Journal of Innovations in Engineering Education
JIEE 2023, Vol. 6, Issue 1.

https://doi.org/10.3126/jiee.v6i1.42452

THAPATHALI CAMPUS
Institute of Engineering
Tribhuvan University

Existing and alternative air pollution monitoring platforms in Nepal: A systematic review

Prateek M. Shrestha [a,*], Sudip Bhattrai [b], Kamal Darlami [b], Ashish Karki [b] and Rakesh C. Prajapati [c]

[a] *Independent*
[b] *Department of Mechanical and Aerospace Engineering, Tribhuvan University Institute of Engineering, Pulchowk Campus*
[c] *Orion Space Pvt. Ltd., Sanothimi, Kathmandu, Nepal*

ARTICLE INFO

Article history:

Received 18 Jan 2022
Revised in 30 Nov 2023
Accepted 11 Dec 2023

Keywords:

Air pollution
Sensors
Mapping
Unmanned aerial
Satellite
Monitoring
Nepal

Abstract

Air pollution has become one of the most significant threats to the well-being of humanity and the environment in many developing countries, including the Himalayan nation of Nepal. The use of both stationary and mobile instrumentation platforms for environmental and atmospheric research has witnessed a significant growth globally in the last two decades. In this review, we explore the current status of air quality monitoring infrastructure as well as a future scope of using new platforms using low-cost air sensors for pollution mapping in Nepal. While large-scale regional dynamics of air pollution in the country have been previously studied using both experimental and modeling-based approaches, usability of low-cost instrumentation platforms in Nepal have not been explored by past studies. From the retrospective discussions regarding the past studies, we discuss here the data needs that can be fulfilled with low-cost measurements using land-based, automotive, aerial and satellite-based platforms. The importance of hyper-local air quality monitoring is highlighted in the context of Nepal, followed by the identification of recent advancements in sensor technologies, available facilities and infrastructure in Nepal.

1. Introduction

Ambient air pollution is a collective term which comprises of several individual pollutants such as ultrafine, fine and coarse particulate matter (PM_1, $PM_{2.5}$ and PM_{10}, respectively), oxides of sulfur (SO_x), oxides of nitrogen (NO_x), ground-level ozone (O_3), carbonaceous gases (CO, CO_2), volatile organic compounds (VOC_s), lead (Pb), inorganic trace gases (NH_3, HCl, HNO_3), black carbon (BC) in elemental and/or organic form (EC and OC, respectively), formaldehyde (HCHO), benzene (C_6H_6), etc. Along with these major air pollutants, various other mixtures of chemical, biological and radiological agents may also contaminate ambient air that can produce undesirable health effects in living beings including humans. The smaller PM particles are considered more dangerous when inhaled because they can penetrate into the deeper parts of human lungs which eventually results in an increased severity of respiratory health effects[1]. SO_x is a collective term used to refer to a mixture of individual oxides of surfur such as sulfur dioxide (SO_2), sulfur trioxide (SO_3) and other oxides of sulfur. Similarly, NO_x is a collective term referring to a mixture of nitrogen dioxide (NO_2) together with nitrogen trioxide (NO_3) and other oxides of nitrogen. There is a plethora of data available on both the health effects and climatic impacts of air pollution available in the scientific literature, most of which were published within the last century, particularly within the last three decades [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16].

Ambient or outdoor air pollution is recognized by the World Health Organization (WHO) as the leading cause for 4.2 million deaths worldwide. Air pollution has been attributed to health problems in humans including chronic and acute respiratory diseases, heart disease, stroke, and lung cancer. While almost all (99%) of the global population breath air that exceed the WHO guide-

*Corresponding author:
prateek.man.shrestha@gmail.com (P.M.S.)

line limits, people living in low- and middle- income countries are exposed to the highest levels of air pollution [2].

Nepal is a developing South-Asian nation stretching along the himalayan range, and is nestled between the two most populous countries of the world: India and China. India and China are also the two nations producing nearly 37% of the global emission of CO_2 through combustion of fossil fuel and industrial processes[3]. Although not being a heavily industrialized nation, a total of 8.9 Tg of CO_2, 110 Gg of CH_4, 2.1 Gg of N_2O, 64 Gg of NO_x, 1714 Gg of CO, 407 Gg of non-methanogenic VOCs (NMVOCs), 195 Gg of $PM_{2.5}$, 23 Gg of BC, 83 Gg of OC and 24 Gg of SO_2 emissions were estimated to have been produced in Nepal in 2011[4]. The Climate and Health Country Profile of 2015 by the WHO reported that with a population of roughly 28 million and a population growth rate of 1.2% but with a GDP per capita of 692 USD, Nepal is also one of the most vulnerable nations facing the dire impacts of both domestic and regional air pollution, and global climate change [5]. The same WHO report also highlighted the Government of Nepal-reported values of spring and winter season mean ambient $PM_{2.5}$ concentrations of over 70 and 80 $\mu g/m^3$, respectively. For reference, the WHO annual mean $PM_{2.5}$ guideline value is 10 $\mu g/m^3$. In addition, the report also highlighted that over 91% of rural and 29% of urban population in Nepal rely on solid fuels for cooking, creating dangerous levels of greenhouse gases and hazardous air pollutants, leading to roughly 54,900 total deaths attributable to household air pollution, based on 2012 data.

1.1. Population distribution by geography

More than 75% of Nepal's surface area consists of rugged mountainous terrain[6]. The location of urban cities within Nepal like Kathmandu, Pokhara, Hetauda, Gorkha and Ilam are located within or around valleys and basins surrounded by tall mountains. Other major cities of Nepal include Birtamod, Jhapa, Damak, Itahari, Biratnagar, Dharan, Janakpur, Birgunj, Butwal, Bharatpur, Nepalgunj, Dhangadi etc. are all located along the southern Terai belt of the country bordering with India, which South of the Himalayan foothills, and is primarily is plain in topography. The remainder of the smaller urban, semi-urban and rural populations live spread out in the hilly and mountainous terrain of the country. Figure 1 illustrates the population distribution of the country across the different districts. The three districts of Kathmandu, Bhaktapur and Lalitpur that are located within the Kathmandu Valley alone contain roughly 10% of Nepal's population[7]. With a population growth rate of 4.2%, Kathmandu Valley's population is projected to exceed 5,740,000 by 2031[8]. Given the uneven distribution of population across the country, the generation of air pollution and the impacts of air pollution on public health and environment can also be expected to vary significantly across the country based on the density of population and the level of air pollution generating human activities.

1.2. Atmospheric pollution trends

Geographies similar to that of the Kathmandu Valley with the majority of the urban population living within densely populated urban Valleys and basins surrounded by high mountains, generally tend to suffer from poor air quality conditions triggered by even low levels of air pollution generation activities and events [9]. The surrounding mountains act as physical barriers to horizontal winds that can blow away locally emitted air pollutants in those Valleys and basins. The air pollution dispersion patterns in such geographies become highly dependent on the orientation of mountain passes that define the local wind patterns and meteorology. During the night time, the drop in the surface temperature of the surrounding mountains cause the cooler and heavier air masses to congregate close to the Valley surface, thus trapping and concentrating air pollutants in the lower atmospheric layers[17]. Severe air pollution events are often reported in big cities like Kathmandu and Pokhara during atmospheric inversion events and periods of higher long-distance transport of regional air pollutants from the surrounding countries and regions[18, 19]. The geospatial features of the Kathmandu Valley and its associated wind patterns result in noticeable elevation in pre-monsoon concentrations of pollutants attributable to the tailpipe emissions from poorly maintained gasoline and diesel powered vehicles, biomass burning, and solvent/gasoline evaporation, and often exceeding the World Health Organization 24h guideline by factors up to 8.3[10].

While numerous past studies have focused on improving the general understanding of air pollution sources, migration patterns and major factors that contribute in improving or worsening of air pollution levels in the Kathmandu Valley[9, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23],there are limited data available for other urban and rural centers of the country. From the limited available literature, it is known that in the city of Pokhara, atmospheric aerosol concentrations as reflected by aerosol optical depth (AOD) has a strong seasonal trend. One past study [24] has attempted to profile vertical distribution of atmospheric pollution in the Pokhara Valley. This study showed that the pre-monsoon season AOD values were significantly higher ($AOD_{500\ nm}$>0.6) compared to the monsoon season ($AOD_{500\ nm}$ 0.2-0.3). The same study also showed

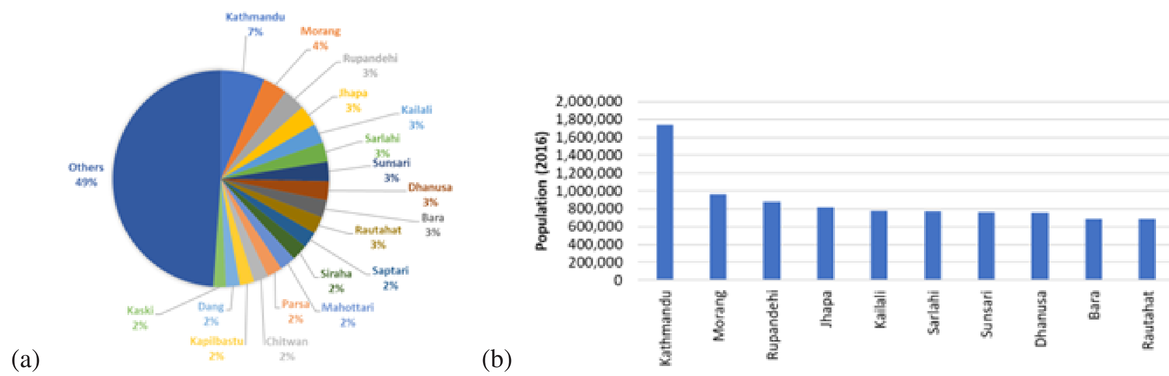

Figure 1: (a) Population of all 77 districts in Nepal as a percentage of the total population; and (b) Bar chart comparing populations of the top ten populous districts of Nepal (Data Source: [7]).

that the vertical atmospheric profile of aerosol specis showed decreasing concentration with altitude, with near-surface BC concentrations of Pokhara Valley being much lower than that of Kathmandu Valley and similar in range to the larger Indo-Gangetic Plain sites such as in Kanpur, India. In the cities located along the southern Terai plains of the country as well as the Pokhara Valley, the air pollution concenrations are dominated by nearby industrial emissions as well as regional influx of air pollution from the northern states of India along with the westerly wind patterns[24]. A study by Rupakheti et al.[20]on the pre-monsoon air quality over Lumbini region of Nepal showed that the 24 h average $PM_{2.5}$ and PM_{10} concentrations exceeded the WHO guidelines very frequently (94 and 85%, respectively) during the sampling period of 3 months (April-June 2013). Sand storms in the Thar Desert, agricultural fires in the western part of the Indo-Gangetic Plain and forest fires in the eastern part produce disgnificant amounts of air pollutants that migrate over Nepal [21]. The regional transport of air pollution from China, however, is of lower significance in Nepal than the influx of air pollution from India because of the geographical separation of the air pollution generation sources in China by the thinly populated Tibetan Plateau. In fact, the westerly wind patterns drive the South Asian air pollutants such as BC aerosols into the Tibetan Plateau through mountain valley wind alleys instead of the other way around [22, 23].

