International Journal for Multidisciplinary Research (IJFMR)

E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Black Carbon: Its Sources, Environment and Health Impacts & Mitigation Solutions for Sustainable Development

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Abstract

Black carbon (BC), in spite of being a short-lived climate pollutant (SLCP), with life time of only few days, is found to be a powerful climate forcer that has hundreds to thousand times more potential of warming the atmosphere than carbon dioxide. It severely affects climate, cryosphere, human health, ecosystems and agricultural productivity.

BC is a formed by the incomplete combustion of fossil fuels, wood and other fuels. Household cooking methods are the major contributor of the global carbon emissions, followed by transport, industrial and agriculture sectors. Wild fires also contribute to BC emission. BC absorbs the incoming solar radiation which heats the atmosphere, affecting the cloud formation and rainfall in the region. which is critical for agriculture, affecting human livelihoods in addition to ecosystem. This, in turn, affects the economy. Its deposition on ice/snow, reduces its surface albedo that increases the absorption of sunlight, in turn, faster melting of ice/glaciers and rise in sea level. The Arctic and glaciated regions of Himalayas are under high risk. Being small enough in size, black carbon can be inhaled, contributing to respiratory and cardiovascular diseases leading to lung cancer and even to birth defects.

Coordinated efforts would be required for attaining zero carbon emission for sustainable development, a goal set by UNEP. This paper presents a review on the various sources of black carbon, its effects on environment, health and economy. The steps to be taken to reduce the black carbon level for sustainable development are also reviewed.

Keywords: Black carbon, cryosphere, glacier melting, health, economy, environmental degradation, sustainable development

1. Introduction

Black carbon (BC), in spite of being a short-lived climate pollutant, with life time of only 4-12 days, is found to be a powerful climate forcer having hundreds to thousand times more Global warming potential (GWP) than carbon dioxide. It severely affects climate, cryosphere, human health, ecosystems and agricultural productivity. BC Emissions are the second largest contributor to current global warming, next to CO_2. BC's climate forcing is 1.0–1.2 W/m^2, nearly 55% of that of CO_2. Household cooking methods contribute to more than 50% of the global carbon emissions, followed by transport sector with nearly 25%, brick kiln with 6 % and agriculture sector 5%. Wild fires including Zombie fires also contribute to black carbon emission. The Arctic fires during 2019-2020 were found to be spreading underground in addition to burning trees and grass on ground, are known as "zombie fires". They burn slowly and release vast amounts of smoke into the atmosphere and are harder for fire fighters to extinguish. Wildfire emissions include various organic species along with carbon dioxide, and black carbon (Yokelson et al.,2007) and their percentage depends on meteorological conditions, vegetation type, humidity, and topography of the land etc. To curb the global BC due to wildfires a complementary action to curb 'Soot' and 'Smog' pollution could help limit global temperature rise to below 2 degrees (UNEP/WMO 2011).

BC absorbs the incoming solar radiation which heats the atmosphere, affecting the cloud formation and rainfall in the region which is critical for agriculture, affecting human livelihoods in addition to ecosystem. This, in turn, affects the economy. BC deposition on ice/snow, reduces its surface albedo due to darkening of its surface that increases the absorption of sunlight, results in faster melting of ice/glaciers and rise in sea level. The Arctic and glaciated regions of the Himalayas are severly affected. BC in snow/ ice in the Himalayan region are much higher than that in the polarregions. (https://doi.org/10.1016/j.earscirev.2020.103346). A decrease in BC concentration in 1970s in Arctic and European ice cores were due to the First Clean Air Act 1956 formulated and implemented after severe London Fog in 1952 which killed nearly 16000 people (https://www.legislation.gov.uk/ukpga/Eliz2/4-5/52/enacted) . The concentration of BC depends on a number of factors including population growth, individual energy usage, urbanization, transformation to gas from wood or coal for domestic cooking and upgradation of cook stove. An updated estimation of annual global BC emissions from wildfires and various man made sources, including power generation, industry, on road motor vehicles, off-road machinery, shipping, aviation along with domestic, agriculture and waste burning taking into account all the above mentioned factors is reported by Xu et al.(2021). The residential BC emissions show significant increase due to population as well as per capita energy consumption increase. The increase, however, was slowed down due to switching to better fuel use and stove upgrading.

