in areas with limited data and offers solid insights into emission sources.
- Background and high-altitude site observations show how regional transportation affects NMHC levels, highlighting the fact that the effects of air quality go beyond local emissions.
- Significant observational gaps continue to exist in north-eastern India, rural interiors, desert regions, and coastal zones, underscoring the need for more long-term monitoring to support efficient air-quality and climate policies.

Supplementary Materials

The supporting information can be downloaded at https://journals.bilpubgroup.com/files/JASR-12677-Supplementary-Materials.docx.

Author Contributions

S.Y. wrote the original draft and made figures and tables; C.M. conceptualised the idea and the structural logic, and provided overall supervision and editing. Both authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

As it is a review article, most of the data are collected from available manuscripts, and the data used will be made available on request.

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Conflicts of Interest

The authors declare that they have no competing interests.

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