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AAKASH
आकाश

Aakash Project:

Towards mitigating particulate air pollution for improved public health along with sustainable agriculture in Northwest India

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Aakash プロジェクト終了によせて

総合地球環境学研究所では、いくつかの研究プロジェクトをプログラムで束ねる「プログラム―プロジェクト制」によって、既存の学問分野や領域を超えた、総合的な研究の展開を図っています。

Aakash プロジェクトは 2018 年に、実践プログラム 1「環境変動に柔軟に対処しうる社会への転換」（杉原薫プログラムディレクター）に属して、林田佐智子教授をプロジェクトリーダーとして予備研究から始まりました。2023 年にプラビール・パトラ教授にリーダーが交代するのと同じくして、私がプログラムディレクターをつとめる地球人間システムの共創プログラムの所属となりアドバイスを送ってきました。

プロジェクトが本研究に移行した 2020 年早々から、COVID-19 パンデミックの影響でインドでのフィールド活動、特に健康調査に大きな制限がつく大変困難な状況になりました。しかしそれを逆手に取り、デリーのロックダウンによって経済活動が停滞したことで、首都圏の大気汚染の定量化につながる研究成果を出すなど、着実に成果を発表し続けてきました。

Aakash プロジェクトは、農業活動によるわら焼きが原因で発生する、大気汚染による健康被害がプロジェクトを通観する研究課題です。人（健康）と社会（農業）と自然（大気環境）のつながりを明らかにする、因果関係の解明が第 1 にあります。地球研の研究の特徴の一つである学際研究として、多くの学術分野の研究者が共同で研究を進め、総合的な研究が行われました。その上で、わら焼きがなぜやめられないのか、どのような持続可能な農業の在り方があるのかなど、社会課題へのアプローチも強く、インドの行政や企業、市民など、様々なステークホルダーと共同して行なった超学際研究として、成功を収めました。多くの研究成果だけではなく、メデイアでもたくさん取り上げられ、注目を集めたプロジェクトとなりました。

プロジェクトは今年度で終了しますが、終了後 3 年間は CR（Completed Research）期間として、成果発信の期間を設けています。また、このプロジェクトから今後、発展する、あるいはスピンオフする新たな共同研究の芽も多く出ています。これからの展開も大変楽しみにしています。

地球人間システムの共創プログラム
プログラムディレクター　谷口真人

Summary

In northwestern India, including the states of Punjab and Haryana, large quantities of rice straw are burned after paddy harvesting every year (hereafter referred to as crop residue burning, CRB). The burning of more than 20 million tons of crop residues results in the release of large amounts of toxic pollutants and greenhouse gases (GHGs) into the atmosphere. These atmospheric pollutants are locally transformed and transported across large regions, even extending to the National Capital Region of Delhi (Delhi-NCR) and neighbouring areas. The Aakash Project aims to explore avenues for changing people's behaviour towards rice straw burning to promote a shift to sustainable agriculture for achieving clean air and improved health benefits.

We studied the impact of CRB on air pollution near the Delhi-NCR via the continuous monitoring of fine particulate matter ($PM_{2.5}$) and select gaseous pollutants using 30 low-cost sensors (Compact and Useful $PM_{2.5}$ Instrument with Gas Sensors, CUPI-G). The distribution of air pollutants resulting from CRB was clarified via a regional chemistry–transport model (WRF-Chem) in comparisons with CUPI-G observations. We concluded that CRB emissions exert a greater impact on increasing air pollution in Punjab and Haryana than in the Delhi-NCR. The lockdown phases from March–May 2020 associated with the COVID-19 pandemic also created a never-before opportunity to define background air pollution criteria for the Delhi-NCR.

Several surveys involving farmer households, agricultural cooperatives and policymakers were performed to better understand the evolution of crop residue management and the adoption of rice cultivation practices over the years/decades. The socioeconomic conditions of farmers were analysed to address the constraints to abandon CRB while maintaining household livelihood. Our field experimental results suggested crop diversification as a sustainable farming solution, but many logistics conditions must be created for a smooth transition. Various options for the effective use of crop residues were evaluated with the aim of creating new business models, such as claiming carbon credits by GHG emission mitigation mechanisms.

The impacts of air pollution resulting from CRB on human health were assessed using a standard long-term exposure method and a newly developed short-term exposure method. Awareness of the effects of pollutants on human health has increased among citizens through various activities performed by collaborative institutions during and after the COVID-19 pandemic. When monitoring the progress in pollution mitigation policies, campaign measurements of all major pollutant gases and bacteria in $PM_{2.5}$ were obtained, which could serve as baseline data for future studies.

March 2025

はじめに

インドの北西部に位置するパンジャーブ州やハリヤーナー州では、毎年、水田の収穫後に大量の稲わらが焼かれています。2000 万トン以上の稲わらを焼却すると、大量の有毒な大気汚染物質や温室効果ガスが大気中に放出されます。これらの大気汚染物質は局所的に拡散し、化学変化して輸送され、デリー首都圏とその周辺地域まで広がります。デリー首都圏の大気汚染は秋から冬にかけて特に深刻で、経済活動に大きな制限を伴う規制が年間に 10 日以上発令されます。

2020 年 4 月に人間文化研究機構総合地球環境学研究所・実践研究プロジェクトとして開始された Aakash プロジェクトの正式名称は、「大気浄化、公衆衛生および持続可能な農業を目指す学際研究：北インドの藁焼きの事例」です。私たち、日本・インド他の約 60 名の共同研究者は、稲わら焼きを減らすように人々の行動を変える道を模索し、持続可能な農業への移行を推進し、人々がきれいな空気のもとで健康に暮らしていけるよう追求する 5 年間のプロジェクトを進めてきました。

大気班・観測班は、この地域に約 30 の低コストの大気汚染物質観測装置 (CUPI-Gs) を設置して微小粒子状物質 ($PM_{2.5}$) や大気汚染ガスを継続的にモニタリングし、デリー首都圏近郊の大気汚染に対する稲わら焼きの影響を定量的に評価しました。稲わら焼きから発生する大気汚染物質の分布の科学的根拠を、大気化学輸送モデルを用いて明らかにしています。そして、稲わら焼きによる汚染物質の排出は、デリー首都圏よりもパンジャーブ州とハリヤーナー州の大気汚染の増加に大きく影響することを明らかにしました。また、2020 年 3 月から 5 月にかけての、COVID-19 のパンデミックの際に行われたロックダウンは、デリー首都圏での人間活動による大気汚染の基準量を明瞭にするこれまでにない機会となりました。

農村研究班は、農家世帯、農業協同組合、政策立案者を対象に、何年にもわたる作物残渣管理の変遷とコメの栽培方法の採用に関する聞き取り調査を実施しました。農家の社会経済状況を分析し、生計を維持しながら稲わら焼きをやめるために解決すべき課題は何であるかを調べました。ラブリープロフェッショナル大学で実施した圃場実験では、持続可能な農業ソリューションとして作物の多様化を提案しました。しかし、このような農業へのスムーズな移行には多くのロジスティクスを構築する必要があることがわかりました。作物残渣の有効利用については、温室効果ガス排出削減メカニズムによるカーボンクレジット取引など、新たなビジネスモデルの創出を目指して、さまざまな選択肢を検討しています。

健康班は大気班と共同して、稲わら焼きによる大気汚染が人間の健康に与える影響を、従来の手法を用いた長期曝露と、観測データと大気モデルによる新たな手法を用いた短期曝露の双方から見積もり評価しました。COVID-19 パンデミック中およびその後、私たちの協力機関によるさまざまな活動を通じて、人の健康に及ぼす汚染物質に対する市民の意識が高まっています。私たちが実施した大気汚染物質の集中観測によって、主な大気汚染ガスと $PM_{2.5}$ に含まれるバクテリアの観測値が記録されています。これは将来、汚染緩和政策の進捗状況を追跡する際のベースラインとして役に立つでしょう。

このレポートは、Aakash プロジェクトで取り組んできた 5 年間の研究成果をまとめたものです。プロジェクトから発表した多くの学術論文の内容を中心に、3 つの班の研究成果と、それらを統合して洞察を加え、このプロジェクト研究から得られた持続可能な農業と大気汚染の緩和のための提言を最後に掲げています。林田佐智子教授が立案し、3 年間プロジェクトリーダーとして進めた研究を、インド出身のプラビール・パトラ教授が引き継ぎ、発展させてきました。二人の新旧プロジェクトリーダーと共同研究者が、今後それぞれにあるいは共に、この大切な成果を手に日本とインドの行政機関・研究機関などへ働きかけ、さらなる展開を目指します。「Aakash」はヒンディー語で「空」を意味します。いつの日かインドの空が青く澄んだきれいな空気で満たされることを願ってやみません。

2025 年 3 月

総合地球環境学研究所／海洋研究開発機構　プラビール・K・パトラ
総合地球環境学研究所　安富奈津子

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1. Introduction

Severe air pollution caused by particulate matter with an aerodynamic diameter smaller than 2.5 μm ($PM_{2.5}$) still occurs worldwide, particularly in developing countries. Inhalation of $PM_{2.5}$ can cause respiratory diseases, chronic obstructive pulmonary disease (COPD) and other human health issues. With respect to the number of deaths attributable to air pollution, India is one of the most severely affected countries (GBD, 2015; Irwin, 2014; Balakrishnan et al., 2019). In 2019, India accounted for 1.67 million deaths attributable to air pollution, and the resulting reduction in disability-adjusted life-years (DALYs) accounted for 1.36% of India's gross domestic product (Pandey et al., 2021). Delhi's geographic and climatic conditions, combined with elevated levels of anthropogenic emissions, result in the maintenance of severe air pollution ($PM_{2.5}$) levels, particularly during the autumn season. The degradation in the seasonal air quality in the Delhi-NCR has been attributed to kharif crop residue burning (CRB) in Punjab and Haryana, which also occurs during the autumn season. This issue is controversial because of the lack of sufficient long-term measurements of air pollutant species (as noted by Singh et al. (2023) and Mangaraj et al. (2025)), as is the adoption of modelling systems (Biswal et al., 2025).

Punjab and Haryana states, located in northwestern India, are significant food production centres (referred to as the rice bowl/bread basket of India), as they provide a significant amount of grains to the Indian public distribution system under the National Food Security Act (NFSA, 2013; George and McKay, 2019). However, mechanised farming in recent decades has led to the abandonment of large amounts of crop residues in the field. Punjab alone is estimated to produce 20 million tons of paddy crop residues (Kumar et al., 2022). Multiple cropping cycles began in the region following the Green Revolution during the 1960s (Balwinder-Singh et al., 2019; Hayashida, 2024). Rice cropping was introduced and became popular during the 1970s, which provided a much-needed grain supply to the rest of the country, as the local staple food is based on wheat. This extra rice crop provided farmers in Punjab and Haryana with a much-needed source of stable income because rice from this region was procured by the government of India at the minimum support price (MSP).

With the intensification of kharif rice cropping and mechanisation during the 1980s, e.g., through the use of combine harvesters (Ramulu et al., 2023), large amounts of crop residues were left in the field to be removed by farmers before wheat seeding (Fig. 1). Because rice cultivation is

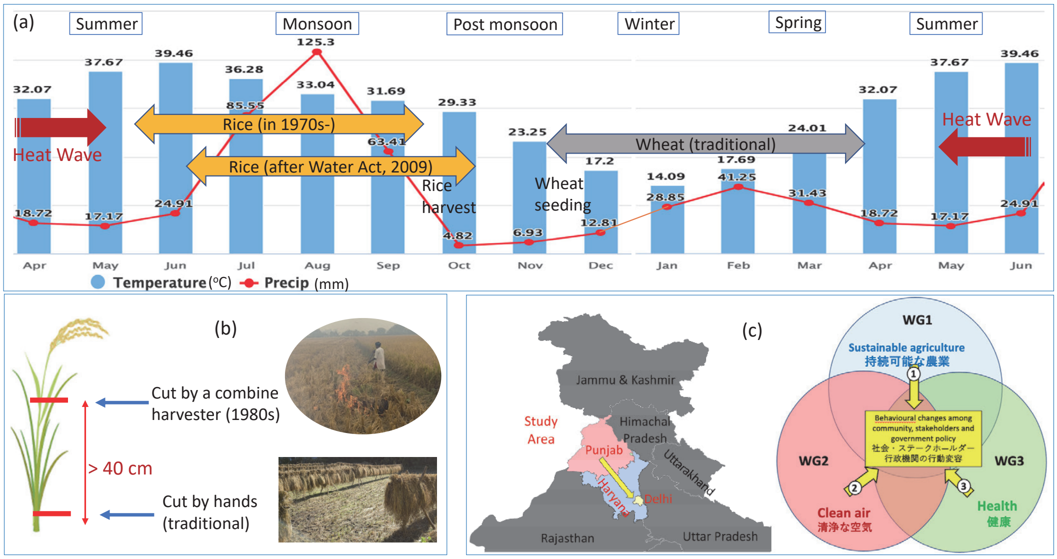

Figure 1. Circumstances of kharif crop residue burning in northwest India. The time series of the seasonal temperature (blue bars) and rainfall (red line) are shown in the background to explain the rainwater and heat limitations on kharif and rabi crop timing (a). The increase in crop residue in the field after rice crop harvesting by combine harvesters in India is shown in comparison with traditional rice harvesting in Japan (b). The bottom-right panel shows the study areas of the Aakash Project–the states of Punjab and Haryana and the Delhi-NCR and a Venn diagram of the Working Groups of the project (c). The seasonal climate plots of rainfall and temperature were obtained from https://weatherandclimate.com/india/punjab-india, and the other images were obtained from various sources (e.g., https://surveyofindia.gov.in/pages/political-map-of-india) or prepared from our own resources.