These increments in BC concentration have deteriorating health effects. Being small enough in size ($PM_{2.5}$), black carbon can be inhaled, contributing to respiratory and cardiovascular diseases leading to lung cancer and birth defects. Coordinated efforts would, therefore, be required for attaining minimise carbon emissions for sustainable development. So, Climate and Clean Air Coalition (CCAC) ministers under UNEP approved strategies in 2021 to significantly reduce the SLCPs—including methane, HFCs, black carbon, and tropospheric ozone—by 2030. This paper presents a review on the various sources of black carbon, its effects on environment, health and economy. The steps to be taken to reduce the black carbon level for sustainable development are also reviewed.

2. Sources and properties of Black Carbon

Black carbon is released as soot, a complex mixture of gases including carbon dioxide, carbon monoxide, volatile organic compounds, and particulate matter organic carbon from burning of various types of fuels. The complex mixture of gases and particulate matter that arises from this process is often referred to as soot. Black carbon is far more efficient at retaining heat than carbon dioxide, thus making it a much more serious contributor to global warming that is between 460 and 1,500 times greater than CO_2. Fig.1 shows the black carbon emissions from different parts of the world, indicating that Asia and pacific region account for nearly 59% with 3.9 million tons. Indo-Gangetic plains, Eastern China and other South East Asian countries being hotspots with the China (1220 Gg) and India (1044 Gg) being at the top (Hu et al.,2021). The rate of melting of ice on Antarctica has tripled making the corresponding rise in sea level from 0.2 to 0.6 2012 mm/year for the period from2012 to 2017 (The IMBIE team,2018).