1.3. Major and minor sources of air pollution

Historically, Nepal has not been a highly industrialized nation. Industrialization began to significantly increase in Nepal starting from the 1930s with the formulation of the Nepal Companies Act and establishment of government-owned industries with support from China and the then USSR[24]. However, the industrial sector now consumes over 10% of the national energy and is considered a major emission source of air pollutants[25]. In the industrial sector, location of cement factories and brick kilns close to urban settings and along the Southern Terai belt are also known to be the major sources of air pollutants such as CO_2, CO, SO_x, NO_x, $PM_{2.5}$, and several other HAPs. In 2014, the manufacturing industries of Nepal accounted for 32.7% of the country's CO_2 emissions[26].

Transportation sector is another major contributor to the air pollution problem in Nepal. Transportation infrastructure rapidly increased in the country soon after the first highway opened in 1957. In 1956, about 13,000 km of strategic road network, including highways and feeder roads were constructed in the country[27]. However, more than 50% of the country's road network is still unpaved[28], which leads to significant emission of fugitive dust (mostly PM_{10}) due to vehicular movement [29]. One study [30] showed that in Bhaktapur Municipality alone that is located within the Kathmandu Valley and occupies roughly 1/3rd of the Valley's area, the vehicular emissions accounted for 3,310 tons/year of total air pollutants that included CO_2, CO, NO_x, HC, and PM_{10}. Among these, CO2 accounted for 94.36% of the total emissions, followed by CO (4.39%), HC (0.72%), NO_x (0.35%), and PM_{10} only accounted for 0.18%. By comparison, the transportation sector in the United States is responsible for over 55% of NO_x emissions, less than 10% of VOC emissions, and less than 10% of the $PM_{2.5}$ and PM_{10} emissions [31]. The transportation sector also contributes to the emission of a number of other air toxics including benzene (C_6H_6), formaldehyde (HCHO) and diesel particulate matter (soot), known to cause cancer and other serious health and environmental effects [31].

The increase in emissions from the industry and transportation sectors in the country is particularly alarming. A recent report showed that in the period of 2001 to

2016, the total industrial emissions tripled and emission from the transportation sector quadrupled [25].

Besides the industrial and transportation sectors, other sources of significant air pollution in the country include household and commercial cooking activities with the biomass burning and liquified petroleum gas (LPG), seasonal forest fires, and emission from coal powered thermal power plants and industries [20, 32, 33, 34, 35]. Unlike other industrial nations like the United States, China and European nations, private households contribute to a much larger portion of the total energy consumption (comprising of mostly biomass burning), and is reposible for 58% of soot emissions [25]. Lack of stringent legal action has also provided no strong barrier against the general public burning household waste in their backyards in both rural and urban settings. Open household trash burning has been a major source of the emission of various kinds of HAPs in the immediate vicinity of residential settings throughout Nepal, and contributes to global warming[36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46]. Domestic and industrial use of diesel and gasoline generators as a result of grid power failures and scheduled power cuts also contribute to the increasing air pollution in the urban population centers. Agricultural crop residue burning, mostly in the rural areas, lead to seasonal elevation of haze ($PM_{2.5}$), BC, and CO_2 in the country's atmosphere between October and November of every year[21, 47]. Occasional disruptions to the trash collection from the urban settings also lead to significant emission of VOCs and biologically active pathogens within the highly populated urban areas, often leading to soil and water contamination in those areas.

1.4. Current situation

In the recent years, the air pollution problem of Nepal has often put the country in the top most ranks of the most polluted countries in the world. In March, 2020, the State of Global Air Report placed Nepal as the 8th most polluted country in the world with a $PM_{2.5}$ annual average concentration of 44.46 μg/m^3[26]. One study even recorded the high average daily $PM_{2.5}$ concentrations in the Kathmandu Valley of up to 160 μg/m^3[27]. Nepal ranks as 178th out of the 180 countries listed in Yale's 2020 Environmental Performance Index [28]. One past study has reported that about 44%, 15%, 52%, and 52% of the population in the Kathmandu are living in areas of higher than 40 μg/m^3 of NO_2, SO_2, PM_{10} and $PM_{2.5}$, respectively[16].

The significance of the degree of contribution from the day-to-day air pollution generating activities in the urban centers of the country became clearly evident during the multiple COVID-19 lockdowns faced by the country during the year 2020. One study recorded that there were statistically significant drops in $PM_{2.5}$ concentrations in six major cities of Nepal ranging from 26% to 81% [29].

Real-time monitoring of the various air pollutions of concernt to the public health and environment is essential to be aware of the condition of the atmosphere and its potential impact so that appropriate response strategies can be formulated and enacted by the regulatory agencies as well as the general public.

2. Environmental regulations and policies governing the air quality

Environmental regulations are legislated by the Department of Environment under the Ministry of Forest and Environment for the Government of Nepal (GoN). Primarily, the Environmental Act 1996 and Regulation 1997 govern the environmental regulations in Nepal. In 2011, GoN also introduced the National Climate Change Policy. Vehicular emission regulations under the federal jurisdiction are

- The National Transport Policy 2001,
- The Transport Management Act 2049, and
- Vehicles and Transport Management Rules 2054.

With respect to the industrial sector, the governing regulations pertaining to air pollutant emissions and environmental sustainability are enforced through

- The Industrial Policy 2011,
- Foregin Direct Investment Policy 2015, and
- The Industrial Enterprises Act 2073.

With respect to the energy sector, the policies relevant to environmental sustainability and air pollution are

- The Hydropower Development Policy 2001
- The Rural Energy Policy 2006
- The Renewable Energy Subsidy Policy 2016

There are several other action plans and national pollution control strategies that are still in the drafting process [8]. The issues and challenges regarding air pollution control has been recognized by GoN, which has also attempted to deal with the problem with several task forces and technical committees such as

- The Task Force on Air Pollution Control in Kathmandu Valley, 2073
- High level committee on probing and solving the issues on 20 year old vehicles through the Min-

istry of Population and Environment (MOPE), 2058

- Committee on Implementation of the Order of Supreme Court on Phase-out of 20 Year Old Vehicles (MOLTM) 2058/59
- Committee on Review of Vehicle Emission Standard and Monitoring Mechanism (MOPE) 2060
- Technical Committee on the Relocation of Brick Industries from Kathmandu Valley (MOICS) 2060
- The Air Quality Management Action Plan for Kathmandu Valley

Among these, the Air Quality Management Action Plan for Kathmandu Valley introduced by GoN in 2017 has laid out plans to establish an integrated air quality management framework by establishing an air quality mangement decision support system that involves

- Air quality monitoring system,
- Emission inventories
- Use of air dispersion modeling
- Use of source apportionment studies
- Health, environmental and economic impact assessment
- Developing and reviewing air quality standards,
- Developing, evaluating, and implementing control options

Despite a number of legislations and regulatory efforts to curb air pollution in Nepal, most of the GoN efforts seem to be centered around the Kathmandu Valley's air pollution problems alone. Also, the legislations are not strictly enforced or are often blatantly neglected by all sectors, often resulting in hazardous and severe air pollution events several times a year.

Some drastic attemps have been made several times in the past by regulators to curb air pollution, but these drastic measures have also been focused mainly in the Kathmandu Valley. In 1999, the government announced the phasing out of the Indian imported diesel engine-run three wheeler commuter transport known as 'Vikram Tempos' in the Kathmandu Valley[48]. The phased out Vikram Tempos were repurposed with the help of local manufacturers by an American NGO called the Global Resources to run using electric motors powered by deep-cycle lead acid batteries and were named as 'Safa Tempos'. By the year 2000, the fleet of Safa Tempos running in Nepal reached 600, and was identified as the largest fleet of all electric commuter transport in the world [49]. Currently, very few of the Safa Tempos are sill running in the Kathmandu Valley, ferrying people around the city on a daily basis. However, poor government policy towards promoting electric commuter vehicles and the transit cartels have to led to their rapid decline in numbers[49]. Another example of a drastic government effort to curb Kathmandu Valley's air pollution was in 2002 with the decommissioning of Himal Cement Factory located in the outskirts of Kathmandu[25].

The impact of these drastic responses were measured and reported by several studies and reports based on the then available air monitoring infrastructure.

3. Air monitoring in Nepal

Many past studies mentioned in Sections 1 and 2 have used air monitoring instrumentation as a one-time event, but consistent and continuous use of air monitoring instrumentation and stations are limited in number and scope. GoN started installing and operating ambient air monitoring stations in Nepal since the early 90s using high volume and medium volume samplers as campagin monitoring. In 2002, the Ministry of Population and Environment, with the support from the Danish International Development Agency, established six air monitoring stations in Kathmandu Valley. These air monitoring stations collected continuous data of PM_{10} and $PM_{2.5}$ but soon became dysfunctional in 2006[8]. By the end of 2017, a total of 11 air monitoring stations were operations throughout the country[30]. Since 2012, GoN has also regulated the National Ambient Air Quality Standards (NAAQS) for various air pollutants. Table 1 below lists the nine pollutants regulated by the GoN NAAQS. However, not all the nine pollutants are monitored by the 11 air monitoring stations spread throughout the country. As a developing nation with one of the world's lowest GDP per capita, Nepal also suffers from a lack of resources to consistently operate and maintain many air monitoring stations and use many laboratory facilities capable of high-end environmental sample analysis capabilities. Even the operational air monitoring infrastructure has questionable data reliability, as the GoN-maintained website streaming the air monitoring data[31] provides no information regarding the instrumentation, calibration methods and schedules, data accuracy and data completeness about any of the publicly reported data. The NAAQS of Nepal are comparable to the NAAQS of the United States for the same averaging time periods [50].

The air monitoring stations operated by GoN are illustrated, as shown in Figure 2, by the GoN Department of Environment website [31]. The website currently shows 26 air monitoring stations spread throughout the

Table 1: National Ambient Air Quality Standards of different regulated pollutants in Nepal[30].

Pollutant	Units	Averaging Time	Maximum Concentration	Approved Detection Methods
TSP†	µg/m³	24-hour	230	High-volume sampling and gravimetric analysis
PM_{10}	µg/m³	24-hour	120	High-volume sampling and gravimetric analysis, TEOM†*, Beta attenuation
$PM_{2.5}$	µg/m³	24-hour	40	$PM_{2.5}$ sampling gravimetric analysis
SO_2	µg/m³	Annual	50	Ultraviolet fluorescence, West and Gaeke Method
		24-hour	70	Same as annual
NO_2	µg/m³	Annual	40	Chemiluminescence
		24-hour	80	Same as annual
CO	µg/m³	8-hour	10,000	Non-dispersive infrared (NDIR) spectrophotometry
Pb	µg/m³	Annual	0.5	High-volume sampling followed by atomic absorption spectrometry
C_6H_6	µg/m³	Annual	5	Gas chromatographic technique
O_3	µg/m³	8-hour	157	Ultraviolet spectrophotometry

† TSP = Total suspended particulates
†*TEOM=Tapered element oscillating microbalance

country, but only 12 of the stations show live streaming data as of November 2021. In addition to the GoN air monitors, air monitoring stations are also operated and maintained by the US Embassy at two locations in Kathmandu (Phora Durbar Recreation Center in Thamel area, and US Embassy grounds at Lazimpat area) [51].