more water intensive than the cultivation of any other crop and because irrigation is supported by groundwater pumping, the groundwater table decreased during the 1990s (Rodell et al., 2009; Sato, 2021; McStraw et al., 2022). To avoid water loss during the hot summer months of May–June (Fig. 1), the government of Punjab enacted the Preservation of Subsoil Water Act in 2009 by delaying sowing in paddies to later than May 10, whereas transplantation commenced on June 16 for more effective use of the southwest monsoon rain (hereafter referred to as the 2009 Water Act). Thus, the gap between kharif (rice paddy) and rabi (wheat/potato) crops has been reduced by several weeks over the past few decades. While kharif crop harvesting is delayed (also due to the introduction of long-duration high-yield rice cultivars), wheat cultivation cannot be shifted because of crop damage due to extreme heat in May. Exposure of wheat plants to higher temperatures during the stem elongation phase could lead to early heading and flowering and thus significantly affect the crop yield. These conditions forced farmers to adopt CRB for efficient land clearing, while the retention of burned residue in the field is helpful to maintain soil carbon health and prevent the occurrence of weeds/insects, e.g., pink borers, in subsequent crops (Kaur et al., 2021).

In addition to CRB, socioeconomic activities and meteorological conditions can cause severe air pollution in surrounding areas (Sawlani et al., 2019; Singh et al., 2023; Mangaraj et al., 2025). There have been serious concerns that pollutants resulting from CRB can reach the Delhi-NCR, home to more than 70 million people. New policies to avoid straw burning are currently being promoted with financial incentives from both the central and state governments (Kurinji et al., 2024; Kumar et al., 2022). The issue of air pollution in the Delhi-NCR resulting from CRB has become an environmental problem that has received international attention, and several high-profile national/international projects have been launched in the areas of atmospheric chemistry and agricultural sciences. The Aakash Project aims to address this air pollution issue, including the exploration of greenhouse gas (GHG) emission mitigation cobenefits, in a transdisciplinary manner. In particular, we aimed to link public health awareness among residents to behavioural changes to eliminate CRB and associated air pollution while minimising economic losses due to crop production mechanisms. Citizens, farmers and policymakers must work together to generate effective ways to reduce CRB emissions along with other industrial emissions, and awareness plays a critical role in developing solutions.

The Aakash Project was initiated at the Research Institute for Humanity and Nature (RIHN) in 2019 under Programme 1 (Societal Transformation under Environmental Change), which aims to provide realistic perspectives and options for transforming society into one that can respond flexibly to environmental changes caused by human activities, such as global warming and air pollution (RIHN mission statement). This research focused on pursuing pathways for social change towards cleaner air, improved public health and sustainable agriculture, which conforms with the objectives of Programme 1 (until March 2023). During the final two years, our project is part of the RIHN research programme Cocreation of the Earth–Human System, which contributes to research on the interactions of nature and human activities. We elucidated the interrelationships between intensive agricultural activities causing local air pollution and groundwater depletion and their adverse effects on human health.

2. Methodology and project implementation

A Suomi National Polar Satellite Visible Infrared Imaging Radiometer Suite (VIIRS) dataset from the National Aeronautics and Space Administration (NASA), with a 375-m resolution and a 13:30 local transit time, and an EOS-Terra/Aqua satellite Moderate Resolution Imaging Spectroradiometer (MODIS) dataset, with a 1-km resolution and 10:30 and 13:30 local transit times, were employed for fire detection (Jethva et al., 2019; Sawlani et al., 2019). The fire detection counts (FDCs) from the MODIS (since 2002) and VIIRS (since 2012) datasets could be considered proxies for open CRB during the post-harvesting season in Punjab and Haryana. Notably, although they provide global coverage, these polar-orbiting satellites lack temporal coverage to capture the full day's activities (Misra et al., 2025).

Particulate matter and several other air pollutants are most efficiently removed from the atmosphere via washout during rainfall or under high-humidity conditions. To explain $PM_{2.5}$ and pollutant species, accurate information on the temporal and spatial extents of rainfall is critical. The rainfall data used in our analyses were obtained from the Indian Meteorological Department (IMD) Daily Merged Satellite Gauge Rainfall Dataset with a 0.25°×0.25° grid resolution (Mitra et al., 2009). This dataset is derived from Global Precipitation Measurement (GPM) satellite rainfall data merged with accumulated daily rain gauge data (valid at 0300 UTC) from IMD stations. The data are available from the IMD (2024).

The Compact and Useful $PM_{2.5}$ Instrument with Gas Sensors (CUPI-G) consists of various sensors that continuously monitor $PM_{2.5}$, temperature (T), relative humidity (RH), GPS signals (coordinates and time), and several key air pollutants, such as carbon monoxide (CO), nitric oxide (NO), nitrogen dioxide (NO_2), and potential ozone (combined O_3 and NO_2). The $PM_{2.5}$ sensor provides light scattering measurements to calculate mass concentrations (Nakayama et al., 2018). The $PM_{2.5}$ sensors were calibrated and validated at the laboratories of Nagoya University and Nagasaki University prior to field deployment. The Alphasense (UK) manufactured CO-B4 carbon monoxide sensor, NO-B4 nitric oxide sensor, NO2-B43F nitrogen dioxide sensor, and OX-B431 oxidising gas sensor were employed for measuring gaseous compounds (https://www.alphasense.com). Details on the Aakash measurement campaigns and measurement quality assurance (QA)/quality control (QC) processes can be found in Singh et al. (2023) and Mangaraj et al. (2025). The sensors were placed as uniformly as possible along the path of seasonal winds from northwest to southeast, given the infrastructure available for site access, electricity and mobile communication. Almost all the devices were installed in farmers' houses in villages, and locations were selected away from large roads or other pollution sources via Google Maps. Referring to the air mass pathways reported by Takigawa et al. (2020), we divided the target region into 30 grids and designed the network so that each grid would include at least one site. The existing monitoring stations of the Central Pollution Control Board (CPCB) are located near large cities in the region (Fig. 2). We were the first to establish an air pollution monitoring network in a rural area in campaign mode. Any bias/prejudice in site selection would have prevented achieving the goal of revealing air pollution unknowns in CRB source regions and their transport to densely populated urban regions.

Various regional chemical transport model (CTM) simulations were performed to account for uncertainties due to the model framework,

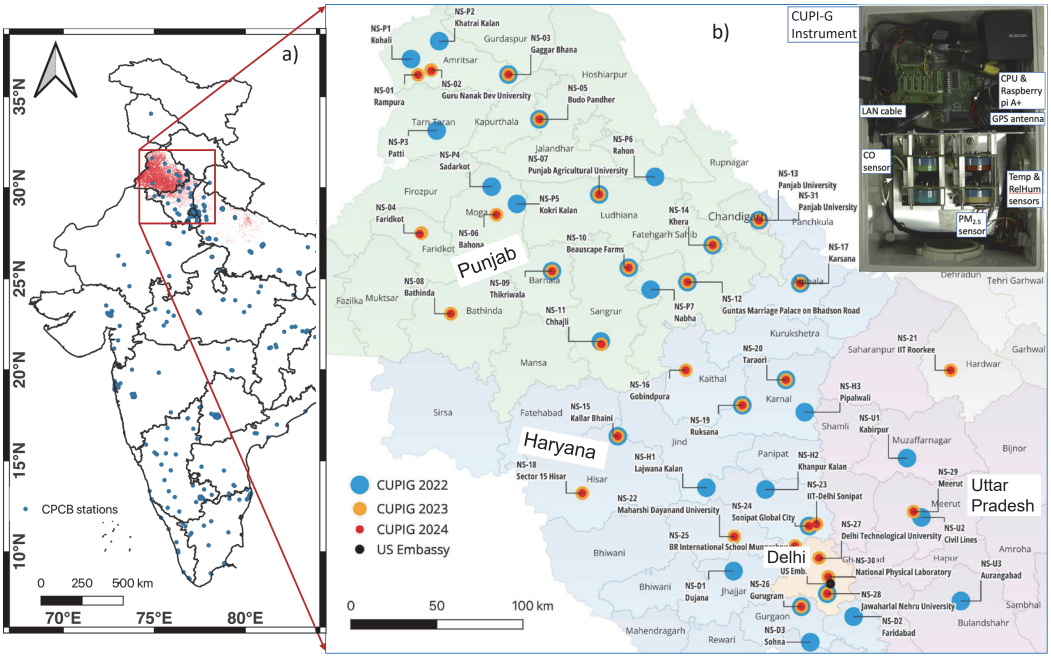

Figure 2. Geographical location of the study area of the intensive campaign using low-cost sensors. The small red dots denote the VIIRS FDCs in 2022, and the blue dots denote the locations of the CPCB air quality monitoring stations in India (a). The locations of CUPI-G deployment for air pollutant measurements in Punjab, Haryana, Delhi and Uttar Pradesh are shown on the right (b). The top-right image-inset displays the front view of CUPI-G sensor. The shapefile for the India map was obtained from https://www.aigr.co.in/page/download (last accessed: 22 July 2023), and the plot was generated using QGIS (https://www.qgis.org/en/site/), as described in Singh et al. (2023).

emission inputs and chemical schemes. Full-chemistry model simulations were conducted using the nonhydrostatic model coupled with chemistry (NHM-Chem) (Kajino et al., 2025), the Weather Research and Forecasting model coupled with the Community Multiscale Air Quality model (WRF-CMAQ) (Yamaji et al., 2024) and the WRF-Chem model (Biswal et al., 2025). Technical achievements in 2023 included the preparation of daily forecasts of CRB emission signals via WRF-FLEXPART simulations (Takigawa et al., 2020). Kajino et al. (2025) estimated $PM_{2.5}$ emissions on the basis of CUPI-G measurements. Yamaji et al. (2024) identified a lack of secondary aerosol formation from anthropogenic sources to simulate the regional distribution of $PM_{2.5}$, which agrees well with secondary organic aerosol fraction measurements obtained upwind of the Delhi field site (Rathore et al., 2025). Biswal et al. (2025) performed multiple WRF-Chem simulations to quantify the role of CRB in shaping $PM_{2.5}$ concentrations in the region, which can be used for assessing the health impacts of CRB alone (Joshi et al., 2024). Only the WRF-Chem simulation results are described here for brevity.

The project is characterised by (1) a transdisciplinary nature achieved by the fusion of humanity, medical, agriculture and physical sciences teams and (2) the development of a novel method for local implementation including the monitoring of the distribution of air pollutants, conducting health hazard surveys and raising awareness among residents. When this project started, there was little concern in rural areas regarding air pollution, as well as limited awareness that straw burning can cause serious air pollution, which can harm human health. To change people’s attitudes to act positively, we provided concrete evidence, which has been lacking in the area due to the absence of ground-based (exposure-level) observations.

Along with a review of the current cropping system that is biased towards rice and wheat, we proposed a concrete business model for ensuring the livelihoods of farmers. New government policies, such as cofiring biomass fuels in thermal power plants, a shift towards shorter-duration rice cultivars, in situ management of rice straw, and crop diversification, were considered to provide sustainable agricultural pathways for farmers. Our field and laboratory experiments were also designed to improve soil properties, e.g., by preserving soil carbon and other mechanisms for sequestering CO_2 and lowering total GHG emissions by including methane (CH_4) and nitrous oxide (N_2O).

Because the problem originated from the intensive rice–wheat double-cropping system and the mechanisation following the Green Revolution, we analysed the social context of the region to better understand various uses of rice straw and explored incentives to facilitate behavioural changes among farmers. Unit members examined the socioeconomic advantages and disadvantages of various options for crop residue use and management through questionnaires, interviews and literature surveys (Asada and Vatta, 2022; Murao et al., 2023; Asada, 2025). We surveyed 2200 households, covering 22 districts across the state of Punjab in 2020, to assess the awareness of the effect of particulate air pollutants on human health. It is in our nature to ignore global, regional or national issues if our own health or finances are not affected.