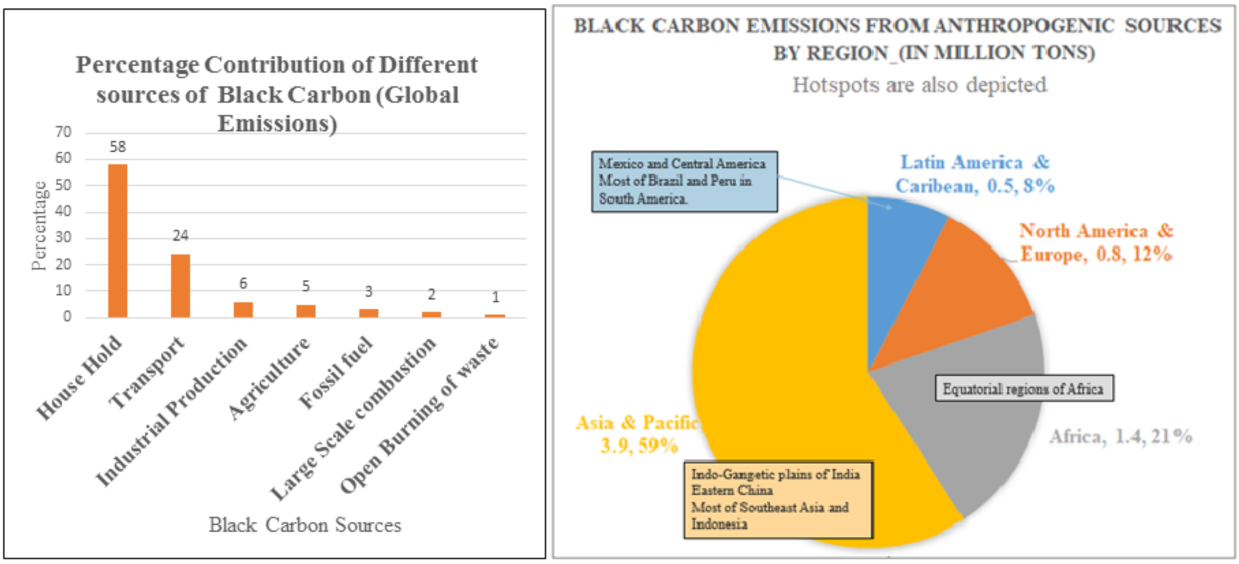

Fig.1: Anthropogenic sources of black carbon by region with hotspots

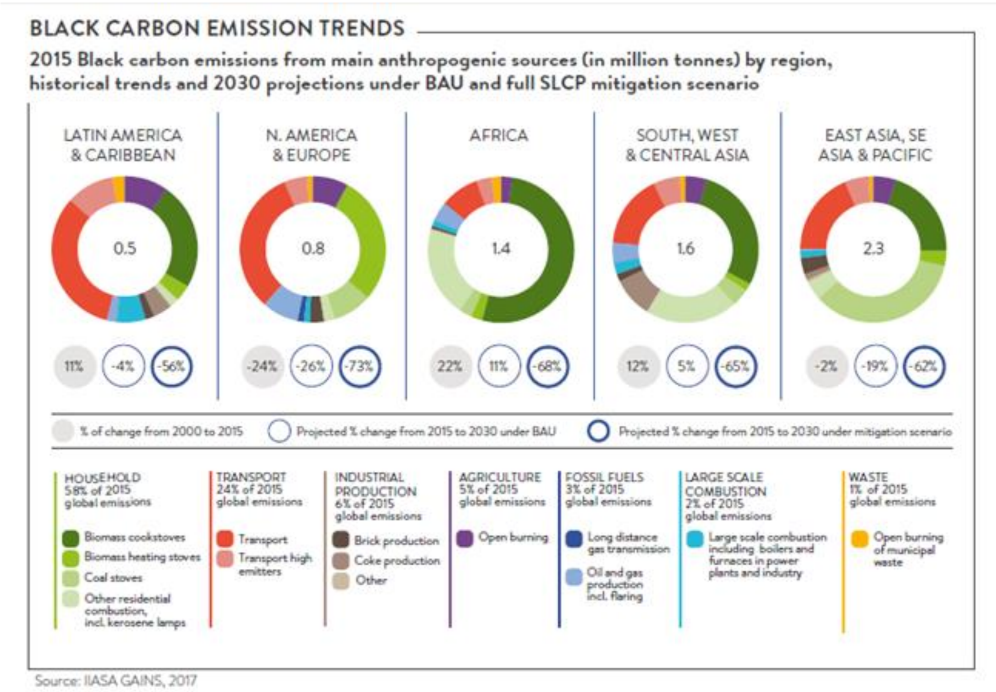

Fig.2: Black Carbon Emission Trends from various anthropogenic Sources along with projections for future (with and without mitigation) (https://www.acoem.com/india/blog/black-carbon-why-is-this-air-pollutants-effect-on-climate-change-not-addressed-more-often/)

In Asia and Africa, main contributor is residential solid fuels contributing 60-80% of emissions, whereas in Europe and North America BC is mainly emitted by diesel engines (70% of emissions). The physical and chemical properties of BC are important for predicting their radiative forcing in the atmosphere. These aerosols pass through coagulation, condensation and oxidation processes in the atmosphere and become hydrophobic to hydrophilic, which influence their activation capacity to become cloud condensation nuclei (CCN) and consequently affects cloud formation. These aerosols are normally small of nanometer size with large specific surface areas and they could be easily inhaled and deposited in the respiratory track. BC particles with size smaller than 2 mm, remain airborne in the atmosphere and can either suffer long distance transport or may be deposited in the soil, river or oceans through precipitation and runoff. Larger BC particles may, however, deposit on the soil, close to where these are produced. These help in promoting C sequestration and enhancing nutrient sorption via bioturbation.

3. Measurement and modeling of Black Carbon emissions

In spite of being an SLCP, BC plays a vital role in global climate system (Skiles et al.,2018). Increased BC enhances the absorption of light (Lee et al.,2022) and that induces snow and ice melting, that in turn, affects the regional hydrology (Pritchard,2019). However, the role of BC in the cryosphere is not properly understood owing to the discrepancies in the results of snow and ice in the earlier reported studies which are dependent on the measurement method/simulation model used (Kang et al.,2020). Firstly, the presence of mineral dust also affects the deduced BC concentrations which forms agglomerates, causing reduction of the evaluated BC concentrations (Wang et al.,2012). So, the origin of BC should also be considered for the determination of its concentrations. Due to little knowledge of the vertical distributions of BC modelling studies of BC was limited. The first real-time black carbon measurements of its vertical distributions in the Arctic region were acquired with an aethalometer (Hansen et al., 1984). These measurements showed considerable concentrations of black carbon in the western Arctic troposphere including the North Pole. Aethalometers and thermal-optical analyzers are now used to measure the optical properties of aerosols. A multi-angled absorption photometer uses transmitted as well as reflected light. Satellite based measurements of optical depth are applicable, generally, for large areas (https://en.wikipedia.org/wiki/Black_carbon). Due to its very short life time, it first effects the local environment. Thus, an accurate estimation of black carbon (BC) emissions at regional level is needed for evaluating its health and climate impact.