3.1. Limitations of the current air monitoring infrastructure

Figure 2 illustrates the geo-spatially sparse nature of the air monitoring site locations in Nepal. There are some major limitations of such an air monitoring networks. Each individual air monitoring location can sometimes report extremely high values resulting from very localized events which may not be representative of the general air quality of the region. A past study by Li et al.[32] concluded that in may urban areas, more than one or two measurement locations per km^2 is essential to quantify the air pollution spatial patterns with high enough fidelity (such as <2 ppb NO_2or <1 µg/m^3 PM_1). The failure of some air monitoring stations in a sparesly located air monitoring network will also obscure the scenario of air pollution impacts within a certain region which makes it hard for researchers and regulators to forecast future trends that can be expected regarding the air pollution temporal patterns. It is also very hard to assess the number of people affected by a certain source of air pollution such as a single stationary source such as an industrial stack, or fugitive road dust emanating from a single busy road due to vehicular movement.

3.2. Need for higher geo-spatial resolution monitoring

As evident from Section 1.1, a huge portion of the population living in the major cities may be subject to hazardous levels of air pollution. Kathmandu Valley, for example, has an estimated average population density of approximately 2800 individuals per km^2 (2011 estimate)[8], majority of who live near to very busy and under-maintained roads. Schools, offices and hospitals are also often located right next to residential buildings in major cities like Kathmandu. Other building types besides the residential ones can also be expected to suffer the same levels of exposure to air pollutants. The degree of impact on their health due to both local and regional air pollution cannot be reasonably quantified and assessed without measurement of different air pollutants at a high geo-spatial resolution, such as at the negihborhood level. While large-scale atmospheric dynamics

(a)

(b)

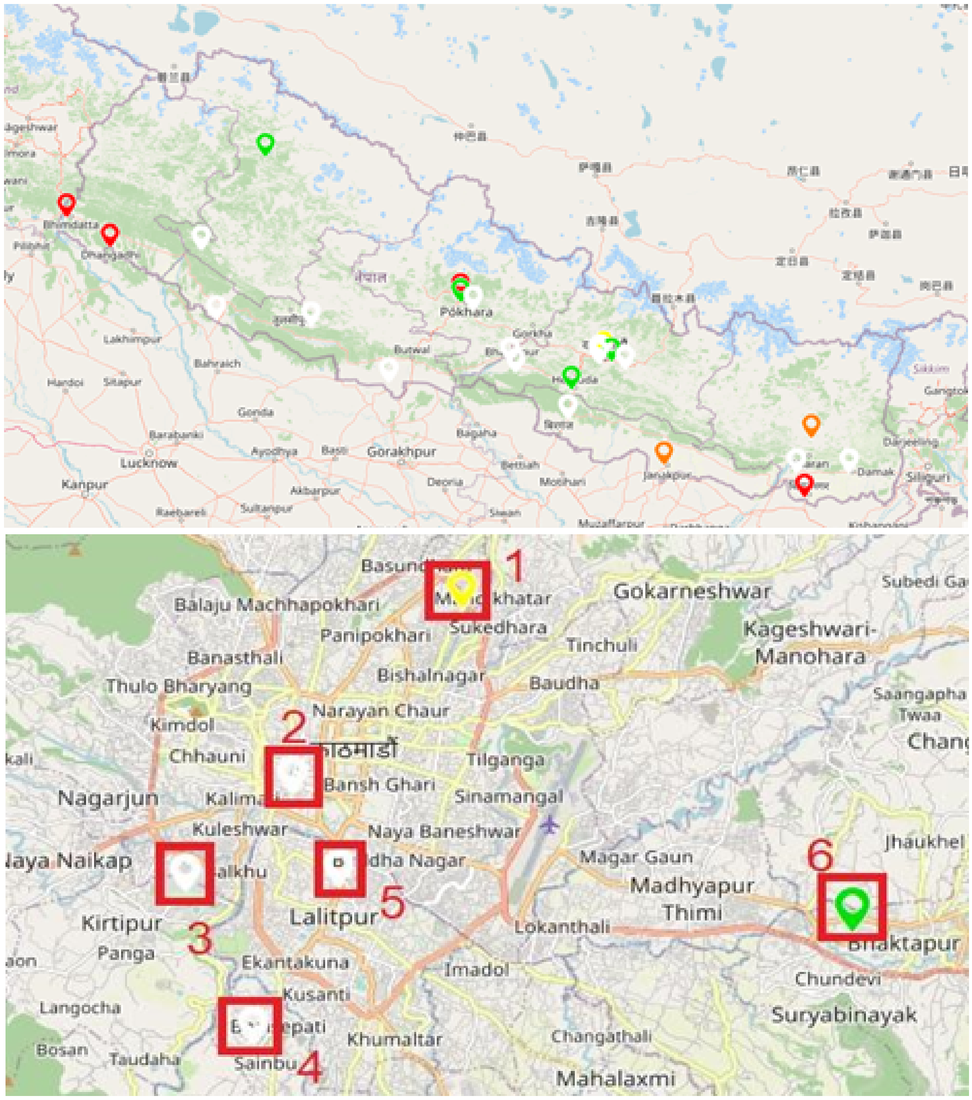

Figure 2: (a) Locations of air quality monitoring stations maintained by GoN throughout the country; and (b) Locations of air quality monitoring stations within the Kathmandu Valley[31]. The pins in the maps are color-coded according to the United States Environment Protection Agency-defined air quality index, and the white pins represent air monitoring stations that are not streaming live data (Credit: GoN website sourcing the basemap from © OpenStreetMap contributors). The numbers are just the identifiers for air monitor installation sites.

and advection of various air pollutants have been extensively studied in the South Asian region, hyper-local scale studies have hardly been conducted with reusable and low-cost instrumentation in the urban settings of Nepal. If air pollution data is available at such a hyper-local geo-spatial scale, it can also guide future urban planning efforts. Future research can also help to identify the human exposures to various air pollutants as a result of the infiltration of outdoor air pollutants into indoor built environments, if the spatial distribution patterns of air pollutants can be mapped at a high enough resolution.

More localized data availability can help address some of these shortcomings of stationary air monitoring stations. However, an increase in the number of air monitoring locations also means a drastic increase in the associated resources and cost. Hence, a more distributed air monitoring system capable of providing hyper-local data at a neighborhood-scale resolution, should also be low-cost and affordable.

4. Low-cost sensors and citizen science

Air monitoring stations maintained by government-level regulatory agencies (often called "reference grade instruments") are often very expensive, bulky, and require dedicated skilled operators for their timely maintainance and calibration. An example is the reference-grade instrument suite used by an air monitoring stations maintained according to the European CSN EN 12341 Standards for standard gravimetric measurement of PM_{10} and $PM_{2.5}$ mass concentrations[52]. In the United States, Federal Reference and Equivalence Methods are used as the "gold standard" for air pollution monitoring and ensure data quality through standardized instrumentation and calibration processes in accordance with the federal law of the United States (40 CFR § 53.1) that implements the U.S. Clean Air Act requirement of monitoring six "criteria pollutants" (CO, O_2, SO_2, NO_2, Pb and PM)[53]. The typical cost for each individual reference monitor used by the US EPA is between $15,000 to $40,000 (USD)[54].

Emerging low-cost sensor technologies can provide a promising alternative solution to the need of a high number of real-time air monitors at a reasonable cost for hyper-local air monitoring. Hundreds of brands of low-cost air quality sensors (<300 USD) are now available in the market which have been used in many countries to improve the spatial granularity of collected data and supplement the network of reference monitors maintained by regulatory agencies[55, 56, 57, 58, 59, 60, 61, 62, 63, 64][65, 66, 67, 68, 69, 70, 71, 72, 73, 74]. Internet of things (IoT) architecture is often utilized to collectively assess various types of air pollutants using a distributed network of low-cost sensors (LCS) that are either fixed at a certain location, or are used in mobile platforms. The US EPA has even developed an Air Sensor Guidebook to help those interested in using LCS for air quality measurements[75]. The use of LCS also enables the general public without high degree of technical knowledge and skills to engage in air quality monitoring and reporting activities. Such involvement of the general public is commonly known as citizen science. As an encouragement to the general public to get more involved, the United States government has even maintained an official website [76] "designed to accelerate the use of crowdsourcing and citizen science across the U.S. government". Other public-private partnership such as the Citizen Weather Observer Program[77], and other citizen science associations and groups are gaining momentum in almost all the continents around the globe[78, 79, 80, 81, 82, 83].

The LCS can consist of various types of sensor technologies to monitor different types of pollutants. Generally, electrochemical sensors and metal oxide sensors are used for the measurement of various gaseous air pollutants such as CO, O_2, SO_2 and NO_2. The electrochemical sensors may have temperature and humidity senstivity along with cross-sensitivities with other gaseous compounds, but require low power to operate. On the other hand, metal oxide sensors generally consume higher power due to the need to heat the sensor element up to 200 to 500 °C to increase its sensitivity to the measurand gas and the response time. Metal oxide sensors also have low humidity sensitivity, but may still show cross-sensitivities with other compounds present in the measurement environment, just like the electrochemical sensors [54]. For PM concentration measurements, optical sensors using light scattering is commonly used by LCS[63].

Besides the valuable advantage that the LCS add to the air monitoring capabilities of towns and cities, they do suffer from certain inherent limitations as well. LCS can report values that are unstable and may often show cross-sensitivities to interfering compounds and environmental conditions with are installation site-dependent. In general, the performance characterization and evaluation of the LCS are performed through "collocation" method, which means the LCS are placed in close proximity to reference grade monitors and their data are simultaneously collected and later compared[84]. For their general usability to monitor local air quality, LCS being used need to show a good level of agreement with the reference grade air montors with a coefficient of determination (R^2) > 0.75 and a slope close to 1.0[63].

Besides continuous air monitoring, passive sampling techniques can also be used as low-cost methods to quantify time-weighted average values of different air pollutants such as NO_x, SO_x, O_3, ammonia, formaldehyde, hydrogen cyanide, elemental mercury, benzene, toluene, xylenes, ethylbenzenes, and many other VOCs and semi-volatile organic compounds (SVOCs)[85, 86, 87, 88, 89, 90, 91, 92]. Air sampling using such passive samplers use a sorbent-laden sampling media that is exposed to the air to be analyzed for a specified period of time. Deployment of such samplers can be done for several days to several months at a time. Evacuated canisters and bags can also be used to collect samples of air. The passive samplers or canisters containing collected air samples are then taken to a laboratory and analyzed using standardized analysis methods such as the US EPA Methods TO-15 [93], TO-11A [94], TO-13A [95], TO-17[96],etc. based on what compounds are of interest for analysis. Passive samplers have been used in numerous past studies since the 1970s and are known to yield results equivalent to other established methods for many VOCs and other pollutants[85]. The advantage of the passive sampling technique is its simplicity and low cost associated with sample collection. However, once the samples have been collected, sample handling must be done with extreme care, conforming to the temperature, humidity and storage time requirements that are unique to each type of sample collected. Also, an infrastructure of analytical laboratories capable of providing standardized analytical services should be available along with a fast enough transportation and courier service so that samples can be properly and accurately analyzed within the time frame required by the analytical methods, depending on the compounds being analyzed. Although in limited numbers and capabilities, some commercial laboratories are emerging in Nepal that are capable of providing some analytical services for environmental samples, including air samples[97, 98, 99, 100].