In a separate study, our collaborators performed an east–west comparison of the values of rice straw in India through onsite fieldwork to investigate farmers' perceptions of the value of straw (Urban Cordeiro et al., 2024). In parallel, we conducted experiments in crop fields and explored the possibility of switching from rice to other crops in collaboration with local universities in Punjab, with the aim of diversifying crops and moving away from the intensive rice–wheat double-cropping system (Sahara et al., 2025; Sharma et al., 2025). Furthermore, we surveyed the use of rice straw for biomass cofiring in thermal power plants, which the central government of India has promoted in recent years, and we explored the possibility of support from Japanese and Indian stakeholders.

Three working groups jointly considered measures to promote behavioural changes among farmers and stakeholders, such as local communities and governments, to achieve the overarching objectives of the Aakash Project. The project membership comprises approximately 29 members from Japan and 40 members from India and other countries. The Japanese members are researchers and postgraduate students from universities and national research institutes. The Indian members are researchers and graduate students from core state/national universities and research institutes (please refer to the affiliations in the list of authors). The members belong to one of the working groups and work in units for improved communication pertaining to a wide range of research topics.

Most of the analyses, particularly those related to air pollution and atmospheric processes, are already available on the Aakash Project website (https://aakash-rihn.org/en/data-set/), and the CUPI-G measurements were shared in near real time during project implementation. This approach was adopted to evaluate the air pollution situation in a large area in northwestern India. This section provides a brief outline, and the methodology, as appropriate, is detailed to a greater extent in the Results and discussion section.

3. Results and discussion

3.1 Satellite detection of crop fires and trends in rice cultivation

The delays in kharif rice cropping and intensification of CRB can be tracked by remote sensing satellites as FDCs and burned area (BA) anomalies, respectively (Fig. 3). Our analysis results suggested that FDCs depend more significantly on the satellite measurement pixel size (the number of VIIRS FDCs is approximately 5 times greater than that of MODIS FDCs in both Punjab and Haryana), whereas the BA values are comparable for both satellites because a larger burned pixel area is assumed in the MODIS data than in the VIIRS data (H. Araki, RIHN, unpublished data). Fig. 3 shows the changes in the MODIS FDC and BA values from 2002 to the last CRB season in 2024. During the overlapping period (2012–2024), both the MODIS and VIIRS data showed similar FDC trends, as expected from rice

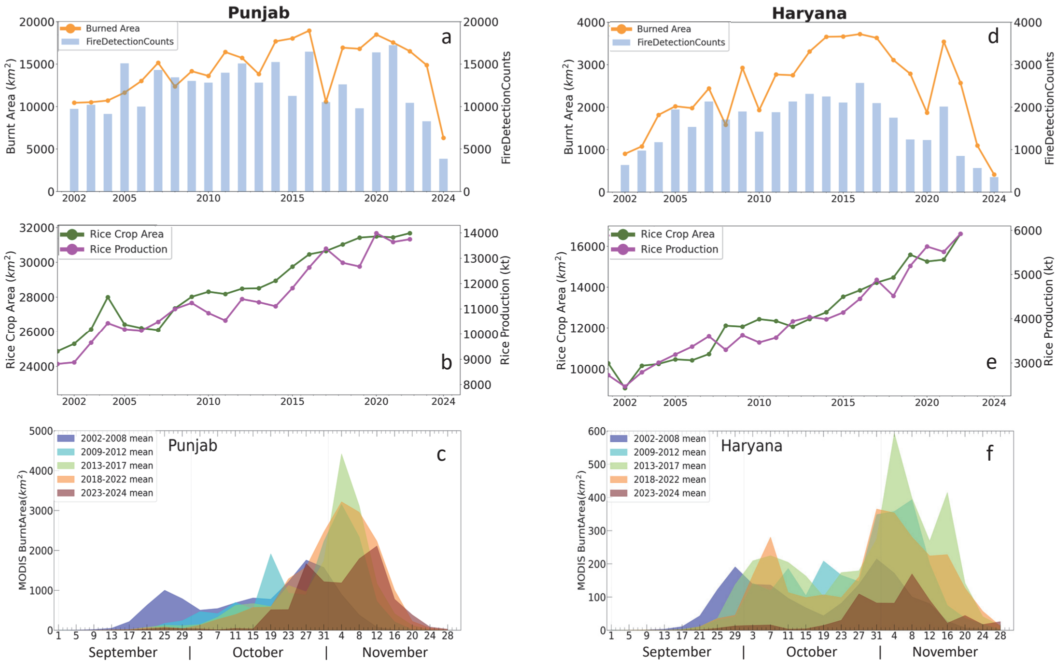

Figure 3. The hypothesis that the extensive clearing of rice fields via residue burning, via the use of proxies of fire counts and burned areas (a, d), as rice cropping continues to intensify (b, e) in Punjab and Haryana is supported by Earth observation satellites, e.g., the MODIS and VIIRS sensors. A shift in burned area coverage to November is also observed in Punjab (c) but is not as notable in Haryana (f) as a result of the 2009 Water Act. The statistics of the annual rice crop area and production were obtained from the Directorate of Economics and Statistics, Department of Agriculture and Farmers Welfare, Ministry of Agriculture and Farmers Welfare, Government of India (https://data.desagri.gov.in/website/crops-apy-report-web).

cropping intensification and the 2009 Water Act.

Our results revealed that the MODIS FDCs and BAs reached high levels by 2005 in both Punjab and Haryana and peaked in approximately 2016. FDCs in Punjab remained constant or decreased slightly in recent years (40% from 2022–2024 compared with that from 2014–2016), but no decrease in BA values was observed until the previous year (2024). Significant decreases in both the FDC and BA values were observed in Haryana, at approximately 25% from 2022–2024 compared with that from 2014–2016. The FDCs exhibited a declining trend following the National Green Tribunal Act (2010) and the 2016 amendment of transboundary waste movement, which included banning agricultural residue burning in the northwestern states of India, except for 2020 and 2021. Demonstrations by farmers against the Indian Agricultural Acts or the Farm Bill (September 2020) targeting excess CRB in Punjab started immediately in September 2020 and continued through November 2021 until the Farm Bill was repealed, whereas farmers in Haryana were active only in 2021, as they joined the demonstration after the 2020 CRB season (Fig. 3a, d) (Mangaraj et al., 2025).

As shown in Fig. 3b and e, the state total rice crop production increased by approximately 50% and 100% in 2022 relative to the levels in 2002 in Punjab and Haryana, respectively, as the cultivation area increased by 23% and 50%, respectively. An increase in rice production is associated with a greater amount of crop residue, as new cultivars are resistant to environmental conditions and support higher yields by developing stronger and longer stems (P. Patra, Punjab field visit, Jan 2025). Up to approximately 60% and 25% of the rice crop areas in Punjab and Haryana, respectively, were cleared of paddy stubble via burning from 2002–2023. A clear shift in the timing of the BA peak was observed from 2002–2008 to 2018–2023, more prominently in Punjab (from double peaks to a single peak in November), and a delayed first peak was observed in October in Haryana (Fig. 3c, f) (also refer to Sawlani et al. (2019)). Note that the Preservation of Subsoil Water Act Preservation Act (2009) was enacted by the Punjab government, and any changes in policies targeting Haryana farmers were voluntary. The overall impacts of government policies can be tracked well via long-term MODIS (and VIIRS over a shorter period) satellite observations.

3.2 Farmers' constraints for resorting to CRB

The first survey was conducted at the household level between August 2020 and January 2021 to identify the ground conditions that force farmers to burn rice crop residues (Asada and Vatta, 2022). As travel to India was restricted during the COVID-19 pandemic, this survey was conducted in collaboration with Indian institutions. Questionnaire surveys on the family structure, occupation, landholding patterns, cropping patterns, livestock husbandry, and perceptions were conducted. This process was followed by other questionnaire surveys at the village and block levels from January 2022 through 2024 involving representative respondents who were aware of the overall agricultural situation in their villages, including sarpanches, secretaries of cooperative societies, nambardars and progressive farmers (Asada et al., 2025).

The regional characteristics of CRB became increasingly evident with the calculation of the burning ratio (the ratio of the area where crop residue was fully or partially burned after the rice harvest to the total rice area) at the block level (Fig. 4a). Averaging the data for all villages within each block revealed distinct burning trends in the three divisions of Punjab, as divided by the Sutlej and Beas Rivers. The northeastern Doaba region exhibited the lowest burning rate, with 28.6% of the total paddy fields affected on average. While the Majha region in the northwestern part of the state attained a

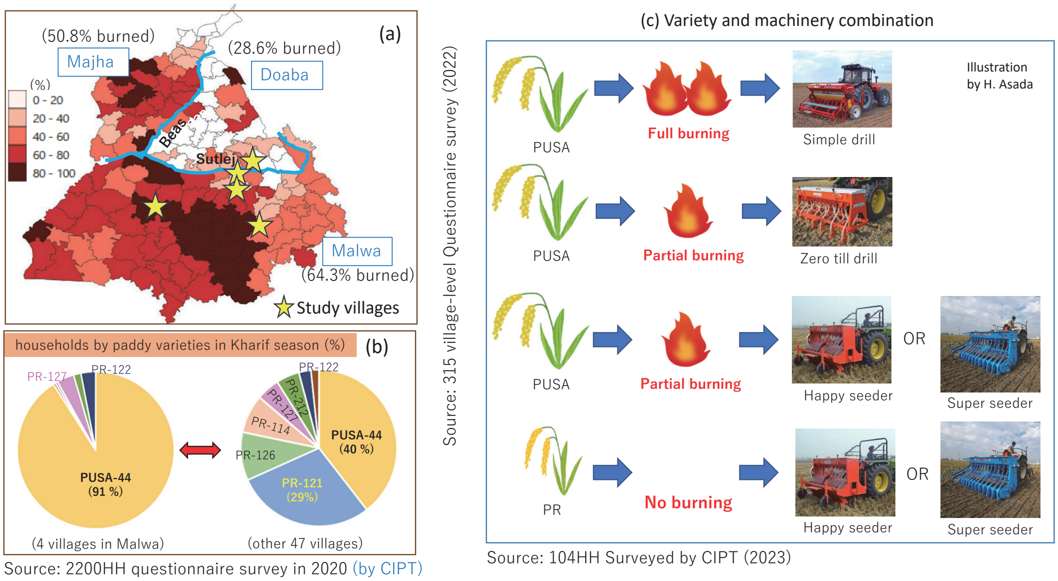

Figure 4. Burning ratios of crop residues in 151 blocks in Punjab based on 315 village questionnaire surveys (a: top left). Rice cultivars adopted in 4 villages within the Malwa region of Punjab are contrasted with those adopted in the other 47 villages surveyed (b: bottom left). Relationships were established for farmers' practices of crop residue management depending on the cultivar chosen and access to modern machinery (c: right). The figures were assembled from reports of H. Asada.

moderate burning rate of 50.8%, the Malwa region in the southern part exhibited the highest rate, at 64.3%. Notably, the highest burning ratio was recorded in the central part of the Malwa region.

In the northwestern Majha region, the proportion of the cultivated area of basmati rice was also relatively high (21%). Basmati rice cultivation was initially confined to the Amritsar and Gurdaspur districts, but the area where this crop is cultivated has increased considerably over the last 15 years due to the introduction of high-yield varieties, such as the long-duration 1121 basmati variety and the short-duration 1509 basmati variety. Basmati rice is typically harvested manually for export purposes, and its straw can be used as cattle feed, thereby leaving less residue in the field than that during non-basmati rice farming. In the southern Malwa region, the average area of paddy fields in the village was the largest, and the mean interval between paddy harvesting and wheat sowing was the shortest (approximately 24 days) because of the preference for long-duration PUSA-44 varieties to obtain higher profit margins. Farmers likely faced the necessity of managing substantial residue quantities within a brief period, with no alternative but to resort to CRB (Fig. 4b). In the Doaba region, farm households possess a relatively small area of arable land. However, many farmers lease land from other households to expand their operational landholdings. They diversify their sources of income by growing not only paddy crops and wheat but also other crops, such as potatoes and maize, which are highly profitable on the market but has higher risks compared to rice-wheat cycle. They own, rent, or collectively employ multiple rice straw processing machines (e.g., balers and super seeders).

The results revealed that straw burning varied greatly from field to field, depending on various socioeconomic and cultural factors, such as land ownership/rental, relationships with stakeholders, rice variety selection, relationships among different sociocultural groups, the grain procurement system, and ownership of rice straw management machinery. Both the surveys and the literature indicated that marginal farmers who chose to grow PUSA-44 likely adopted outdated machinery (simple/zero-till drills) and resorted to full burning, whereas their more affluent counterparts had access to advanced machinery (super seeders) and cultivated newer premium long-grain non-basmati rice varieties (parmal rice, PR) (schematically shown in Fig. 4c). Statistics indicated a gradual decrease in the fraction of PUSA-44 farming to approximately 12% in 2023, after peaking at approximately 35% from 2005–2016, as a result of governmental efforts to phase out long-duration varieties that leave large amounts of poor-quality residue (to be discussed in section 4).