If BC is measured optically, it is called equivalent black carbon (EBC). It is found that EBC concentrations during the heating season were much higher than those during the non heating season (Chen et al, 2021). The main sources of EBC aerosols are liquids during the whole year whereas during the heating season solid sources are dominant. https://clearseas.org/en/blog/black-carbon-in-the-arctic-what-you-need-to-know/

4. Black Carbon Emissions in India

Delhi the most polluted capital city in the world (IQAir, 2022 https://www.iqair.com/world-air-quality-report). Measurement of particulate matter including BC over urban areas is very important to understand its adverse effects on health and climate. Recently, BC mass concentration measurement for Delhi are reported using a characterized continuous soot monitoring system (COSMOS) (Malik et al., 2022). Winter is found to be the most polluted season. Regional emission from crop burning in nearby states along with cracker burning in festivals during October and November is the main contributor of increased pollution. Ambient equivalent black carbon (BC) measurements were taken at Satopanth and Bhagirath-Kharak Glaciers of Central Himalaya (Sandeep et al., 2021). Hourly BC showed large variations. Monthly averaged BC recorded during pre-monsoon season was the highest that got decreased to minimum in the monsoon season due to fast removal due to wet deposition before it is transported to long distance. During June, September, and October the transport of BC from the polluted Indo-Gangetic Plain (IGP) region, wildfires, and vehicular emissions towards the valley region was responsible for the high influx of BC An aircraft study was done to get the major aerosols and their physical and chemical properties along with their special distribution across the Indo-Gangetic Plain (Brooks et al.,2019). Forest fires are a regular phenomenon in Uttarakhand and the regions are classified into 5 categories, namely, extremely, highly normal, moderately, less fire prone forests. There is was a positive correlation between the number of forest fires and maximum temperature. These fires caused the loss of carbon sequestered in forest biomass carbon stock (Mina et al.,2023; Kumar et al.,2019). We have studied the fire activity during 2019 to 2021 using the satellite data through Giovanni and Firms for forest fire counts and associated, pollutants NO_2, SO_2, including brightness and temperature (Gaur et al., 2021). It was found that maximum fire events were reported on May 8, 2019 (1833), December 27, 2020 (191) and April 3, 2021(1855). That study is further extended to find the columnar mass density of black carbon, on the days with high fire events to investigate the effect of fire on the BC and to study the correlation between forest fire activity and BC concentration. Fig.3 shows that the BC has a maximum three days later after the maximum number of fires occurred for the years 2019 and 2021 whereas the BC column mass density attained maximum value on the same day in the year 2020. The column mass density for the whole February month in each of these year were also found when there was negligible fire activity and presented in fig. 4. Comparing figures 3 and 4, it is found that for the year 2020, the BC density is found to increase 2 times whereas BC got decreased for the year 2021. In the year 2019, it was two order of magnitude higher in February than in May, in spite of high fire activity. This may be due to COVID-19 lockdown. These figures also show that there is a diurnal variation found in the column mass density.

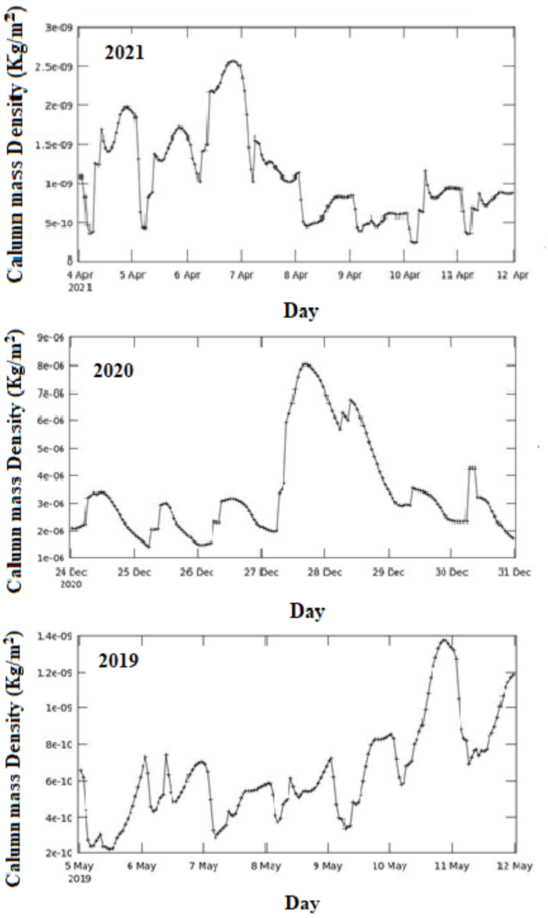

Fig.3 Column mass densities of BC during highest fire activity in 2019,2020 &2021