5. Mobile platforms for air pollution monitoring

5.1. Aircraft

The fundamental challenge for satellite-based measurement is to identify the near-surface concentrations of various air pollutant species accurately, and isolate these near-surface concentrations from the remainder of the measurements. The near-surface concentrations of air pollutants are of greater importance since they are directly inhaled by the people and vegetation, and has a direct impact on their health. Aircrafts are capable of taking real-time measurements at various altitudes and can fulfill the gap in measurement capabilities that satellites cannot easily provide.

Aircraft platforms have been used for conducting atmospheric measurements since the 1940s, starting from the British Royal Air Force aerial missions to better understand the occurrence of contrails behind flying airplans [101]. Numerous stratospheric missions were executed through aircraft measurements between 1985 and 2000, such as through NASA's ER-2 aircraft to measure very reactive free radicals responsible for stratospheric ozone hole creation over Antarctica. Other examples of NASA's use of an aerial platform for an indepth atmospheric measurement is the DC-8 aircraft used for the ATom mission, the P-3B four-engine turboprop research aircraft, and the smaller two-engine UC-12 aircraft [101]. These aircrafts have capabilities of measuring O_3 and PM (including soot), NO_2 and HCHO. Similar to NASA, NOAA utilizes the NOAA WP-3D and the NOAA Twin Otter aircrafts for field campaigns of making atmospheric measurements, some of the campaigns being focused on characterising air pollutants emanating from wildfires [102]. A more recent example of aircraft-based air monitoring instrumentation use is a study utilizing aircraft measurements of physicochemical evolution of atmospheric aerosols in air pollution plumes over a megacity and suburban areas [103]. Similar efforts of aerosol and chemical characterization of the long-range air pollution plumes arising from Southeast Asia, India and China were conducted over the upper troposphere of Europe using the DLR Falcon research aircraft in 2006[104]. Numerous other studies have utilized aircrafts as instrumentation platforms to gather atmospheric pollution data for individual research campaigns[105, 106, 107, 108, 109, 110, 111, 112, 113, 114, 115].The only past study of its kind using an aircraft-mounted instrumentation was done in the Pokhara Valley by the researchers from the International Centre for Integrated Mountain Development (ICIMOD)[116]. In this study, vertical atmospheric profiling were done for aerosol number and size distribution (0.3-2 μm), total particle concentration (>14 nm), aerosol adsorption (370-950 nm), black carbon (BC), and meterological variables using instrumentation mounted onboard an ultralight IKARUS-C42 aircraft. This study has demonstrated that aircraft-based measurements are viable as well as important for gaining more insights about atmospheric pollution dispersion patterns over the skies of Nepal.

Aircrafts do offer high payload capacities and provide unique perspectives into many layers of the atmosphere with direct in-situ measurements. However, the major limitation of aircraft-based instrumentation is that the air monitoring campaigns are better suited for one-off research activities due to their high cost and complicated logistics to coordinate with the local air traffic control systems. An alternative approach is to use passenger aircrafts themselves as data gathering platforms. In Europe, an international non-profit association (IAGOS-AISBL) have initiated a system of using air monitoring instrumentation onboard commercial aircraft traveling around the globe to create and maintain databases of atmospheric meteorological and air quality mointoring and forecasting [117]. Similar efforts integrated with smaller and lighter domestic airliners within Nepal can definitely provide alternative and enhanced capabilities to collect and analyze more meaningful data from Nepal's atmosphere.

5.2. Drones and UAVs

Remotely piloted aircraft, drones and Unmanned Aerial Vehicles (UAV) – also referred to as Unmanned Aerial Systems (UAS) are increasingly being considered in the recent decades as aerial platforms for remote sensing payloads and generating hyper-local maps of air pollution dispersion. UAV systems overcome the limitations of cost and complexity associated with manned aircrafts and offer greater versatality, flexibility, and can be deployed with minimal planning and scheduling. UAVs have been used by numerous past studies to investigate a plethora of air pollutants [118, 119, 120, 121, 122, 123, 124, 125, 126, 127, 128][129, 130, 131, 132, 133, 134, 135, 136, 137, 138, 139, 140][141, 142, 143, 144]. They can fly at low altitudes, slowly, with the ability of acquiring high spatio-temporal resolution data from often hazardous environments without endangering the safety of people operating the UAV or people on the ground[57]. There are several variants of UAVs that can be utilized for the purpose of air quality monitoring, such as fixed wing drones and Vertical Take-Off and Landing (VTOL) drones (these include rotorcraft such as quadcopters, hexacopters, octacopters, and helicopters). Depending on the size, weight and the technology used, the flight time and horizontal travel distance of these platforms can vary greatly, between a few minutes to several hours. Each type of configuration and design (fixed wing/VTOL) has its own benefits and limitations.

Villa et al.[142] has shown various applications of UAVs for the environmental monitoring which entails for both low and high implementation cost. These UAVs are deployable with multi-objective missions to implement monitoring of time and space in high resolution and low cost. From indoor monitoring of CO_2 with camera mounted on UAV to recognize source of the gas autonomously[145] to a lightweight laser-based sensors for the measurement of traces of gas species[146], UAVs promises effective and flexible solutions for implementation of environmental monitoring systems. These UAS often entails a high implementation cost with added features such as a highly sophisticated data processing systems and autonomous capabilities[147, 148].

The fixed wing configuration is easy to construct and can carry remote sensing instrumentation payloads to longer distances with lower energy consumption. However, VTOL configurations with hovering capabilities can position themselves in any desired point in a three-dimensional space, enabling the researchers to collect the desired data from a desired location.

Maintaining a scheduled operation system of drones can definitely supplement ground-based air monitoring systems. The hyper-local data gathering capability of the UAVs can not only fillfill the data gaps between the physically distant air monitoring stations on the ground, but also provide information on the variation of the concentration of different air pollutants at various altitudes as well as horizontal distances from major roads[149].

The use of drones in Nepal is currently limited to tourism and commercial videography applications. However, the Civil Aviation Authority of Nepal has recently developed regulations for operating UAVs that also apply towards the drones being used for scientific research[150].

5.3. Sounding balloons

Stratospheric balloon systems (often called 'weather balloons' or 'sounding balloons') and airships are also used for gathering atmospheric data for scientific research. They use lighter-than-air gas trapped within an enclosure such that the buoyancy genrated by the difference of densities between the enclosed gas and the surrounding air provides the necessary lift. Capable of long duration flights (excess of 50 days), and reaching altitudes of over 100,000 ft (30,480 m), these systems are often used to study high-altitude stratospheric phenomena rather than low-altitude air pollution advection. Use of balloons also has a major limitation of being able to precisely control their flight path in the desired direction at a desired speed, and they can hardly hover at a precise location for an extended period of time. The balloons are also very sensitive to even mild levels of winds. Hence, while the balloons have found their applications in numerous other types of scientific research, they may not be a good alternative for hyper-local air pollution mapping at lower altitudes. However, the upper air data provided by such balloons can help modelers define conditions to accurately model dispersion of atmospheric pollutants over long distance[151].

5.4. Sounding rockets

Sounding rockets or rocketsonde, are smaller suborbital rockets that are designed to carry research instrumentation to the altitudes of 48 to 145 km above the surface of the earth, an altitude range between those of the weather balloons. NASA has developed and sponsored such rockets for reseach activities since 1959 and has developed the NASA Sounding Rocket Program (NSRP) as a low-cost solution to provide up to 20 flight opportunities per year to launch various instruments[152]. The European Space Agency, Canada, Japan, China, Russia and many other space agencies have also used sounding rockets for conducting various research activities and have deemed sounding rockets being suitable to study atmospheric parameters including air pollution transport physics[153, 154, 155, 156, 157, 158, 159]. Similar to the sounding balloons, sounding rockets are also better suited for higher altitude atmospheric and space-related research and may not be widely applicable to lower altitude air monitoring use.

In the context of Nepal, the development of sounding rockets is still at its infancy. However, one team has recently initiated the development of sounding rocket[160], opening the path to further experimental development of the sounding rocket technology with potential application into environmental monitoring applications.

5.5. Satellite platforms

Satellite instrumentation and observation platforms have been used all over the world, including Nepal, to track the generation and movement of air pollutants. Mahapatra et al.[17] studied columnar aerosol loading trend of the Kathmandu Valley using satellite-derived AOD from Moderate Resolution Imaging Spectroradiometer (MODIS) onboard the Aqua and Terra (3×3 km, Level 2) observations in tandem with Cloud-Aerosol LiDAR and Infrared Pathfinder Satellite Observation (CALIPSO). Satellite imagery was used by Dhungel et al.[161] to study the transport of regional-scale pollutant advection through a trans-Himalayan Valley in Nepal. Several other studies have also used satellite data to analyze air pollution transport dynamics at a regional scale in and around Nepal[23, 32, 162, 163, 164] . The United States National Aeronautics and Space Administration (NASA) maintains the open-access Earth Observation Data [165], and the National Oceanic and Atmospheric Administration (NOAA) maintains the NOAA STAR program [166] for air quality remote sensing, that are also usable for analalysis by the general global public. NOAA STAR is science arm of the National Environmental Satellite, Data, and Information Service (NESDIS) through which NOAA uses the Geostationary Satellite Server (GOES) satellites, the STAR Joint Polar Satellite System (JPSS) and many other satellite platforms to generate data products including the infrared and visible spectrums of earth imaging together with water vapor generation and movement tracing. Aerosol and cloud detection can be performed using artificial neural networks and machine learning algorithms using such space-based Lidar data[167], which is also applicable in the context of Nepal.

While satellite-based instrumentation platforms use have been attempted and even successfully used at various instances to provide more localized higher spatial resolution insights related to air pollution in various cities around the world, near-surface measurement still outweigh the satellite-based measurements in many respects[168]. Satellites, however, can act as a fast and efficient route for data transfer from several monitoring locations, often dispersed into very remote locations, to one or more central locations where the data can be collected and analyzed real time.

Besides the high-end satellite instrumentation and imagery/observation platforms, recent developments in the satellite technology since the late 1990s and early 2000s are also paving a path to use very small satellites such as CubeSats, NanoSats and PicoSats for various kinds of data transfer. The basic design of a CubeSat is a 10-centimeter cube with a mass of less than 1.33 kg which can be utilized as earth observing systems. As of mid-2018, more than 2,100 CubeSats have been launched into low-earth orbit [169]. NanoSats or nanosatellites range between 1 to 10 kg, PicoSats or picosatellites weigh between 0.1 to 1 kg (5 cm cube), and FemtoSats or femtosatellites weigh less than 100 g. Other variants such as PocketQubes, TubeSat, and SunCubes are also emerging as a new generation of miniature satellite technologies [170]. Such miniature satellites are easier and cheaper to launch into space, and can form a constellation of communication nodes in-orbit [171], even if they may not be large enough to hold sophisticated instrumentation necessary for remote sensing and earth observation for air pollution mapping applications. With the launch of Nepal's first CubeSat called 'NepaliSat-1' into space on 17 April 2019[172], an important pathway of space technology has definitely opened up for using smaller satellite platforms for at least data transmission related to air pollution mapping of the atmosphere over Nepal.