The relationship between rice paddy farming and technological changes was studied to assess farmer income and the likelihood of crop diversification other than rice and wheat. For marginal and small farmers, it was economically rational to burn rice straw between rice harvesting and wheat sowing without introducing modern machinery if they wanted to increase their income by reducing production and straw management costs (Fig. 5). Modern machines, such as Happy seeders/super seeders, which enable farmers to process straw without burning, are operated using high-horsepower tractors, which increases the costs of fuel and machinery maintenance. Therefore, this drives them to the practice of straw burning. Moga district, Malwa region, was selected as the study area. T. Sato and colleagues conducted 3 household- and village-level surveys in Moga district (population: 160,000 people in 2011), with a total workforce comprising 28% cultivators, 22% agricultural labourers, and 32% other labourers, including nonfarm workers.

Fig. 5 shows the effect of introducing modern machinery on agrarian changes based on the case study. Under stagnated agricultural productivity, all farming households aimed to increase their income by increasing the

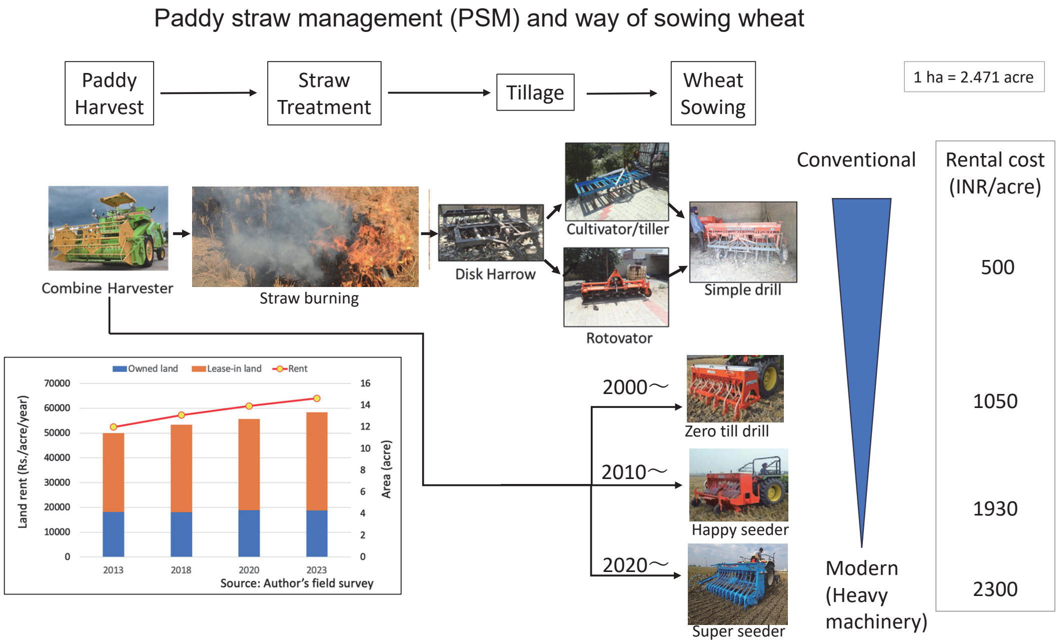

Figure 5. Process of rice straw management before wheat sowing. The costs encountered by farmers in lending farmland (bottom left) and renting modern machinery (right) influence their decisions regarding the field preparation method (figures adopted from an analysis by T. Sato).

amount of land farmed or growing more profitable crops or crop varieties. Although such strategies were common to all farming household types, the actual responses differed according to the land ownership situation. As observed in the case study, the production costs of smaller farmers include a greater share for renting land. These farmers aimed to increase their incomes only by selecting profitable crops or high-yield varieties. A change from wheat to potato during the rabi season was observed in this village, but only at larger farms because potato cultivation requires the use of new machinery (potato planters, soil-covering machines, and potato harvesters) or intensive machinery use for careful soil management, thus increasing machinery costs. Therefore, farmers generally cultivated long-duration varieties to obtain relatively high yields. As indicated by our interview with a super seeder owner, compared with those associated with straw incorporation without burning, paddy stubble burning decreases production costs.

The analysis of the land-holding situation indicated that marginal to small land holders dominated, but the operational land holdings of medium-sized farmers from 2013 to 2023 increased more than those of farmers in the other land ownership classes did, partially because of the high cost of renting land from smaller farmers who engaged in nonfarm work in the urban area. Farmers using modern machinery burned less stubble, and larger land holders typically adopted modern machinery. The cost and return of paddy–wheat production showed that the introduction of these machines could reduce net incomes, with the greatest negative effects on small land holders who leased relatively more land. Farmland consolidation by medium-class land holders may positively affect the problem of stubble burning, but such agrarian changes may ensure the livelihoods of marginal to small land holders only when sufficient nonfarm work is available.

3.3 Baseline air pollution (COVID-19)

To quantify the impact of rice straw burning in Punjab and Haryana on the air quality in the Delhi-NCR using observational data (in situ and remote sensing), model simulations are needed to verify the relationship between air pollution in the Delhi-NCR and rice straw burning in adjacent states. This study is essential for providing a concrete basis for this connection, as the lack of scientific evidence has caused confusion in the community. Limited monitoring data in rural areas constitute a bottleneck in establishing scientific knowledge. However, our research plan for $PM_{2.5}$ sensor deployment was disrupted by the COVID-19 pandemic. This provided an unprecedented opportunity for us to collect significant information on anthropogenic vs.

natural emissions of air pollutants by analysing remote sensing and local data from 2020. Large number of studies quickly appeared in peer-reviewed literature on lowered of air pollution at Indian cities and the Asia region as a whole (Kiendler-Scharr et al., 2021). More importantly, we learned ways to communicate and perform research collaborations through teleworking and online methods (Sembhi et al., 2021). Although air pollution returned to the Delhi-NCR due to CRB in Punjab or Haryana, online communication tools proliferated globally and still persist today.

Dhaka et al. (2020) reported that during the first phase of the COVID-19 lockdown in India from 25 March to 14 April 2020, the cessation of various human activities (e.g., traffic, industry, and construction) caused a dramatic reduction in $PM_{2.5}$ in the Delhi-NCR (Fig. 6a). Measurements by CUPI-G sensors, Delhi Pollution Control Committee (DPCC), and CPCB revealed notable reductions (ranging from 40–70%) in $PM_{2.5}$ during the first lockdown week (25–31 March 2020) compared with pre-lockdown concentrations of 60–120 μg m^{-3}. However, O_3 pollution remained high during the lockdown because of nonlinear chemistry and dynamics under relatively

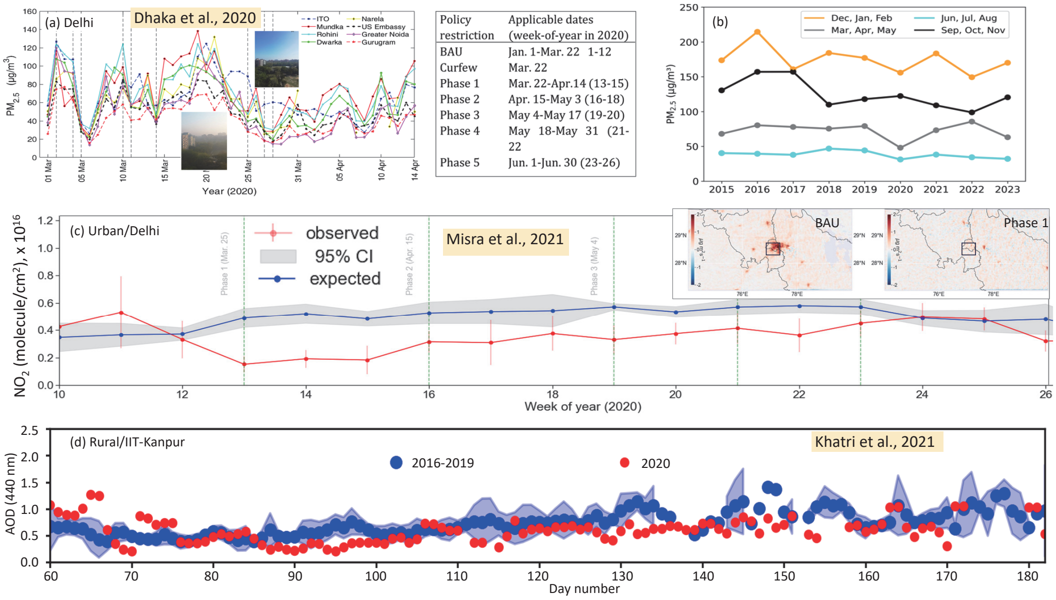

Figure 6. The time series of the in situ $PM_{2.5}$ concentration (a: top left), TROPOMI NO_2 column density (b: middle row), and AERONET aerosol optical depth (c: bottom row) revealed a reduction in air pollutants in urban regions, especially the Delhi-NCR, during the COVID-19 lockdown (top-centre). However, the effect of the COVID-19 lockdown was limited to March–May 2020, as indicated by the seasonal average $PM_{2.5}$ time series from the US embassy in New Delhi (d; top right). The insets in panel b are showing maps of TROPOMI NO_2 vertical column density in the business as usual (BAU) and Phase 1 lockdown periods.

low loadings of aerosols and nitrogen oxides (NO_X=NO+NO_2) (Kiendler-Scharr et al., 2021). Notably, events of increased $PM_{2.5}$ levels (300–400 μg m^{-3}) were observed at night and during the early morning hours of the first week of April after the air temperature decreased to the dew point (~15–17°C). A haze formation mechanism is suggested through the uplift of fine particles. This study highlights the highly complex interplay between base-line pollution and meteorology, leading to counterintuitive enhancements in pollution, in addition to an overall improvement in the air quality during the COVID-19 lockdown in this part of the world. As shown in Fig. 6b, the effect of the COVID-19 lockdown lasted only from March–May 2020, which exhibited the 3rd-highest seasonal average $PM_{2.5}$ concentration (the highest seasonal average concentration occurred from December–February, followed by September–November; Fig. 6d).

Furthermore, the impact of sudden suspensions of human activities on air pollution was analysed by studying the changes in satellite-retrieved nitrogen dioxide (NO_2) concentrations and top-down NO_X emissions in urban and rural areas around Delhi (Misra et al., 2021). NO_2 was chosen because it is the most indicative of the emission intensity because of its short lifetime, which is on the order of a few hours within the planetary boundary layer. We present a robust temporal comparison of Ozone Monitoring Instrument (OMI)-retrieved NO_2 column density data during the lockdown with counterfactual baseline concentrations extrapolated from long-term trends and seasonal cycle components of NO_2 via observations from 2015 to 2019. The NO_2 concentration in the urban area of Delhi exhibited an anomalous relative change ranging from a 60% decline during Phase 1 of the lockdown (March 25–April 13, 2020) to 3.4% during Phase 5 after the lockdown (Fig. 6c). In contrast, we observed no substantial reduction in NO_2 concentrations in rural areas (insets in Fig. 6c). The situation during Phase 1 of the lock-down resulted in a blue sky over the entire Indo-Gangetic Plain (IGP), providing a baseline for clean air conditions and increasing expectations for citizens (Ravindra et al., 2022; Dhaka et al., 2020).

To segregate the impact of the lockdown from that of the meteorology, weekly top-down NO_X emissions were estimated from high-resolution TROPOspheric Monitoring Instrument (TROPOMI)-retrieved NO_2 data by accounting for horizontal advection derived from the steady-state continuity equation. Compared with those during the pre-lockdown business-as-usual phase, the NO_X emissions in urban Delhi and power plants exhibited mean declines of 72.2% and 53.4%, respectively, during Phase 1. The emission estimates for urban areas and power plants correlated well with activity reports, suggesting the applicability of this approach for studying emission changes. A greater anomaly in emission estimates suggests that a comparison of only concentration changes, without accounting for dynamic and photochemical conditions, may lead to misinterpretation of the impact of the lockdown. Our results will also have broader implications for optimising bottom-up emission inventories and setting locally administered policy guidelines for clean air in megacities.

Aerosols in the IGP also exert strong climate feedback by changing the radiation budget of the Earth's atmosphere, e.g., by modulating the regional climate, monsoons, and Himalayan glacier retreat. Thus, this region is important for understanding aerosol perturbations and their resulting impacts on atmospheric changes during the COVID-19 lockdown period, which created natural experimental conditions. By analysing 5 years (2016–2020) of aerosol data and performing radiative transfer calculations, we found that the columnar and near-surface aerosol loadings decreased during Phase 1 of the lockdown, leading to reductions in radiative cooling at the surface and top of the atmosphere and atmospheric warming during the lockdown period. Furthermore, satellite data analysis revealed increases in the cloud optical thickness and the effective radius of cloud particles and a decrease in the lower tropospheric air temperature during the lockdown period. These results reflected the critical influences of the COVID-19 lockdown on the regional climate and water cycle in the IGP.