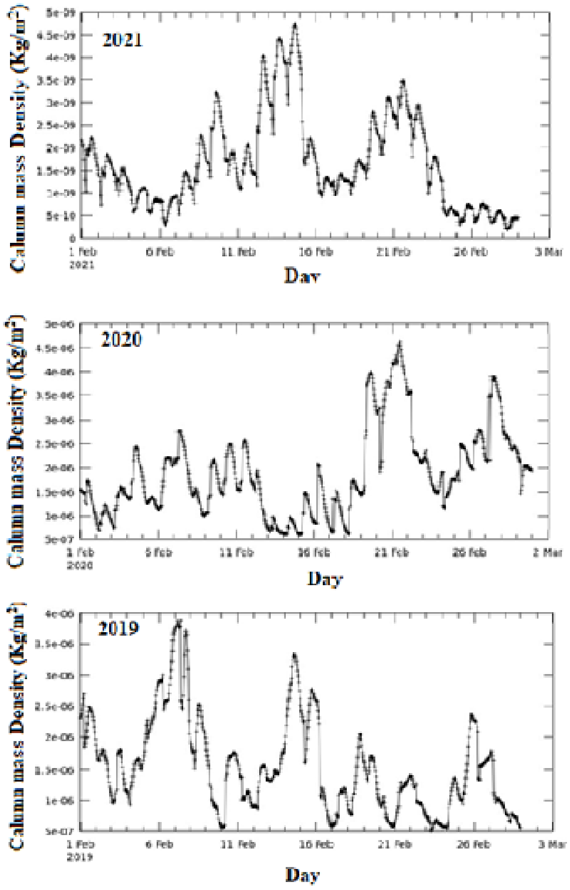

Fig.4.Column mass densities of BC during entire February month with no fire activity in 2019, 2020 & 2021

Himalayan region is very important to the Indian subcontinent in deciding the weather and climate in the region. The glaciers in the region are melting at a high rate due to the global warming and thus is being studied and monitored by various research scientists from India and abroad as well as government agencies and organization. The Geosphere Biosphere Programme of Indian Space Research Organization (ISRO) is network of aerosol observatories. The long-term measurements of BC over the Indian region show a decreasing trend (0.24 µg $m^{-3}year^{-1}$) in the past decade.

. The mean retreat rate of Hindu Kush Himalayan glaciers is 14.9 ± 15.1 meter/annum (m/a); considering three main rivers Indus, Ganga and Brahmaputra river basins in the Himalayan region. The breaking of dams can cause increased flooding leading to glacier lake outburst floods (GLOFs). This increases the risk of extreme weather events and risk related to glacier hazards impacting the agro practices in high Himalayan region. (Gul et al.,2021) have shown that black carbon contributed 39% to the total on glacier melting in pre monsoon season in central Himalayan region during the period.

5. Presence of BC in soils

Up to 60% of the total organic carbon stored in soils is due to BC that participates in various biogeochemical processes with positive impacts on the ecosystem besides its harmful effects (Lian, and Xing,2017). It serves as reservoir for nutrients especially for tropical soils. Soils with high BC are more fertile than those without it eg. Terra preta soil of central Amazonia which has better nutrient retention capacity in addition to higher content of organic matter as compared to the neighbouring infertile soils.

(Glaser B.,2007). BC content in the soil is also increased by using slash and burn agricultural practices. It increases the productivity of the soil by releasing nutrients from the burned vegetation. However, it adds high emissions of CO_2 and volatile BC to the atmosphere also, so for a sustainable management, a better method of slash-and-char practice should be used.