5.6. Vehicle-mounted mobile air monitoring platforms

Hyper-local air pollution mapping can also be done by mounting air monitoring instrumentation aborad the road vehicles as well. A study published in 2017 utilized Google Street View cars to generate daytime NO, NO_2, and BC data with a resolution of a city block (30 m) in an urban location of Oakland, California in the US [173]. Similar studies have been conducted in Hamilton, Ontario, Canada [174]; Cambridge, Massachusetts, US[175]; Seattle, Washington, US[176], and Antwerp, Belgium [177] among many others. While presenting a promising solution to creating very high-resolution pollution maps of cities and towns, there are a couple of inherent concerns for using the technique of mounting air monitoring sensors directly on vehicles driving around on the streets. First, there is a potential of skewness in data being introduced by traffic patterns. For example, the monitoring vehicle constantly trailing the same high-emitting vehicle for prolonged periods of time. The data can also only be representative of the streets on which the monitoring vehicle is operated on, and there will be no data available for other elevations than the street height. Sensor calibration process and self-emission interference can also pose significant challenges if the monitoring vehicle itsef has a tailpipe emission. Despite these challenges, mobile platforms such as electric cars, buses and trains can still provide valuable real-time data that can be very informative to the regulatory agencies as well as the general public. Such all-electric options are not yet available in Nepal. However, smaller and light-weight low-cost sensors can definitely be a mobile air monitoring option for bicyclists in the urban streets.

6. Discussions

Upon reviewing numerous past research work and the existing air monitoring infrastructure of Nepal, it can be said that there is a massive room for improvement in the air monitoring capabilities in Nepal. Air pollution monitoring not only helps regulators set environmental regulations and policies, but is essential for the greater good of the public health and environment. Knowing the rapidly changing conditions of air pollution dispersion both at larger regional scales as well as smaller hyper-local scales will enable the general public to stay aware about the potential health hazards as well as potential mitigation measures to protect themselves. A better, more prominent environmental protection mechanism similar to the Clean Air Act in the US, and strict enforcement of such regulations is an urgent need for Nepal, given the dire ambient concentrations of air pollutants, such as $PM_{2.5}$ and O_3. Air monitoring is also essential near landfill sites and hospital waste incineration sites to track the movement of HAPs to the surrounding areas, but such monitoring activities are non-existent in Nepal. Also, the emergence of some advanced laboratory facilities capable of providing analytical services such as biological and chemical speciation and quantification of pollutant concentrations in air is also providing new opportunities for the use of passive sampling techniques. Meanwhile, improvement on the current air monitoring mechanisms and supplementing the existing regulatory air monitoring system with the help of citizen science backed by a distributed low-cost instrumentation system (both stationary and mobile) will only help to increase the public awareness and potentially encourage the regulatory agencies as well as general public to act more on their part for the betterment of the air quality in Nepal.

Author contributions

Conceptualization, P.S., R.C.P., S.B., K.D. and A.K.; methodology, P.S., R.C.P., S.B., K.D. and A.K.; investigation, P.S., S.B., K.D., A.K.; resources, P.S., S.B., R.C.P. ; data curation, P.S.; writing—original draft preparation, P.S.; writing—review and editing, R.C.P., S.B., K.D. and A.K.; visualization, P.S.; supervision, R.C.P., S.B., K.D. and A.K.; project administration, P.S., R.C.P., S.B. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no external funding.

Conflicts of interest

The authors declare no conflict of interest.

References

[1] Environmental Defense Fund. Health impacts of air pollution[EB/OL]. https://www.edf.org/health/health-impacts-air-pollution.
[2] Shaffer R M, Blanco M N, Li G, et al. Fine particulate matter and dementia incidence in the adult changes in thought study[J/OL]. Environ. Health Perspect., 2021, 129. DOI: 10.1289/EHP9018.
[3] California Air Resources Board. Health[EB/OL]. https://ww2.arb.ca.gov/our-work/topics/health.
[4] WebMD. Health effects of air pollution[EB/OL]. https://www.webmd.com/a-to-z-guides/ss/slideshow-health-effects-air-pollution.
[5] Johns Hopkins Bloomberg School of Public Health. Graduate programs[EB/OL]. https://publichealth.jhu.edu/departments/environmental-health-and-engineering/programs/graduateprograms.
[6] Kampa M, Castanas E. Human health effects of air pollution[J/OL]. Environ. Pollut., 2008, 151: 362-367. DOI: 10.1016/J.ENVPOL.2007.06.012.
[7] National Geographic Society. air pollution[EB/OL]. https://www.nationalgeographic.org/encyclopedia/air-pollution/.
[8] Air pollution health impacts - global clean air[EB/OL]. https://www.globalcleanair.org/air-pollution-health-impacts/.
[9] Manisalidis I, Stavropoulou E, Stavropoulos A, et al. Environmental and health impacts of air pollution: A review[J/OL]. Front. Public Heal., 2020, 8: 14. DOI: 10.3389/FPUBH.2020.00014.
[10] Health impacts of air pollution in europe, 2021[EB/OL]. https://www.eea.europa.eu/publications/health-risks-of-air-pollution/health-impacts-of-air-pollution.
[11] Centers for Disease Control and Prevention. Air pollution[EB/OL]. https://www.cdc.gov/climateandhealth/effects/air_pollution.htm.
[12] Ambient air pollution[EB/OL]. https://www.who.int/teams/environment-climate-change-and-health/air-quality-and-health/ambient-air-pollution.
[13] Research on health effects from air pollution[EB/OL]. https://www.epa.gov/air-research/research-health-effects-air-pollution.
[14] Juginović A, Vuković M, Aranza I, et al. Health impacts of air pollution exposure from 1990 to 2019 in 43 european countries[J/OL]. Sci. Reports, 2021, 11: 1-15. DOI: 10.1038/s41598-021-01802-5.
[15] Shi L, Zanobetti A, Kloog I, et al. Low-concentration pm2.5 and mortality: Estimating acute and chronic effects in a population-based study[J/OL]. Environ. Health Perspect., 2016, 124: 46-52. DOI: 10.1289/EHP.1409111.
[16] Air pollution and health[EB/OL]. https://unece.org/air-pollution-and-health.
[17] Mahapatra P S, Puppala S P, Adhikary B, et al. Air quality trends of the kathmandu valley: A satellite, observation and modeling perspective[J/OL]. Atmos. Environ., 2019, 201: 334-347. DOI: 10.1016/j.atmosenv.2018.12.043.
[18] Putero D, Cristofanelli P, Marinoni A, et al. Seasonal variation of ozone and black carbon observed at paknajol, an urban site in the kathmandu valley, nepal[J/OL]. Atmos. Chem. Phys., 2015, 15: 13957-13971. DOI: 10.5194/ACP-15-13957-2015.
[19] Begum B A, Biswas S K, Pandit G G, et al. Long–range transport of soil dust and smoke pollution in the south asian region[J/OL]. Atmos. Pollut. Res., 2011, 2: 151-157. DOI: 10.5094/APR.2011.020.
[20] Rupakheti D, Adhikary B, Praveen P S, et al. Pre-monsoon air

quality over lumbini, a world heritage site along the himalayan foothills[J/OL]. Atmos. Chem. Phys., 2017, 17: 11041-11063. DOI: 10.5194/ACP-17-11041-2017.

[21] Jethva H, Satheesh S K, Srinivasan J. Seasonal variability of aerosols over the indo-gangetic basin[J/OL]. J. Geophys. Res. Atmos., 2005, 110: 1-15. DOI: 10.1029/2005JD005938.

[22] Cong Z, Kang S, Gao S, et al. Historical trends of atmospheric black carbon on tibetan plateau as reconstructed from a 150-year lake sediment record[J/OL]. Environ. Sci. Technol., 2013, 47: 2579-2586. DOI: 10.1021/ES3048202/SUPPL_FILE/ES3048202_SI_001.PDF.

[23] Authors C L, Panday A, Kang S, et al. Air pollution in the hindu kush himalaya[M/OL]// Hindu Kush Himalaya Assess. 2019: 339-387. DOI: 10.1007/978-3-319-92288-1_10.

[24] Times N. Waiting for an industrial revolution[EB/OL]. https://archive.nepalitimes.com/regular-columns/Economic-Class/waiting-for-an-industrial-revolution,784.

[25] Sadavarte P, Rupakheti M, Bhave P, et al. Nepal emission inventory - part i: Technologies and combustion sources (neemi-tech) for 2001-2016[J/OL]. Atmos. Chem. Phys., 2019, 19: 12953-12973. DOI: 10.5194/ACP-19-12953-2019.

[26] Nepal - co2 emissions from manufacturing industries and construction as a share of total fuel combustion[EB/OL]. https://knoema.com/atlas/Nepal/topics/Environment/Emissions/CO2-emissions-from-manufacturing-industries-percent.

[27] Pokharel R, Bertolini L, Brommelstroet M, et al. Spatio-temporal evolution of cities and regional economic development in nepal: Does transport infrastructure matter?[J/OL]. J. Transp. Geogr., 2021. DOI: 10.1016/j.jtrangeo.2020.102904.

[28] Nepal road network, road length with category and pavement (in kilometer)[EB/OL]. http://ssrn.aviyaan.com/road_network/getNationCategoryAndPavement.

[29] Etyemezian V, Kuhns H, Gillies J, et al. Vehicle-based road dust emissions measurements: I - methods and calibration[J/OL]. n.d. DOI: 10.1016/S1352-2310(03/00528-4.

[30] Neupane P R, Bajracharya I, Manandhar B R, et al. Estimating emission load from road transportation within the bhaktapur municipality, nepal[J/OL]. J. Environ. Public Health, 2020. DOI: 10.1155/2020/2828643.

[31] Smog, soot, and other air pollution from transportation[EB/OL]. https://www.epa.gov/transportation-air-pollution-and-climate-change/smog-soot-and-local-air-pollution.

[32] Lawrence M G, Lelieveld J. Atmospheric pollutant outflow from southern asia: A review[J/OL]. Atmos. Chem. Phys., 2010, 10: 11017-11096. DOI: 10.5194/ACP-10-11017-2010.

[33] Saud T, Gautam R, Mandal T K, et al. Emission estimates of organic and elemental carbon from household biomass fuel used over the indo-gangetic plain (igp), india[J/OL]. Atmos. Environ., 2012, 61: 212-220. DOI: 10.1016/J.ATMOSENV.2012.07.030.

[34] Sharma S K, Mandal T K, Srivastava M K, et al. Spatio-temporal variation in chemical characteristics of pm10 over indo gangetic plain of india[J/OL]. Environ. Sci. Pollut. Res., 2016, 23: 18809-18822. DOI: 10.1007/S11356-016-7025-2/FIGURES/6.