3.4 Systematic measurements in the region using CUPI-G sensors

Following the COVID-19 pandemic, an intensive measurement campaign was conducted in 2022 using a network of 30 CUPI-G sensors in rural, semirural and urban areas of Punjab, Haryana, Delhi-NCR and western Uttar Pradesh (Fig. 2). While Indian institutional ground-based air pollution monitoring networks target mainly urban areas, CUPI-Gs were installed in farmhouses in August 2022, 2023 and 2024. The results provided groundbreaking evidence of a relationship between air pollution in Delhi and straw burning, with regular updates such as RIHN News in 2023 and 2024 (Singh et al., 2023; Mangaraj et al., 2025). Our inability to deploy CUPI-G sensors in the study area and thus the restriction to analysing the available data, as discussed in section 3.3, helped to fine-tune the locations of possible sites to best capture CRB emissions and their transport through the atmosphere. During the first year of deployment, we left out the southern Punjab region and focused on the main transport pathway of CRB emissions to the Delhi-NCR (following the approach of Takigawa et al. (2020)). The 2023 and 2024

CUPI-G networks were readjusted on the basis of the analysis of 2022 data (Singh et al., 2023) to capture CRB emissions from the southern and western Punjab districts.

The $PM_{2.5}$ observations from September–November 2022 revealed high-$PM_{2.5}$ episodes at Delhi-NCR sites on two occasions, 2–3 November and 10–11 November 2022, which were clearly linked to CRB in Punjab or western Haryana when strong winds blew straight from Punjab to Delhi (Fig. 7; Singh et al., 2023). During the first haze event, the $PM_{2.5}$ plume was transported within 12–24 h via Haryana, where the concentration reached as high as 900 µg m^{-3}. The second and most widespread haze event in Punjab was delayed by approximately 72 h before passing over Haryana to the Delhi-NCR, after several days of dissipation towards Rajasthan. The severity and spread of haze could be observed in VIIRS-based true colour images of the Earth's surface and the lowermost atmosphere, along with surface wind vectors and the distribution of VIIRS-based fire hotspots. During the peak burning period, the whole IGP was engulfed by a thick haze layer (transparent grey colours) when winds moved towards the IGP from Punjab through Haryana and the Delhi-NCR from 2–5 November 2022 and from Rajasthan from 9–11 November 2022 (www.chikyu.ac.jp/rihn_e/news/detail/405/).

The uniqueness of the CUPI-G network measurements can be

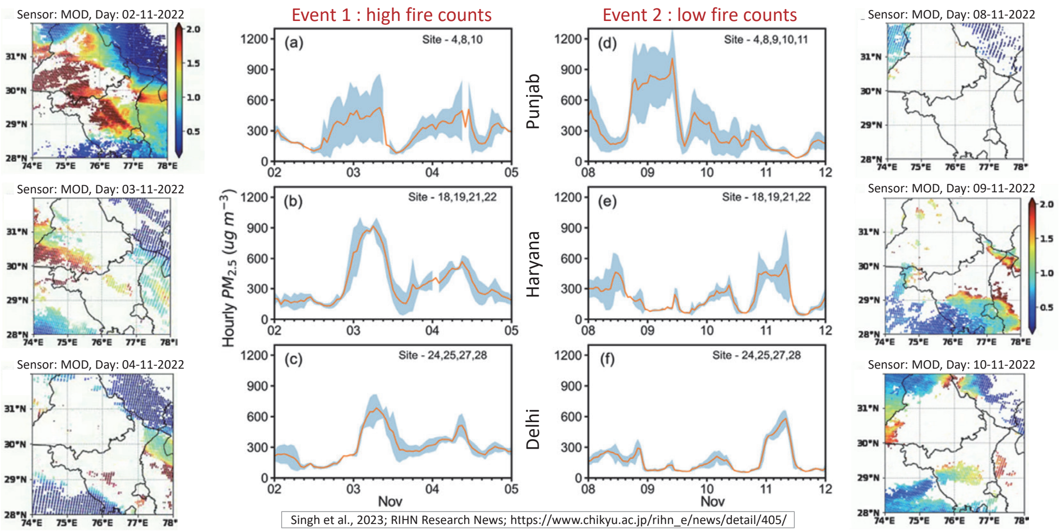

Figure 7. Hourly mean variations in $PM_{2.5}$ along with the standard deviation (shaded area) during two haze periods in 2022 (Singh et al., 2023) in different regions (a, d) of Punjab, (b, d) Haryana, and (c, f) the Delhi-NCR. MODIS-observed satellite scenes are shown in the left and right columns on high-$PM_{2.5}$ days in the region during 2–4 November and 8–10 November 2022, respectively.

enhanced by analysing the cloud cover during intense CRB periods, when the aerosol and fire detection capabilities of satellites are limited (maps on the two sides of Fig. 7). The MODIS Tera/Aqua satellite (MOD/MYD) retrievals of the aerosol optical thickness (AOT; unitless) at local times of 10:30 and 13:30 at the CUPI site locations. The MODIS satellites did not record AOT values corresponding to the peak $PM_{2.5}$ at the surface, as measured in situ by the CUPI sensors. This was due to the mild rainy and overcast conditions from 5–9 November 2022 (Fig. 7d). Similarly, fire detection by the VIIRS was also obscured by cloud cover on days with the highest $PM_{2.5}$ concentrations (daily means exceeding 900 μg m^{-3}) from 8–9 November in Punjab. This was the first instance of very high $PM_{2.5}$ concentrations due to CRB in the field, highlighting the need for continuous in situ measurements to overcome the data gaps for satellites with once-a-day overpass times. The MODIS AOT increased by only up to a factor of 1.1 from September to November when averaged over the Punjab region, whereas the CUPI-G $PM_{2.5}$ concentration increased by more than a factor of 4.5, suggesting that reassessment of human exposure to $PM_{2.5}$ due to CRB is urgently needed. We assumed that air pollution prediction systems using CTMs, which rely mainly on satellite remote sensing measurements in rural areas (Ghude et al., 2024), would miss the transport of high-pollution CRB plumes to the Delhi-NCR.

$PM_{2.5}$ measurements (relative humidity, temperature, CO, NO_X and O_3 measurements are not shown here) were performed successfully in intensive campaign mode during the months of September to December in 2022, 2023 and 2024. Mangaraj et al. (2025) reported that the 6-hour average $PM_{2.5}$ concentrations at all Punjab sites ranged from 40–100 μg m^{-3} in October 2023 to 79–338 μg m^{-3} in November 2023 (Fig. 8; updated by including results for 2024). Similarly, in Haryana, the average $PM_{2.5}$ concentration ranged from 63–112 μg m^{-3} in October 2023 to 136–318 μg m^{-3} in November 2023. The circumstances in 2022 differed, as CRB activities started in early October. The highest $PM_{2.5}$ daily mean peaks at selected sites in Punjab (NS-04, NS-08, NS-11 and NS-10) reached 1146, 832, 665 and 349 μg m^{-3}, respectively, between 1 and 10 November 2023. These Punjab sites are located in Southwest Punjab, where the highest $PM_{2.5}$ concentrations and FDCs were observed. Similarly, the sites in Haryana (NS-15 and NS-19) exhibited $PM_{2.5}$ levels ranging from 375–450 μg m^{-3}. In 2024, we observed the highest $PM_{2.5}$ values from 12–20 November across all the regions in our measurement area (Fig. 8), even though the reported fire counts were much lower than those during the previous 2 years (refer to

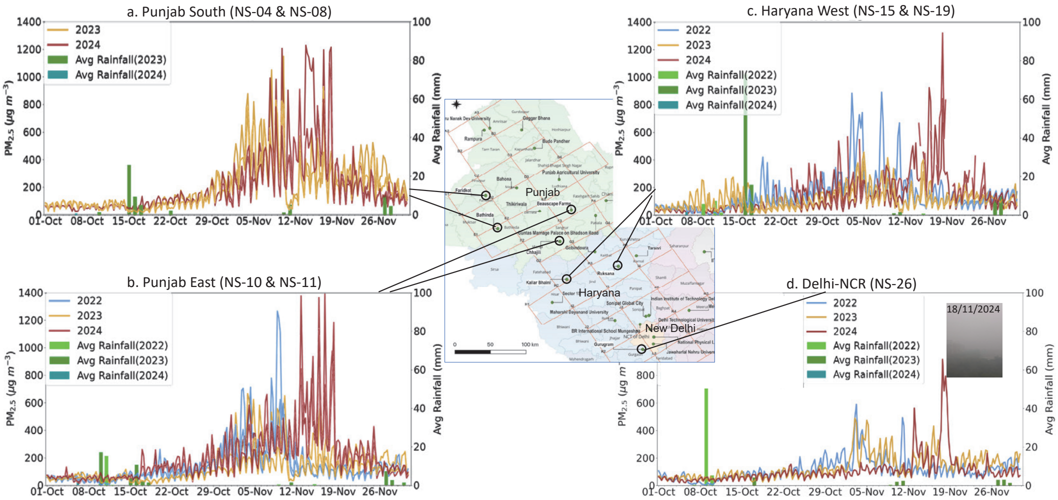

Figure 8. Observed variations in the 6-hourly mean $PM_{2.5}$ concentration at 7 selected sites, namely, (a) Faridkot (NS-04) and Bathinda (NS-08), (b) Beauscape Farms (NS-10) and Chhajili (NS-11), (c) Kallar Bhaini (NS-15) and Ruksana (NS-19), and (d) Gurugram (NS-26) from 1 October to 30 November in 2022 (as per site availability; blue lines), 2023 (yellow lines) and 2024 (red lines). The daily rainfall events are marked by green bars (refer to the legend). The site codes are arranged from northeast to southwest of the CUPI-G network (refer to Fig. 6b). The inset in panel d shows an image when the $PM_{2.5}$ concentration exceeded 600 μg m^{-3} in the Delhi-NCR.

Fig. 3).

The air quality index (AQI) in the Delhi-NCR starts to decrease in October, and a systematic increase in $PM_{2.5}$ through November occurs every year in northwestern India due to changes in meteorology, including minimal rainfall, weak winds, and a decrease in the boundary layer height (BLH) (Sawlani et al., 2019; Mangaraj et al., 2025; Rathore et al., 2025). The Commission for Air Quality Management (CAQM) has implemented the Graded Response Action Plan (GRAP) in stages to regulate the air quality by restricting local sources—an option that is guaranteed to perform well on the basis of recent experiences (CAQM, 2023). The GRAP is categorised into Stages I, II, III and IV, which are associated with AQI values ranging from 201–300 (poor), ranging from 301–400 (very poor), ranging from 401–450 (severe) and exceeding 450 (severe plus), respectively. The implementation of GRAP Stages III/IV usually coincided with high-pollution events in the Delhi-NCR, when the $PM_{2.5}$ concentration exceeded 400 μg m^{-3}. GRAP Stage IV was implemented for a shorter duration in 2022, as there was a notable improvement in the $PM_{2.5}$-related air quality because the wind speed increased to over 2 m s^{-1} in November, whereas in 2023, GRAP Stage IV continued for an extended period under a very low wind speed of ~1 m s^{-1}

(Mangaraj et al., 2025). The rapid decrease in $PM_{2.5}$ levels in the Delhi-NCR was attributed mainly to GRAP Stage IV, when the major $PM_{2.5}$ emissions from road traffic and construction activities, among other sources, were reduced.

Unprecedented, high $PM_{2.5}$ values (exceeding 500 μg m^{-3}) were reported in New Delhi from 13–19 November 2024, when various activities were restricted by the Delhi government to ensure the health and safety of citizens (Fig. 9a; Delhi chokes as air pollution becomes severe, BBC news, 14 November 2024). The movement of air pollutants can be tracked well by the Aakash network of CUPI-G sites, as the $PM_{2.5}$ level decreases drastically when rainfall occurs, and concentrations change with the direction and speed of the prevailing winds (Fig. 9b, c, d; also refer to Mangaraj et al. (2025) and Singh et al. (2023)).