Soil carbon sequestration, also known as "carbon farming", includes various ways by applying low-till or no-till practices, by altering planting schedules or rotations and applying compost/crop residues to fields. These practices not only have economic benefits, but also works as carbon dioxide sinks. It helps in restoring soil health of the degraded soils and thus increases agricultural productivity. Healthier soils require less fertilizers, hence, saving farmers money and reducing environmental impacts and can withstand both droughts and heavy rainfall.

6. Presence of BC in waters

Soluble and colloidal BC from land ultimately drain into rivers and oceans these dissolved BC significantly affects the marine environment (Yamashita et al., 2022). On global scale, the flow of black carbon into fresh and salt water bodies approximates the rate of wildfire black carbon production. An increasing number of ships use Arctic waters, for faster routes between the Pacific and Atlantic oceans. The BC from the engine exhaust settles on to polar ice and snow. That causes 10 times more BC in the Arctic region as compared to other regions of the world. Another source of black carbon in ocean includes oil-spills which is very frequent. One such incident occurred in 2010 in Gulf oil spill. The spilled oil was intentionally burned to and minimize its impacts on marine ecosystems and costal land life. The controlled burning, however, released more than one million pounds of BC into the atmosphere which affects both climate and human health (Perring et al., 2011). This presents a threat to the region and the whole world, so should be tackled with great care and more studies are required to assess the damage and policies should be made for future. (https://clearseas.org/en/blog/black-carbon-in-the-arctic-what-you-need-to-know/#:~:text=Black%20carbon%20emissions%20from%20ships,an%208%25%20increase%20globally2).

7. Mitigation Solutions to reduce black carbon emissions

Due to its short life time, black carbon is rapidly removed from the atmosphere by deposition. Thus, black carbon emission reductions is possible with mitigation strategies. The sources of BC are wide-ranging, so are the ways to cut it down.

(a) Domestic emission curbing

- By stopping slash-and-burn agriculture and using slash-and-char method, in which wood biomass is turned into charcoal by low-intensity covered heating fires.
- By using less-polluting cook stoves that use fuels like LPG. It would reduce fuel cost and time
- That, in turn reduce deforestation.
- By Modernizing traditional brick kilns to Vertical Shaft Brick Kilns

(b) **To curb black carbon emissions from diesel vehicles**

According to a study, 18% of all deaths and a loss of 1.4 % of GDP in 2020 could be attributed to air pollution. In pollution hotpots transport sector contributes 13-18 % during peak pollution months. (Panday et al. 2021). So, following steps are to be implemented.

- Setting vehicle emissions standards,
- Fitting older vehicles with diesel particulate filters or phasing out them

- people should be encouraged by giving incentives to replace old vehicles with newer, cleaner ones
- Providing subsidies to the Promotion of electrical vehicles, e-rikshaw etc
- Fuel cell electric vehicles (FCEVs) are_hydrogen driven will the future vehicles. These are more efficient than conventional internal combustion engine vehicles and only emit water vapor and warm air
- Lower BC emissions would result in improved health
- Create public awareness about the current state of global warming/glacier melting
- Restrictions should be imposed on the shipping through Arctic water by international bodies just as Fairbanks Declaration (2017) to reduce BC emissions https://polarconnection.org/arctic-council-ministerial-meeting/

The Indian Government has taken following measures to control BC emissions:

1. Promoting use of cleaner household cooking fuels (LPG/ BioGas).
2. Advancing the vehicles from BS-IV to BS-VI norms for fuel and vehicles since 1st April, 2020.
3. Metro rail network is being laid down for public transport in many cities.
4. Introduction of cleaner and greener/alternate fuels like CNG, LPG etc, ethanol blending.
5. Setting up Compressed Bio-Gas (CBG) production plants
6. Use of solar and wind energy promoted, encouraged by 30-70 % subsidy for the installation
7. Promotion of Agricultural Mechanization for in-situ management of crop residue in many staes with 50% subsidy to the individual farmers
8. 131 most polluted cities are identified on the basis of ambient air quality levels by Central Pollution Control Board (CPCB)

Conclusion

Black carbon having second highest global warming potential next to carbon dioxide can be completely removed by taking the various mitigation strategies. India has put a target that it will be a zero black carbon country by the year 2070. That would only be possible if each one work for it on individual basis, locally and globally with coordinated efforts all over the world. This will be beneficial for the human health as well as for the environment. This will not only be good for the present population of the world but also for the coming generation.

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