[35] Tiwari S, Singh A K. Variability of aerosol parameters derived from ground and satellite measurements over varanasi located in the indo-gangetic basin[J/OL]. Aerosol Air Qual. Res., 2013, 13: 627-638. DOI: 10.4209/AAQR.2012.06.0162.

[36] Das B, Bhave P V, Sapkota A, et al. Estimating emissions from open burning of municipal solid waste in municipalities of nepal[J/OL]. Waste Manag., 2018, 79: 481-490. DOI: 10.1016/J.WASMAN.2018.08.013.

[37] Stockwell C E, Christian T J, Goetz J D, et al. Nepal ambient monitoring and source testing experiment (namaste): Emissions of trace gases and light-absorbing carbon from wood and dung cooking fires, garbage and crop residue burning, brick kilns, and other sources[J/OL]. Atmos. Chem. Phys., 2016, 16: 11043-11081. DOI: 10.5194/ACP-16-11043-2016.

[38] Solid waste management in nepal: Current status and policy recommendations[EB/OL]. 2013. https://www.adb.org/sites/default/files/publication/30366/solid-waste-management-nepal.pdf.

[39] Burning trash bad for humans and global warming[EB/OL]. https://www.scientificamerican.com/article/burning-trash-bad-for-humans-and-global-warming/.

[40] Yadav I C, Devi N L, Li J, et al. Altitudinal and spatial variations of polycyclic aromatic hydrocarbons in nepal: Implications on source apportionment and risk assessment[J/OL]. Chemosphere, 2018, 198: 386-396. DOI: 10.1016/J.CHEMOSPHERE.2018.01.075.

[41] Saikawa E, Wu Q, Zhong M, et al. Garbage burning in south asia: How important is it to regional air quality?[J/OL]. Environ. Sci. Technol., 2020, 54: 9928-9938. DOI: 10.1021/ACS.EST.0C02830/SUPPL_FILE/ES0C02830_SI_001.PDF.

[42] Open trash burning polluting valley environment[EB/OL]. https://risingnepaldaily.com/main-news/open-trash-burning-polluting-valley-environment.

[43] Authorities fail to control open waste burning as valley residents breathe polluted air[EB/OL]. https://kathmandupost.com/climate-environment/2021/01/19/authorities-fail-to-control-open-waste-burning-as-valley-residents-breathe-polluted-air.

[44] Open burning of waste is doing big harm to the environment, but nepal is little aware[EB/OL]. https://english.onlinekhabar.com/open-burning-of-waste-is-doing-big-harm-to-the-environment-but-nepal-is-little-aware.html.

[45] Open burning of waste contributing to rise in air pollution levels[EB/OL]. https://thehimalayantimes.com/kathmandu/open-burning-of-waste-contributing-to-rise-in-air-pollution-levels.

[46] Nepal K, of Nepal National Planning Commission Central Bureau of Statistics G. Waste management baseline survey of nepal 2020[EB/OL]. 2021. https://unstats.un.org/unsd/envstats/CensusesandSurveys/Waste-Management-Baseline-Survey-of-Nepal-2020.pdf.

[47] Women and crop residue burning in nepal[EB/OL]. 2020. https://lib.icimod.org/record/34976/files/HimalDoc_FL_WomenCropResidueBurningNepal.pdf.

[48] Nepal banning noisy, polluting diesel taxicabs in capital[EB/OL]. https://www.latimes.com/archives/la-xpm-1999-sep-19-mn-11878-story.html.

[49] Why nepal once led the world in electric buses[EB/OL]. https://www.bloomberg.com/news/articles/2019-08-26/why-nepal-once-led-the-world-in-electric-buses.

[50] Naaqs table[EB/OL]. https://www.epa.gov/criteria-air-pollutants/naaqs-table.

[51] Us embassy, kathmandu, nepal air pollution: Real-time air quality index[EB/OL]. https://aqicn.org/city/nepal/kathmandu/us-embassy/.

[52] En 12341 - european standards[EB/OL]. https://www.en-standard.eu/csn-en-12341-ambient-air-standard-gravimetric-measurement-method-for-the-determination-of-the-pm10-or-pm2-5-mass-concentration-of-suspended-particulate-matter/.

[53] Epa scientists develop and evaluate federal reference & equivalent methods for measuring key air pollutants | us epa[EB/OL]. https://www.epa.gov/air-research/epa-scientists-develop-and-evaluate-federal-reference-equivalent-methods-measuring-key.

[54] Clements A, Vanderpool R. Office of research and development epa tools and resources webinar frms/fems and sensors: Complementary approaches for deter-

mining ambient air quality[EB/OL]. 2019. https://www.epa.gov/sites/default/files/2019-12/documents/frm-fem_and_air_sensors_dec_2019_webinar_slides_508_compliant.pdf.

[55] Lim C, Kim H, Vilcassim M, et al. Mapping urban air quality using mobile sampling with low-cost sensors and machine learning in seoul, south korea[J/OL]. Environ. Int., 2019, 131: 105022. DOI: 10.1016/j.envint.2019.105022.

[56] Park Y. A gps-enabled portable air pollution sensor and web-mapping technologies for field-based learning in health geography[J/OL]. J. Geogr. High. Educ., 2021, 00: 1–21. DOI: 10.1080/03098265.2021.1900083.

[57] Varentsov M, Stepanenko V, Repina I, et al. Balloons and quadcopters: Intercomparison of two low-cost wind profiling methods[J/OL]. Atmosphere (Basel), 2021, 12. DOI: 10.3390/atmos12030380.

[58] Rebeiro-Hargrave A, Motlagh N, Varjonen S, et al. Megasense: Cyber-physical system for real-time urban air quality monitoring[C/OL]// Proc. 15th IEEE Conf. Ind. Electron. Appl. ICIEA 2020. 2020: 1–6. DOI: 10.1109/ICIEA48937.2020.9248143.

[59] Vogt M, Schneider P, Castell N, et al. Assessment of low-cost particulate matter sensor systems against optical and gravimetric methods in a field co-location in norway[J/OL]. Atmosphere (Basel), 2021, 12. DOI: 10.3390/atmos12080961.

[60] Liang C, Yu P. Assessment and improvement of two low-cost particulate matter sensor systems by using spatial interpolation data from air quality monitoring stations[J/OL]. Atmosphere (Basel), 2021, 12. DOI: 10.3390/atmos12030300.

[61] Do T, Tsiligianni E, Qin X, et al. Graph-deep-learning-based inference of fine-grained air quality from mobile iot sensors[J/OL]. IEEE Internet Things J., 2020, 7: 8943–8955. DOI: 10.1109/JIOT.2020.2999446.

[62] Zusman M, Schumacher C, Gassett A, et al. Calibration of low-cost particulate matter sensors: Model development for a multi-city epidemiological study[J/OL]. Environ. Int., 2020, 134: 105329. DOI: 10.1016/j.envint.2019.105329.

[63] Karagulian F, Barbiere M, Kotsev A, et al. Review of the performance of low-cost sensors for air quality monitoring[J/OL]. Atmos., 2019, 10: 506. DOI: 10.3390/ATMOS10090506.

[64] Lee C, Wang Y B, Yu H. An efficient spatiotemporal data calibration approach for the low-cost pm2.5 sensing network: A case study in taiwan[J/OL]. Environ. Int., 2019, 130: 104838. DOI: 10.1016/J.ENVINT.2019.05.032.

[65] Heimann I, Bright V, McLeod M, et al. Source attribution of air pollution by spatial scale separation using high spatial density networks of low cost air quality sensors[J/OL]. Atmos. Environ., 2015, 113: 10–19. DOI: 10.1016/J.ATMOSENV.2015.04.057.

[66] Gao M, Cao J, Seto E. A distributed network of low-cost continuous reading sensors to measure spatiotemporal variations of pm2.5 in xi'an, china[J/OL]. Environ. Pollut., 2015, 199: 56–65. DOI: 10.1016/J.ENVPOL.2015.01.013.

[67] Alvear O, Calafate C, Hernández E, et al. Mobile pollution data sensing using uavs[C/OL]// Proceedins 13th Int. Conf. Adv. Mob. Comput. Multimed., 2015. 2015. DOI: 10.1145/2837126.2843842.

[68] Schlickman E, Andrikanis N, Harrell C, et al. Prototyping an affordable and mobile sensor network to better understand hyperlocal air quality patterns for planning and design[J/OL]. Journal of Digital Landscape Architecture, 2021: 94-100. DOI: 10.14627/537705006.

[69] Alvear O, Zema N, Natalizio E, et al. Using UAV-based systems to monitor air pollution in areas with poor accessibility[J/OL]. Journal of Advanced Transportation, 2017. DOI: 10.1155/2017/8204353.

[70] Pummakarnchana O, Tripathi N, Dutta J. Air pollution monitoring and GIS modeling: A new use of nanotechnology based solid state gas sensors[J/OL]. Science and Technology of Advanced Materials, 2005, 6: 251-255. DOI: 10.1016/j.stam.2005.02.003.

[71] Clements A, Reece S, Conner T, et al. Observed data quality concerns involving low-cost air sensors[J/OL]. Atmosphere Environment X, 2019, 3: 100034. DOI: 10.1016/j.aeaoa.2019.100034.

[72] Do T, Nguyen D, Tsiligianni E, et al. Matrix completion with variational graph autoencoders: Application in hyperlocal air quality inference[C/OL]// ICASSP, IEEE Int. Conf. Acoust. Speech Signal Process. - Proc. 2019: 7535-7539. DOI: 10.1109/ICASSP.2019.8683787.

[73] Ganev B, Marinov M, Nikolov D, et al. High-resolution particulate matter monitoring and mapping in urban environments[C/OL]// 12th Natl. Conf. with Int. Particip. Electron. 2021 - Proc. 2021: 12-15. DOI: 10.1109/ELECTRONICA52725.2021.9513728.

[74] Park J, Jo W, Cho M, et al. Spatial and temporal exposure assessment to PM2.5 in a community using sensor-based air monitoring instruments and dynamic population distributions[J/OL]. Atmosphere (Basel), 2020, 11: 1-15. DOI: 10.3390/atmos11121284.

[75] Williams R, Kilaru V, Snyder E, et al. Air sensors guidbook (epa/600/r-14/159)[R/OL]. 2014. https://cfpub.epa.gov/si/si_public_record_Report.cfm?Lab=NERLŹdirEntryId=277996.

[76] About citizenscience.gov[EB/OL]. n.d. https://www.citizenscience.gov/about/}.

[77] Citizen weather observer program[EB/OL]. n.d. http://wxqa.com/.

[78] The citizenscience.asia journal – medium[EB/OL]. n.d. https://medium.com/citizenscience-asia.

[79] Weingart P, Meyer C. Citizen science in south africa: Rhetoric and reality[J/OL]. Public Understanding of Science, 2021, 30: 605-620. DOI: 10.1177/0963662521996556.

[80] de Sherbinin A, Bowser A, Chuang T R, et al. The critical importance of citizen science data[J/OL]. Frontiers in Climate, 2021, 0: 20. DOI: 10.3389/FCLIM.2021.650760.