3.5 WRF-Chem model simulations and air pollution mechanisms

We conducted air pollution simulations via regional atmospheric CTMs, namely, the Japanese NHM-Chem model, the WRF-CMAQ model and the

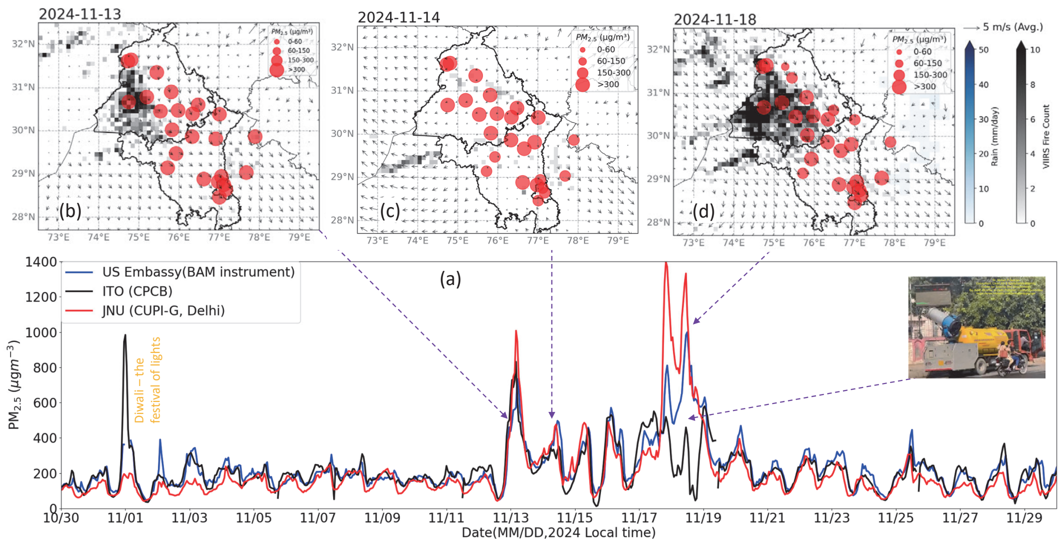

Figure 9. Observed variations in $PM_{2.5}$ at 3 sites in New Delhi managed by 3 independent institutions (refer to the legends) in November 2024 (a). The inset shows an image of a water gun installed near a measurement location. Progression in the daily mean $PM_{2.5}$ level at the CUPI-G sites (red dots), VIIRS fire counts and rainfall maps (shaded), and National Centers for Environmental Prediction (NCEP)-FNL wind vectors at a height of 10 m on selected days in November 2024 (b, c, d). These maps were updated regularly for the September–November campaign periods in 2023 and 2024, available on the Aakash Project website (https://aakash-rihn.org/en/data-set).

WRF-Chem model. By default, secondary aerosol formation is not considered in the models, except for one WRF-CMAQ case, and we therefore expect that the models could underpredict the baseline $PM_{2.5}$ concentrations in areas influenced by urban and industrial emissions (Yamaji et al., 2024). Fig. 10a shows an example of how the regional CTMs are configured with multiple simulation domains over a selected part of the globe. The outermost domain (D01) exhibits the largest grid size (27 × 27 km^2) and the highest area coverage (blue rectangle), and the finer-resolution domain (D02 in this case, at 9 × 9 km^2) is nested within D01. D01 and D02 interact with each other at each model time step to exchange information on the meteorological and chemical states of the atmosphere. Long-range transport information of the chemical species is provided to D01 by a global CTM. Each model simulation starts with the initial state of the atmosphere and includes a spin-up period of several days before the simulations can be used in model–observation comparisons. Some of the salient features of the WRF-Chem model used by the RIHN group with the help of Japan Agency for Marine–Earth Science and Technology (JAMSTEC) researchers/facility are given in tabular form (Fig. 10b). Maps of 6 stable emission sources resulting from regular human activities (industrial and household) are shown in Fig.

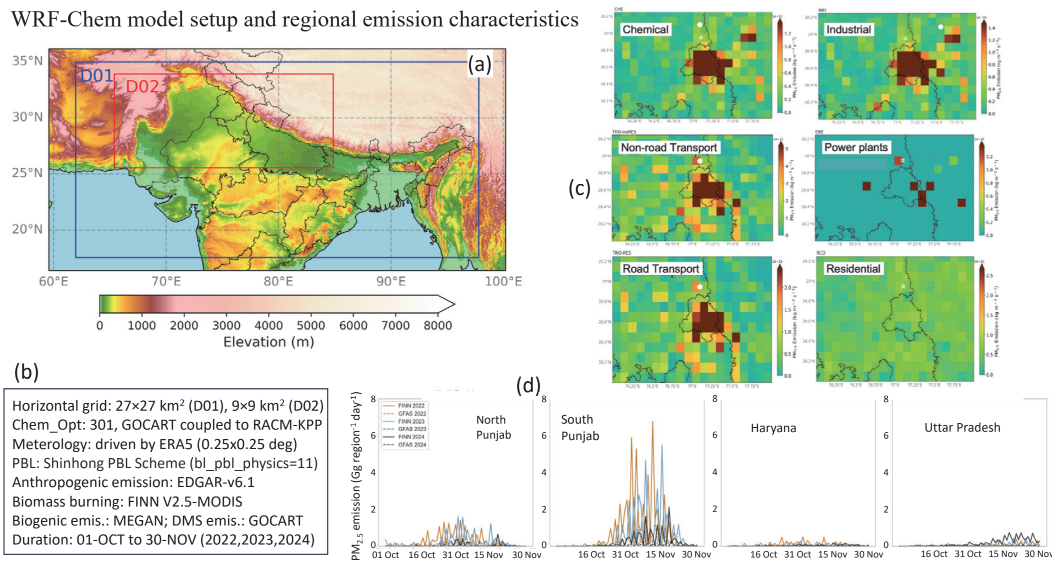

Figure 10. Typical model setup for regional-scale air pollution simulation (WRF-Chem example is shown), where the larger regional domain (D01) is linked to the smaller domain (D02) (a). Salient features of the WRF-Chem model setup on JAMSTEC's supercomputer are shown in (b). Different industrial emission components are processed (c), and a biomass burning emission time series (d) is added for simulation.

10c, and the highly seasonal time series of emissions resulting from CRB (open biomass burning, BB) for the states surrounding the Delhi-NCR are shown in Fig. 10c (Rathore et al., 2025; Biswal et al., 2025). Representative maps of BB and all other sources are shown in Fig. 11.

The bar chart shows a summary of the contribution of CRB to the $PM_{2.5}$ concentration in the four regions of the observation network from October 16 to November 30 in 2022, 2013 and 2024 (Fig. 11). Notably, CRB contributes to the $PM_{2.5}$ concentration in Southwest Punjab, with an average share of 38% in 2022, followed by North Punjab, Central Haryana and the Delhi-NCR, with shares of 28%, 25% and 18%, respectively. Similarly, in 2023, the contribution of CRB to the $PM_{2.5}$ concentration in Southwest Punjab increased to 48%, and in the Delhi-NCR, the share decreased to 16%, mainly because the prevailing winds in 2023 were slower than those in 2022. In

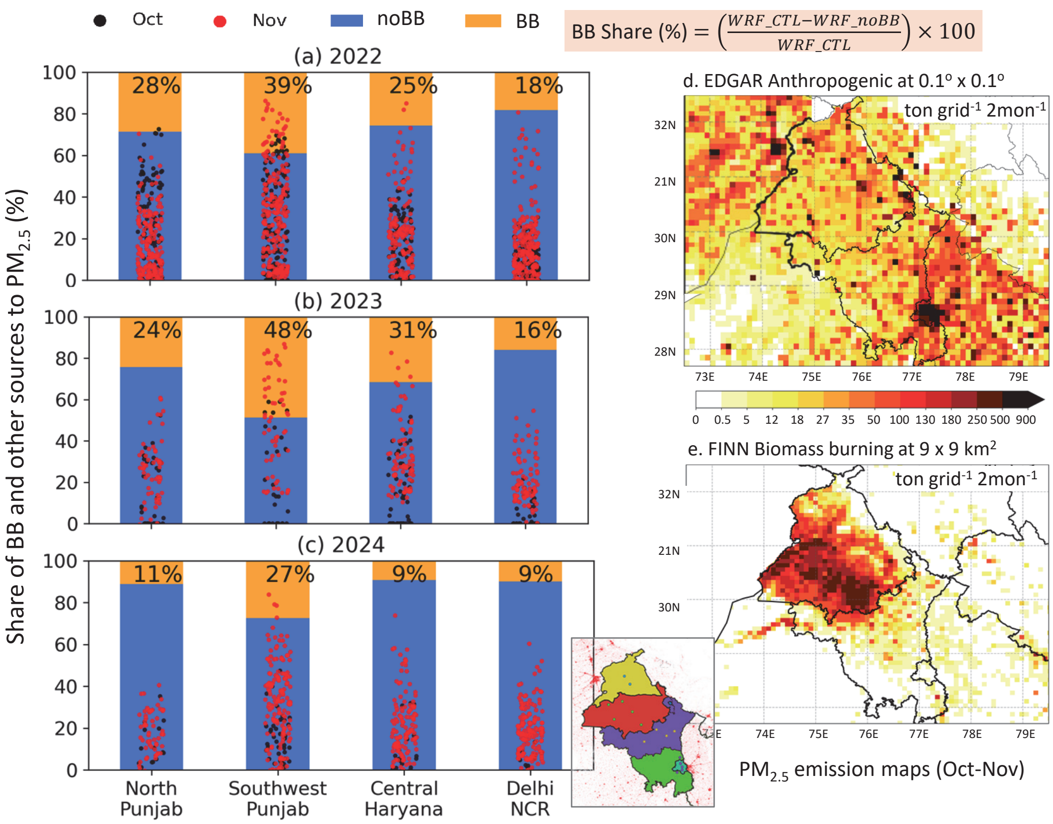

Figure 11. Effects of CRB or biomass burning in general on $PM_{2.5}$ in 4 parts of the study area in 2022 (a), 2023 (b) and 2024 (c). The four bars denote the CRB contributions to 4 regions, as depicted by the inset map at the bottom-centre. Maps of the EDGAR anthropogenic emissions (d; partly of natural origin) and biomass burning emissions (e; mostly of anthropogenic origin) used in the WRF-Chem model are shown.

North Punjab, the contribution of CRB was highest in October, and in the other regions, the contribution was greatest in November. The results suggested that prolonged CRB activities in Southwest Punjab in 2023 did not greatly impact the CRB-induced $PM_{2.5}$ concentration in Delhi because of the absence of a direct transport pathway from the source to the Delhi-NCR. In 2024, the contribution of BB was reduced by half across all regions because of the very few BB emission days (Fig. 10d). Interestingly, the contribution of BB in the CRB source region in southwestern Punjab significantly decreased in 2024. Apparently, the diurnal emission peak shifted by several hours into the afternoon compared with the normal burning hours from midday to the early afternoon in 2024, as per the information from local authorities and newspaper reports. This situation could lead to the avoidance of satellite fire detection (section 3.1). The implications of nighttime burning are far reaching in terms of policy implementation (Biswal et al., 2025).

3.6 Impacts of air pollution on human health and quality of life

We aimed to explore farmers' perceptions of the air quality and health via questionnaires and field visits but could not fully perform activities during the COVID-19 pandemic due to travel restrictions across India. Health-related research is restricted by the ethical review scrutiny of Indian and Japanese institutions. However, we failed to complete ethical clearance procedures to conduct health surveys and health education classes in villages in Punjab to increase awareness of air pollution and improve human health. Through direct interactions, we could more effectively encourage behavioural changes among local farmers. To overcome this situation, we refined the methods employed to assess air pollution perception on the basis of a literature review (Bahrami et al., 2024). We employed the 2200 household surveys from 2020–2021, and a cross-sectional analysis was performed to evaluate the perceptions of air pollution among Punjab residents (Fig. 12a-c), indicating that knowledge and experience with respect to the health risk of air pollution affect their attitudes towards CRB (Yang et al., 2025).

Over 75% of the respondents in Punjab considered air pollution in Delhi to be notable, and among them, 60% described it as severe. However, fewer respondents believed that the level of air pollution in Punjab was severe. Delhi frequently experiences severe air pollution, ranking among the worst globally in terms of the air quality, and perceptions are prevalent that CRB in Punjab and Haryana is one of the main causes of high pollution levels in Delhi. Most respondents did not consider pollution

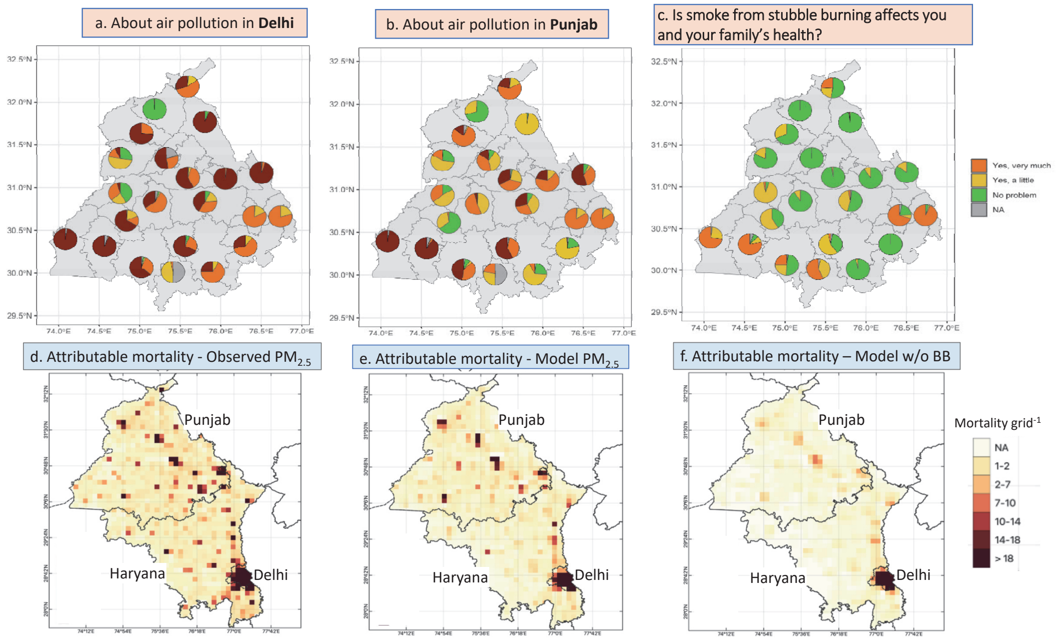

Figure 12. The results of the 2200 household surveys in November 2020 revealed health awareness regarding how people in Punjab think about air pollution in Delhi/ Punjab and how it affects their own health (top row). In the bottom row, we show maps of the human mortality attributable to short-term exposure to $PM_{2.5}$, which were obtained from CUPI measurements (d), the WRF_CRL model (e), and the WRF_noBB model (f).

transported from outside regions, such as Punjab, as a significant cause of air pollution in Delhi. This difference in perception could be attributed to cognitive dissonance. Most respondents were farmers who might be aware that their agricultural activities contributed to air pollution through burning-related smoke. This conflicting awareness may lead to a distorted perception of the problem. We found that CRB contributed only up to 20% to the $PM_{2.5}$ concentration in the Delhi-NCR during the peak burning period from 16 October to 30 November in 2022 and 2023 (Fig. 11). Our results using models and observations could help reduce the gap in our understanding of the relative contribution of CRB to regional air pollution.

For short-term impact assessment of particulate pollution, daily $PM_{2.5}$ concentrations from in situ observations (CUPI-G) and WRF-Chem simulations with and without CRB emissions were combined with risk functions of the World Health Organisation (WHO; de Bont et al., 2024) to estimate mortality during peak CRB months in 2022 (Fig. 12d-f). To help policymaking, we estimated health impacts in the form of attributable mortality, which does not include the costs encountered by most citizens facing health issues who require medical attention. For long-term impacts, annual CRB-attributable premature deaths were calculated using meta-regression–Bayesian regularised trimmed (MRBRT) risk functions for major diseases, including ischaemic heart disease (IHD), stroke, COPD, type-2 diabetes, and lower respiratory infections. District-level $PM_{2.5}$ exposure and CRB contributions from CUPI-G maps and WRF simulations highlighted hotspots such as Ludhiana, Sangrur, Patiala, Firozpur, and Amritsar.

Gaseous toxic air pollutants also generate human and plant stomatal health effects (GBD, 2015). From January–February 2024, nonmethane hydrocarbon (NMHC) levels across various sites in the IGP were measured during four roadside campaigns (Rajwar et al., 2025). Flask air samples were collected during the daytime on most occasions (from 09:00 IST to 19:00 IST). The observed NMHC levels ranged from 19 to 285 ppb, with Delhi-NCR sites showing significantly higher levels (>150 ppb) than the more distant IGP and Himalayan sites (<35 ppb). The urban sites in Delhi-NCR regions (such as Gurugram and Sonipat) were dominated by o-xylene, m-xylene and propane, whereas Haldwani, a semiurban Himalayan foothill site, exhibited relatively high levels of i-pentane and ethylene. Health risks were assessed using the hazard ratio (HR), which revealed that most sites occurred within safe noncarcinogenic limits (HR < 1). However, HR values exceeding this threshold were observed at a few sites, with benzene as the major contributor to the HR, followed by compounds such as p-xylene, o-xylene and toluene (Fig. 13).

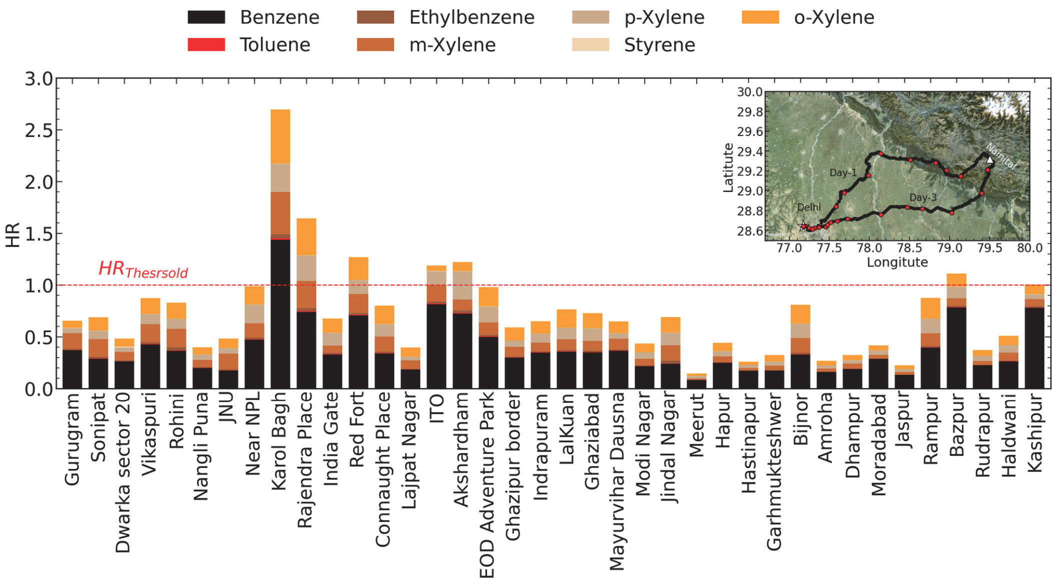

Figure 13. Speciation of air pollutants for more effective attribution analysis of human health risk effects (a). The health risk is mostly caused by high levels of benzyne in the region (bar plot).

The structural variation in airborne microorganisms was studied on the basis of air samples collected three times a day, each for six hours, at the Indian Institute of Tropical Meteorology (IITM) and JNU (Saikh et al., 2025). The samples were classified into four groups according to the meteorological conditions and pollution levels (Fig. 14). On the basis of the target organs in humans, all airborne pathogenic bacterial genera found at the measurement sites can be further classified into four groups: skin, respiratory, gastrointestinal, and oral. Approximately 10% of the total bacterial genera collected in this study were independent of spatial and temporal variations, indicating an urban background for airborne bacteria across Delhi. Meteorological conditions strongly influence urban airborne bacterial populations, and temperature plays a significant role in controlling these populations, with a strong positive correlation. High pathogen concentrations were reported after rain due to the increase in faecal pathogens as rain stirs up sediments. Hospitalisation risk increased in children immediately after rain due to bacterial infections, as reported elsewhere (Lai et al., 2020).

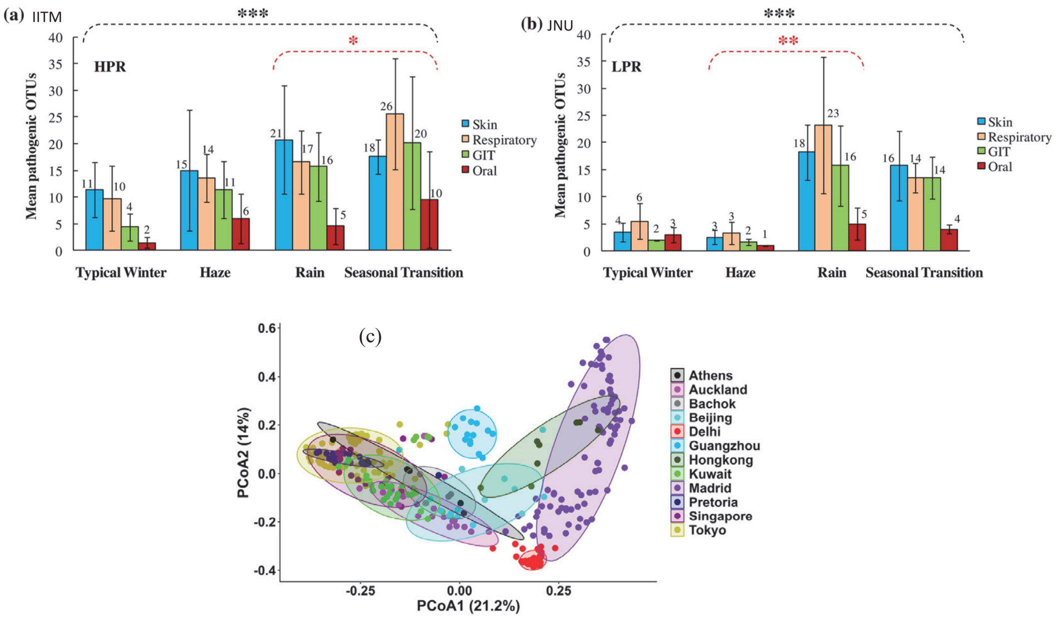

Figure 14. Bacterial community structure in aerosols ($PM_{2.5}$) at two sites in a high-population region and a low-population region (HPR and LPR, respectively), on the IITM and JNU campuses (a, b). Measurements of bacteria in aerosol samples were conducted at two sites in New Delhi, covering different periods of $PM_{2.5}$ loading, indicating unique characteristics compared with those in other cities worldwide. Percentage (%) values of PCoA represent the contribution of PCoA1 and PCoA2 (c). Total 36% (21.2+14) of the total global data has been explained by the two major PCoA components. Global data has been retrieved from published literature.

Principal coordinates analysis (PCoA) plots provide the similarities and dissimilarities of airborne bacterial population derived from the Bray Curtis distances (Fig. 14c). For a comparative study, beta diversities of urban bacterial community over different urban locations across the world are also computed. Each point represents single measurement, and the shaded region represents the area having similar beta diversity clustering all sampling points included within an ellipse calculated from Bray-Curtis dissimilarity. Most of urban areas exhibit similar types of bacterial diversities and fallen within a close proximity by forming a common group. Our study presents that Delhi has completely distinct atmospheric bacterial population with dense cluster unlike to other urban locations, indicating maximum similarities among the samples in winter season that could be due to less variation in sources over Delhi.

3.7 Promotion of sustainable agriculture

Crop diversification and economic incentives to encourage conversion from rice cultivation to alternative crops were realised mainly through field trials at the Lovely Professional University (LPU). LPU colleagues and colleagues from Japan investigated the effects of biochar derived from rice husk and straw (Fig. 15a, b) on soil fertility and crop yield in a wheat–pigeon pea cropping system. Various doses of biochar, including 5, 10 and 15 tons/ha, were applied to the field (Fig. 15c). The experimental results revealed that the addition of 5 tons/ha biochar led to notable improvements in wheat vegetative growth, an increase in the number of grains per panicle, and an increase in grain size. Moreover, there was a substantial increase in the economic yield. These findings underscore the potential of biochar as a beneficial soil amendment for enhancing crop productivity and overall agricultural sustainability within the wheat–pigeon pea cropping system. The pigeon pea trial results revealed that, compared with those under the control treatment and the residual biochar treatment, the application of fresh biochar led to significant improvements in vegetative growth and a notable increase in the number of pods by 30% to 40%. Moreover, the application of fresh biochar substantially increased the economic yield by approximately 35%.