[81] Citizen science for conservation in africa (cisca)[EB/OL]. n.d. https://www.cambridgeconservation.org/project/citizen-science-for-conservation-in-africa-cisca/.

[82] Australian citizen science association[EB/OL]. n.d. https://citizenscience.org.au/.

[83] European citizen science association[EB/OL]. n.d. https://ecsa.citizen-science.net/.

[84] Clements A, Ronald Williams A, Kaufman A. How to evaluate low-cost sensors by collocation with federal reference method monitors epa-office of air quality planning and standards introduction and objective[M/OL]. n.d. https://www.epa.gov/sites/default/files/2018-01/documents/collocation_instruction_guide.pdf.

[85] Remediation C D, L. Passive samplers for investigations of air quality: Method description, implementation, and comparison to alternative sampling methods[M/OL]. n.d. http://www.epa.gov/oswer/vaporintrusion/basic.html.

[86] Khuriganova O, Obolkin V, Golobokova L, et al. Passive sampling as a low-cost method for monitoring air pollutants in the baikal region (eastern siberia)[J/OL]. Atmosphere (Basel), 2019, 10. DOI: 10.3390/atmos10080470.

[87] Passive sampler – ogawa usa[EB/OL]. n.d. https://ogawausa.com/passive-sampler/.

[88] Umex 100 passive sampler for formaldehyde[Z]. n.d.

[89] Vieira L, Korf E, Brandli L. Passive samplers for air quality monitoring in a brazilian university[J/OL]. International Journal of Environmental Pollution, 2013, 53: 148-158. DOI: 10.1504/IJEP.2013.058813.

[90] Passive samplers[Z]. n.d.

[91] Tang Y, Cape J, Sutton M. Development and types of passive samplers for monitoring atmospheric no_2 and nh_3 concentrations[J/OL]. 2001: 513-529. DOI: 10.1100/tsw.2001.82.

[92] Bytnerowicz A, Hsu Y M, Percy K, et al. Ground-level air pollution changes during a boreal wildland mega-fire[J/OL]. Science of The Total Environment, 2016, 572: 755-769. DOI: 10.1016/j.scitotenv.2016.07.052.
[93] Oliver K, Jacumin H, Daughtrey E, et al. Method to-15 supplement analysis of 1,1-dce at pptv concentrations[R/OL]. 2002. https://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=66386ŹLab=NERL.
[94] EPA U. Compendium of methods for the determination of toxic organic compounds in ambient air: Method to-11a determination of formaldehyde in ambient air using adsorbent cartridge followed by high performance liquid chromatography (hplc)[R/OL]. 1999. https://www.epa.gov/sites/default/files/2019-11/documents/to-11ar.pdf.
[95] EPA U. Compendium of methods for the determination of toxic organic compounds in ambient air: Method to-13a determination of polycyclic aromatic hydrocarbons (pahs) in ambient air using gas chromatography/mass spectrometry (gc/ms)[R/OL]. 1999. https://www.epa.gov/sites/default/files/2019-11/documents/to-13arr.pdf.
[96] EPA U. Compendium of methods for the determination of toxic organic compounds in ambient air: Method to-17 determination of volatile organic compounds in ambient air using active sampling onto sorbent tubes[R/OL]. 1999. https://www3.epa.gov/ttnamti1/files/ambient/airtox/to-17r.pdf.
[97] Soil water and air testing laboratory pvt. ltd. - swat lab[Z].
[98] Industrial hygiene air sampling training in nepal[Z].
[99] Ecoconcern[EB/OL]. https://ecoconcern.com.np/enpho_lab.
[100] Nepal environmental and scientific services (ness)[Z].
[101] Notes from the field - long history of using aircraft to understand the atmosphere[Z]. n.d.
[102] Noaa csl: Atmospheric composition & chemical processes: Measurements[Z]. n.d.
[103] Park T, Choi Y, Choi J, et al. Aircraft measurements of physicochemical evolution of atmospheric aerosols in air pollution plumes over a megacity and suburban areas[J/OL]. Aerosol and Air Quality Research, 2020, 20: 2485-2494. DOI: 10.4209/AAQR.2019.12.0649.
[104] Stohl A, Forster C, Huntrieser H, et al. Aircraft measurements over europe of an air pollution plume from southeast asia - aerosol and chemical characterization[J/OL]. Atmospheric Chemistry and Physics, 2007, 7: 913-937. DOI: 10.5194/ACP-7-913-2007.
[105] Li C, Stehr J, Marufu L, et al. Aircraft measurements of so_2 and aerosols over northeastern china: Vertical profiles and the influence of weather on air quality[J/OL]. Atmospheric Environment, 2012, 62: 492-501. DOI: 10.1016/J.ATMOSENV.2012.07.076.
[106] Oh S, Cha J, Lee D, et al. Aircraft measurements of long-range trans-boundary air pollutants over yellow sea[J/OL]. Advances in Environmental Monitoring, 2008: 90-106. DOI: 10.1007/978-1-4020-6364-0_7.
[107] Halo research aircraft measuring the emissions of megacities in emerge project[Z].
[108] Zhao D, Tie X, Gao Y, et al. In-situ aircraft measurements of the vertical distribution of black carbon in the lower troposphere of beijing, china, in the spring and summer time[J/OL]. Atmosphere, 2015, 6: 713-731. DOI: 10.3390/ATMOS6050713.
[109] Eufar - aircraft measurements of air quality in the uk[Z].
[110] Brown S, Baasandorj M, Franchin A, et al. Aircraft measurements to characterize polluted winter boundary layers: Overview of twin otter flights during the utah winter fine particulate matter study[J/OL]. AGU Fall Meeting Abstracts, 2017. https://ui.adsabs.harvard.edu/abs/2017AGUFM.A52B..02B/abstract.
[111] Liu Q, Quan J, Jia X, et al. Vertical profiles of aerosol composition over beijing, china: Analysis of in situ aircraft measurements[J/OL]. Journal of Atmospheric Science, 2019, 76: 231-245. DOI: 10.1175/JAS-D-18-0157.1.
[112] Rosenfeld D, Woodley W, Axisa D, et al. Aircraft measurements of the impacts of pollution aerosols on clouds and precipitation over the sierra nevada[J/OL]. Journal of Geophysical Research: Atmospheres, 2008, 113. DOI: 10.1029/2007JD009544.
[113] NSF - National Science Foundation. Atmospheric scientists take to the skies to study colorado front range ozone pollution[EB/OL]. n.d. https://www.nsf.gov/discoveries/disc_summ.jsp?cntn_id=131977Źorg=NSF.
[114] Somas takes flight to measure air quality in the arctic and nyc[EB/OL]. n.d. https://news.stonybrook.edu/homespotlight/somas-air-flights-will-measure-pollutants-in-the-arctic-and-nyc/.
[115] Carroll J, Dixon A. Keeping tahoe blue through atmospheric assessment: Aircraft and boat measurements of air quality and meteorology near and on lake tahoe, 2004[R/OL]. 2004. https://ww2.arb.ca.gov/sites/default/files/classic/research/apr/past/01-326.pdf.
[116] Singh A, Mahata K, Rupakheti M, et al. An overview of airborne measurement in nepal - part 1: Vertical profile of aerosol size, number, spectral absorption, and meteorology[J/OL]. Atmospheric Chemistry and Physics, 2019, 19: 245-258. DOI: 10.5194/acp-19-245-2019.
[117] Observing the global atmosphere by instrumented passenger aircraft – the story of iagos[EB/OL]. n.d. https://public.wmo.int/en/resources/bulletin/observing-global-atmosphere-instrumented-passenger-aircraft-âĂŞ-story-of-iagos.
[118] Colomina I, Molina P. Unmanned aerial systems for photogrammetry and remote sensing: A review[J/OL]. ISPRS Journal of Photogrammetry and Remote Sensing, 2014, 92: 79-97. DOI: 10.1016/J.ISPRSJPRS.2014.02.013.
[119] Gu Q, Michanowicz D, Jia C. Developing a modular unmanned aerial vehicle (uav) platform for air pollution profiling[J/OL]. Sensors, 2018, 18: 4363. DOI: 10.3390/S18124363.
[120] Villa T, Salimi F, Morton K, et al. Development and validation of a uav based system for air pollution measurements[J/OL]. Sensors, 2016, 16: 2202. DOI: 10.3390/S16122202.
[121] Haas P, Balistreri C, Pontelandolfo P, et al. Development of an unmanned aerial vehicle (uav) for air quality measurements in urban areas[C/OL]// 32nd AIAA Applied Aerodynamics Conference. 2014. DOI: 10.2514/6.2014-2272.
[122] Andaluz V, Chicaiza F, Cuzco G, et al. Autonomous monitoring of air quality through an unmanned aerial vehicle[J/OL]. Lecture Notes in Computer Science, 2019, 11606 LNAI: 146-157. DOI: 10.1007/978-3-030-22999-3_14.
[123] McGonigle A, Aiuppa A, Giudice G, et al. Unmanned aerial vehicle measurements of volcanic carbon dioxide fluxes[J/OL]. Geophysical Research Letters, 2008, 35. DOI: 10.1029/2007GL032508.
[124] Koo V, Chan Y, Gobi V, et al. A new unmanned aerial vehicle synthetic aperture radar for environmental monitoring[J/OL]. Progress in Electromagnetics Research, 2012, 122: 245-268. DOI: 10.2528/PIER11092604.
[125] Fumian F, Di Giovanni D, Martellucci L, et al. Application of miniaturized sensors to unmanned aerial systems, a new pathway for the survey of polluted areas: Preliminary results[J/OL]. Atmosphere, 2020, 11: 471. DOI: 10.3390/ATMOS11050471.
[126] Wang D, Wang Z, Peng Z, et al. Using unmanned aerial vehicle to investigate the vertical distribution of fine particulate matter[J/OL]. International Journal of Environmental Science and Technology, 2020, 17: 219-230. DOI: 10.1007/S13762-019-02449-6.
[127] Szymocha S, Piwowarski D, Anweiler S. Unmanned aerial vehicle application for air pollution monitoring[C/OL]// AIP

Conference Proceedings: volume 2029. 2018: 020073. DOI: 10.1063/1.5066535.

[128] Sulewski M, Ambroziak L, Kondratiuk M, et al. Identification of electric propulsion system for unmanned aerial vehicles[C/OL]// AIP Conference Proceedings: volume 2029. 2018. DOI: 10.1063/1.5066534.

[129] Lee S, Choi Y. Reviews of unmanned aerial vehicle (drone) technology trends and its applications in the mining industry[J/OL]. DOI: 10.1080/12269328.2016.1162115, 2016, 19: 197-204. DOI: 10.1080/12269328.2016.1162115.

[130] Li B, Cao R, Wang Z, et al. Use of multi-rotor unmanned aerial vehicles for fine-grained roadside air pollution monitoring[J/OL]. 2019, 2673: 169-180. DOI: 10.1177/0361198119847991.

[131] Schuyler T, Guzman M. Unmanned aerial systems for monitoring trace tropospheric gases[J/OL]. Atmosphere, 2017, 8: 206. DOI: 10.3390/ATMOS8100206.

[132] Unmanned aerial systems for monitoring trace tropospheric gases[EB/OL]. n.d. https://www.mdpi.com/2073-4433/8/10/206.

[133] Peng Z, Wang D, Wang Z, et al. A study of vertical distribution patterns of pm2.5 concentrations based on ambient monitoring with unmanned aerial vehicles: A case in hangzhou, china[J/OL]. Atmospheric Environment, 2015, 123: 357-369. DOI: 10.1016/J.ATMOSENV.2015.10.074.

[134] Wu C, Liu B, Wu D, et al. Vertical profiling of black carbon and ozone using a multicopter unmanned aerial vehicle (uav) in urban shenzhen of south china[J/OL]. Science of The Total Environment, 2021, 801. DOI: 10.1016/j.scitotenv.2021.149689.

[135] Liu X, Shi X, Di He H, et al. Vertical distribution characteristics of particulate matter beside an elevated expressway by unmanned aerial vehicle measurements[J/OL]. Building and Environment, 2021, 206. DOI: 10.1016/j.buildenv.2021.108330.

[136] A study of vertical distribution patterns of pm2.5 concentrations based on ambient monitoring with unmanned aerial vehicles: A case in hangzhou, china[EB/OL]. n.d. https://www.sciencedirect.com/science/article/abs/pii/S1352231015304908.

[137] Song R, Wang D, Li X, et al. Characterizing vertical distribution patterns of pm2.5 in low troposphere of shanghai city, china: Implications from the perspective of unmanned aerial vehicle observations[J/OL]. Atmospheric Environment, 2021, 265. DOI: 10.1016/j.atmosenv.2021.118724.

[138] Pochwała S, Anweiler S, Deptuła A, et al. Optimization of air pollution measurements with unmanned aerial vehicle low-cost sensor based on an inductive knowledge management method[J/OL]. Optimization and Engineering, 2021, 22: 1783-1805. DOI: 10.1007/S11081-021-09668-2.

[139] Pochwała S, Gardecki A, Lewandowski P, et al. Developing of low-cost air pollution sensor—measurements with the unmanned aerial vehicles in poland[J/OL]. Sensors, 2020, 20: 3582. DOI: 10.3390/S20123582.

[140] Hernández-Vega J, Varela E, Romero N, et al. Internet of things (iot) for monitoring air pollutants with an unmanned aerial vehicle (uav) in a smart city[J/OL]. Lecture Notes Institute of Computer Sciences, Social Informatics and Telecommunications Engineering (LNICST), 2018, 213: 108-120. DOI: 10.1007/978-3-319-73323-4_11.

[141] Lambey V, Prasad A. A review on air quality measurement using an unmanned aerial vehicle[J/OL]. Water, Air, Soil Pollution, 2021, 232: 2323. DOI: 10.1007/S11270-020-04973-5.

[142] Villa T, Gonzalez F, Miljevic B, et al. An overview of small unmanned aerial vehicles for air quality measurements: Present applications and future prospectives[J/OL]. Sensors, 2016, 16: 1072. DOI: 10.3390/S16071072.

[143] Rohi G, Ejofodomi O, Ofualagba G. Autonomous monitoring, analysis, and countering of air pollution using environmental drones[J/OL]. Heliyon, 2020, 6: e03252. DOI: 10.1016/J.HELIYON.2020.E03252.

[144] Real-time atmospheric monitoring of urban air pollution using unmanned aerial vehicles[M/OL]// Air Pollution XXVII. WIT Press, n.d.: 79-88. https://books.google.com/books?hl=enŹlr=Źid=NM2uDwAAQBAJŹoi=fndŹpg=PA79Źdq=unmanned+aerial+drone+air+pollution+measurementŹots=9WdyOcd_alŹsig=kjItozD4zq91QE814mm32qwxbLY}v=onepageŹq=unmannedaerialdroneairpollutionmeasurementŹf=false.

[145] Kersnovski T, Gonzalez F, Morton K. A uav system for autonomous target detection and gas sensing[C/OL]// IEEE Aerospace Conference Proceedings. 2017: 1-12. DOI: 10.1109/AERO.2017.7943675.

[146] Khan A, Schaefer D, Tao L, et al. Low power greenhouse gas sensors for unmanned aerial vehicles[J/OL]. Remote Sensing, 2012, 4: 1355-1368. DOI: 10.3390/RS4051355.

[147] Berman E, Fladeland M, Liem J, et al. Greenhouse gas analyzer for measurements of carbon dioxide, methane, and water vapor aboard an unmanned aerial vehicle[J/OL]. Sensors and Actuators B: Chemical, 2012, 169: 128-135. DOI: 10.1016/j.snb.2012.04.036.

[148] Bates T, Quinn P, Johnson J, et al. Measurements of atmospheric aerosol vertical distributions above svalbard, norway, using unmanned aerial systems (uas)[J/OL]. Atmospheric Measurement Techniques, 2013, 6: 2115-2120. DOI: 10.5194/amt-6-2115-2013.

[149] Zheng T, Li B, Li X, et al. Vertical and horizontal distributions of traffic-related pollutants beside an urban arterial road based on unmanned aerial vehicle observations[J/OL]. Building and Environment, 2021, 187: 107401. DOI: 10.1016/J.BUILDENV.2020.107401.

[150] Caan - drone[EB/OL]. n.d. https://caanepal.gov.np/drone.

[151] Air quality modeling - surface and upper air databases | us epa[EB/OL]. https://www.epa.gov/scram/air-quality-modeling-surface-and-upper-air-databases.

[152] 810-hb-srp nasa sounding rockets user handbook[EB/OL]. 2015. https://sites.wff.nasa.gov/code810/files/SRHB.pdf.

[153] 6 sounding rockets[EB/OL]. http://wsn.spaceflight.esa.int/docs/EUG2LGPr3/EUG2LGPr3-6-SoundingRockets.pdf.

[154] Zhou L, Sheng Z, Fan Z, et al. Data analysis of the tk-1g sounding rocket installed with a satellite navigation system[J/OL]. Atmos., 2017, 8: 199. DOI: 10.3390/ATMOS8100199.

[155] Wijtvliet M, Pont B, Brinkerink C, et al. Pr3: A system for radio-interferometry and radiation measurement on sounding rockets[J/OL]. Microprocess. Microsyst., 2020, 77: 103163. DOI: 10.1016/J.MICPRO.2020.103163.

[156] 2011esasp.700...37e page 37[EB/OL]. http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?bibcode=2011ESASP.700...37EŹdb_key=ASTŹpage_ind=0Źdata_type=GIFŹtype=SCREEN_VIEWŹclassic=YES.

[157] Li J, Sheng Z, Fan Z, et al. Data analysis of upper atmosphere temperature detected by sounding rockets in china[J/OL]. J. Atmos. Ocean. Technol., 2017, 34: 555–565. DOI: 10.1175/JTECH-D-16-0104.1.

[158] Russian meteorological and geophysical rockets of new generation - nasa/ads[EB/OL]. https://ui.adsabs.harvard.edu/abs/2015ESASP.730..467Y/abstract.

[159] Friends of crc[EB/OL]. https://www.friendsofcrc.ca/Projects/SoundingRockets/rocket.html.

[160] Garuda-spaceport america cup-2021 – seds-nepal[EB/OL]. http://sedsnepal.org/garuda-spaceport-america-cup/.

[161] Dhungel S, Kathayat B, Mahata K, et al. Transport of regional pollutants through a remote trans-himalayan valley in nepal[J/OL]. Atmos. Chem. Phys., 2018, 18: 1203–1216. DOI: 10.5194/acp-18-1203-2018.

[162] Regmi R, Kitada T, Maharjan S, et al. Wintertime boundary layer evolution and air pollution potential over the kathmandu

valley, nepal[J/OL]. J. Geophys. Res. Atmos., 2019, 124: 4299–4325. DOI: 10.1029/2018JD030198.

[163] Islam M, Jayarathne T, Simpson I, et al. Ambient air quality in the kathmandu valley, nepal, during the pre-monsoon: Concentrations and sources of particulate matter and trace gases[J/OL]. Atmos. Chem. Phys., 2020, 20: 2927–2951. DOI: 10.5194/ACP-20-2927-2020.

[164] Baral B, Thapa K. Effect of the covid-19 lockdown on ambient air quality in major cities of nepal[J/OL]. J. Heal. Pollut., 2021, 11: 1–17. DOI: 10.5696/2156-9614-11.29.210211.

[165] Air quality | earthdata[EB/OL]. https://earthdata.nasa.gov/earth-observation-data/near-real-time/hazards-and-disasters/air-quality.

[166] Star - noaa / nesdis / center for satellite applications and research - air quality remote sensing program[EB/OL]. https://www.star.nesdis.noaa.gov/star/AQ_index.php.

[167] Yorks J, Selmer P, Kupchock A, et al. Aerosol and cloud detection using machine learning algorithms and space-based lidar data[J/OL]. Atmosphere (Basel)., 2021, 12. DOI: 10.3390/atmos12050606.

[168] Tracking air quality from above – climate change: Vital signs of the planet[EB/OL]. https://climate.nasa.gov/news/547/tracking-air-quality-from-above/.

[169] Cubesats: Tiny payloads, huge benefits for space research | space[EB/OL]. https://www.space.com/34324-cubesats.html.

[170] What is a cubesat? nanosatellite? pocketqube? | nanosats database[EB/OL]. https://www.nanosats.eu/cubesat}tubesat.

[171] Small is beautiful: Us military explores use of microsatellites[EB/OL]. https://www.defenseindustrydaily.com/Small-Is-Beautiful-US-Military-Explores-Use-of-Microsatellites-06720/}definitions.

[172] Nepalisat-1 @ nanosats database[EB/OL]. https://www.nanosats.eu/sat/nepalisat-1.

[173] Apte J, Messier K, Gani S, et al. High-resolution air pollution mapping with google street view cars: Exploiting big data[J/OL]. Environ. Sci. Technol., 2017, 51: 6999–7008. DOI: 10.1021/ACS.EST.7B00891/SUPPL_FILE/ES7B00891_SI_002.XLS.

[174] Adams M, Corr D. A mobile air pollution monitoring data set[J/OL]. Data, 2019, 4: 2. DOI: 10.3390/DATA4010002.

[175] deSouza P, Anjomshoaa A, Duarte F, et al. Air quality monitoring using mobile low-cost sensors mounted on trash-trucks: Methods development and lessons learned[J/OL]. Sustain. Cities Soc., 2020, 60: 102239. DOI: 10.1016/J.SCS.2020.102239.

[176] Xiang J, Austin E, Gould T, et al. Using vehicles' rendezvous for in situ calibration of instruments in fleet vehicle-based air pollution mobile monitoring[J/OL]. Environ. Sci. Technol., 2020, 54: 4286–4294. DOI: 10.1021/ACS.EST.0C00612/SUPPL_FILE/ES0C00612_SI_001.PDF.

[177] den Bossche J V, Theunis J, Elen B, et al. Opportunistic mobile air pollution monitoring: A case study with city wardens in antwerp[J/OL]. Atmos. Environ., 2016, 141: 408–421. DOI: 10.1016/J.ATMOSENV.2016.06.063.