To explore alternatives to the traditional rice–wheat cropping system in Punjab and effectively manage rice straw, we transitioned to the papaya–turmeric cropping system in 2023 (Fig. 15d). This shift aimed to diversify agricultural practices while addressing straw management challenges. By implementing various irrigation techniques and mulching treatments,

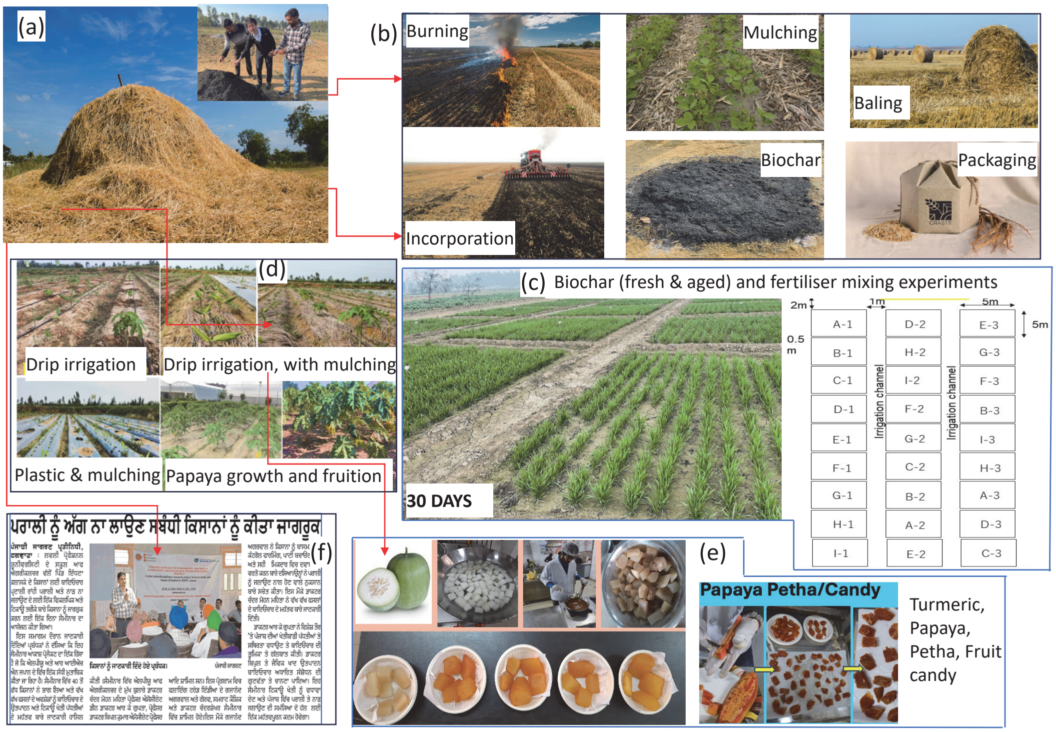

Figure 15. Methods for in situ rice straw management and crop diversification are being explored in collaboration with LPU (Sharma et al., 2025; Sahara et al., 2025). The field experiments included the treatment of soil with rice straw and husk biochar mixed with different fertiliser (NPK) combinations. Crop diversification included the cultivation of turmeric and papaya, and food processing involved dry fruit and peta-sweets.

researchers have reported significant differences in crop growth and yield. Among the various treatments, straw mulch combined with drip irrigation was the most effective, surpassing plastic mulch and other methods. Notably, the turmeric yield under the straw mulch with drip irrigation treatment was considerably greater than that under the alternative treatments. Additionally, this approach facilitated rice straw management, suggesting its dual benefit in enhancing crop productivity and addressing agricultural residue concerns. The adoption of innovative cropping systems coupled with appropriate irrigation and mulching techniques could facilitate sustainable agriculture and the mitigation of environmental challenges in Punjab.

A raw turmeric sample was obtained from the fields of LPU in Phagwara. The rhizomes obtained were healthy and free of insects, pests, fungal infections, and disease. The sophisticated processing of raw turmeric involved cleaning, drying, derooting, peeling, and grinding. Turmeric powder (15–20%) was combined with other ingredients, i.e., ginger powder, skimmed milk powder, sugar powder and stabiliser, in different formulations based on response surface methodology (RSM). The different combinations were analysed for various bioactive compounds, as well as sensory analysis and powder properties, and the best optimised product was then selected. For example, turmeric peel and rhizome powder were incorporated to prepare fried potato and paneer snacks, and the final optimised products were subsequently stored for 1.5 months. However, for petha preparation, turmeric extract, which was added up to a concentration of 4% on the basis of sensory analysis and chemical parameters (moisture content, total phenolic content, total flavonoid content, scavenging activity and curcumin content), was employed. For hard candy, the concentration of turmeric rhizome and peel powder reached 0.75%, while all the analyses and optimisations were performed similarly to the methods used for petha preparation (Fig. 15e). Shelf-life analysis was performed for 1.5–2 months. Different temperature conditions, i.e., 10, 25, and 37°C, were applied in shelf-life analysis. The products from different storage conditions, including hydroxymethyl furfural, total plate count, polyphenol/flavonoid content, peroxide value, and moisture content, were then used for chemical analysis.

On 2 and 4 March 2023, a one-day seminar and workshops were conducted focused on “Biochar as an Alternative and Sustainable Method for Stubble Burning” and “Possible Alternatives to the Rice–Wheat Cropping System in Punjab, India.” The workshops aimed to educate farmers on the harmful effects of straw burning and to explore viable alternatives (Fig. 15f). The participants were informed regarding the detrimental impacts of straw residue and were provided with strategies for managing it effectively. Specifically, discussions revolved around the process of converting rice straw and husk into biochar, thereby highlighting its potential to improve soil properties and enhance crop productivity. Through presentations and practical demonstrations, farmers were introduced to the concept of biochar as a sustainable solution for soil enrichment and were equipped with the knowledge and skills necessary to implement biochar production and application practices in their agricultural activities. These workshops served as crucial platforms for disseminating scientific information and promoting environmentally friendly farming practices among agricultural communities in Punjab, thus ultimately contributing to the mitigation of stubble burning and the adoption of more sustainable cropping systems.

3.8 Cobenefits of sustainable agriculture by reducing GHG emissions

The large-scale post-harvest burning of rice straw in northwest India significantly contributes to air pollution and GHG emissions. This analysis addressed the question of whether mulching/incorporating crop residue, producing compost and biochar from crop residue and applying these products can be implemented to optimise crop residue management strategies for mitigating GHG emissions and enhancing crop yields, with the aim of replacing the current unsustainable burning practices. We collected published data from peer-reviewed papers using Web of Science and Google Scholar and from official reports and statistics published by the Indian government and authorities. We analysed various residue management options, including mulching, incorporation, and the production and application of compost or biochar prepared from crop residue. This study focused on assessing the impacts on soil organic carbon, GHG nitrous oxide (N_2O) and methane (CH_4) emissions, crop yields, yield-scaled GHG emissions and potential trade-offs (Sahara et al., 2025).

In 2019, approximately 20 million tonnes (Mt) of rice residue was generated in rice–wheat cropping systems in Punjab, India. Of this amount, 9.8 Mt was burned across 1.1 million hectares (Mha). The burned rice residue was estimated to reach 8.7 tonnes per hectare (t ha^{-1}), resulting in 3.8 Mt of carbon dioxide equivalent (CO_2 eq) annually. The rice residue generated in Punjab could meet the optimum rate for mulching/incorporation and compost application, as well as half of the optimum rate for biochar application. These management strategies could increase crop yields by up to 20% in Punjab. In contrast, biochar application could increase yields by 0.6–2.5%, and mulching/incorporation and compost application could increase yields by 4.6–14.5% and 15–20%, respectively. The implementation of these strategies could mitigate GHG emissions mainly through soil carbon sequestration. Mulching/incorporation of crop residue could enable the sequestration of 0.7 Mt CO_2 eq annually, whereas compost and biochar application could facilitate the sequestration of 2.9 and 3.4 Mt CO_2 eq, respectively.

However, mulching/incorporation and compost application could also increase nitrous oxide (N_2O) emissions by 0.18 and 0.13 Mt CO_2 eq annually, respectively. Conversely, biochar application could reduce N_2O and methane (CH_4) emissions by 0.11 and 0.06 Mt CO_2 eq annually, respectively. Considering both soil carbon sequestration and GHG emissions, mulching/incorporation could reduce GHG emissions by 0.5 Mt CO_2 eq annually, whereas compost and biochar application could reduce GHG emissions by 2.8 and 3.6 Mt CO_2 eq, respectively. However, compost and biochar can emit 1.2 and 1.6 Mt CO_2 eq annually, respectively. When accounting for GHG emission mitigation, mulching/incorporation, compost, and biochar

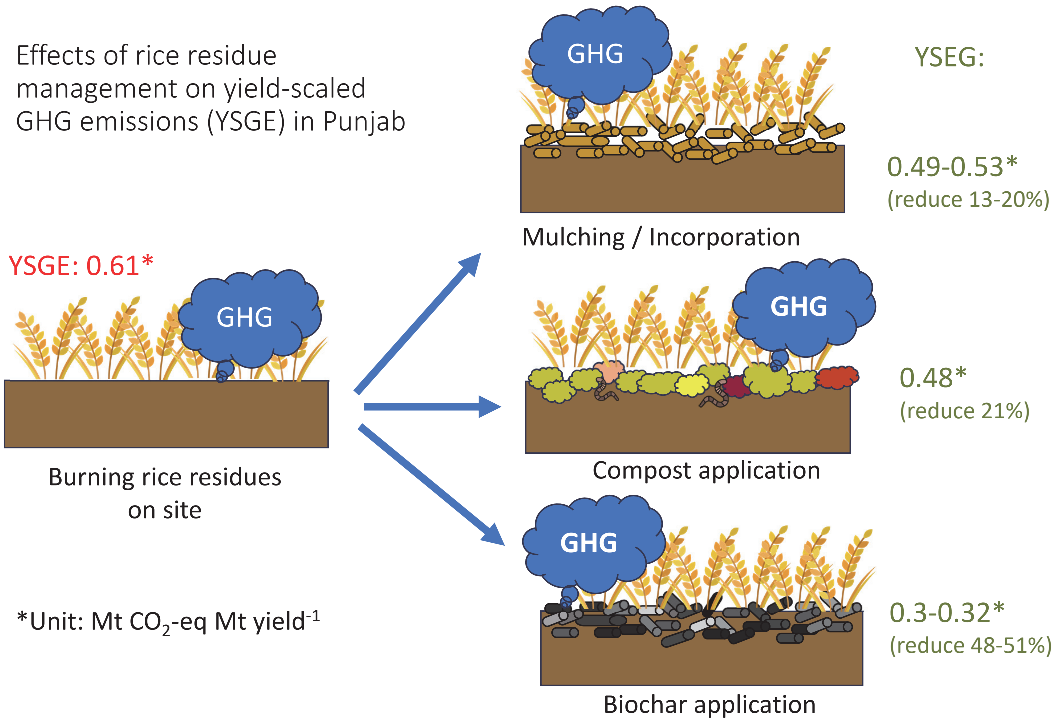

Figure 16. Greenhouse gas reduction potentials of mulching/incorporation of crop residue, producing compost and applying biochar prepared from crop residue.

applications could provide net GHG mitigation potentials of 0.5, 1.2, and 2.4 Mt CO_2 eq annually, respectively. In terms of yield-scaled GHG emissions, mulching/incorporation, composting, and biochar applications could reduce emissions by up to 20%, 21%, and 51%, respectively.

In a farmer field trial during the rabi season, wheat crops were cultivated under the application of biochar provided by the research team alongside seeds and fertiliser. Compared with that in adjacent conventionally farmed fields, the biochar-treated fields demonstrated significantly greater vegetative growth. Researchers visited farmers in the biochar-amended fields, presenting trial results and gathering feedback. Farmers appreciated the notable growth improvements, particularly emphasising the potential of biochar for effectively managing rice residue and curbing harmful straw burning practices. This farmer-centric approach not only highlights the effectiveness of biochar application in promoting crop growth but also highlights its crucial role in sustainable residue management, thereby mitigating environmental risks and protecting public health.

4. Summary and outlook

Rice straw burning in northwestern India is an environmental problem of global concern because agricultural residue management involving burning is a common practice in most parts of the world. The Aakash Project aimed to (1) clarify the extent of air pollution caused by rice straw burning in areas where it occurs and the factors that contribute to its occurrence; (2) promote the awareness of health hazards caused by air pollutants among local residents; (3) provide specific measures for the effective use of rice straw and recommended ways to transform to sustainable agriculture on the basis of the current situation, including the decline in groundwater and the occurrence of soil degradation; (4) analyse local culture and the social context that causes straw burning behaviour; and (5) disseminate research findings to government agencies, local communities and local residents to encourage new policies and changes in daily behaviour.

This study revealed the regional characteristics and socioeconomic factors of CRB in Punjab. Our understanding of the evolution in the socioeconomic situation in northwestern India over the past few decades, in relation to the rest of the country, and the drastic changes over the past decade is shown in Fig. 17. Personal experiences and field surveys suggest that while the production of rice straw has increased greatly following the Green Revolution in India (Punjab and Haryana) and subsequent crop intensification and mechanisation, there has also been a lower domestic demand for rice straw over the past few decades. Farming households no longer keep bulls for ploughing fields or milk cows as a necessity—in Amritsar, Punjab, only 25% of families keep domesticated animals. The author's observation is that the use of straw for thatching houses in villages in West Bengal has almost completely vanished over the past 50 years, which could lead to another environmental problem (India's mud houses: Our solution to climate change?; https://www.un.org; last accessed, 20 February 2025). These transitions are shown in thumbnail pictures at the top of Fig. 17.

Similar to the effect of the 2009 Water Act, the role of the long-duration and highest-yield PUSA-44 rice variety in decreasing the gap between kharif rice harvesting and wheat seeding remains controversial. Fig. 17 shows the satellite-observed fire counts, dynamics of the cropping patterns of rice cultivars and mechanisation since 1990. However, the increase in PUSA-44 variety adoption since its inception during the early 1990s and satellite FDCs from 2002–2016 are highly correlated. This has notably led to policies of the Punjab and Haryana governments for phasing out the

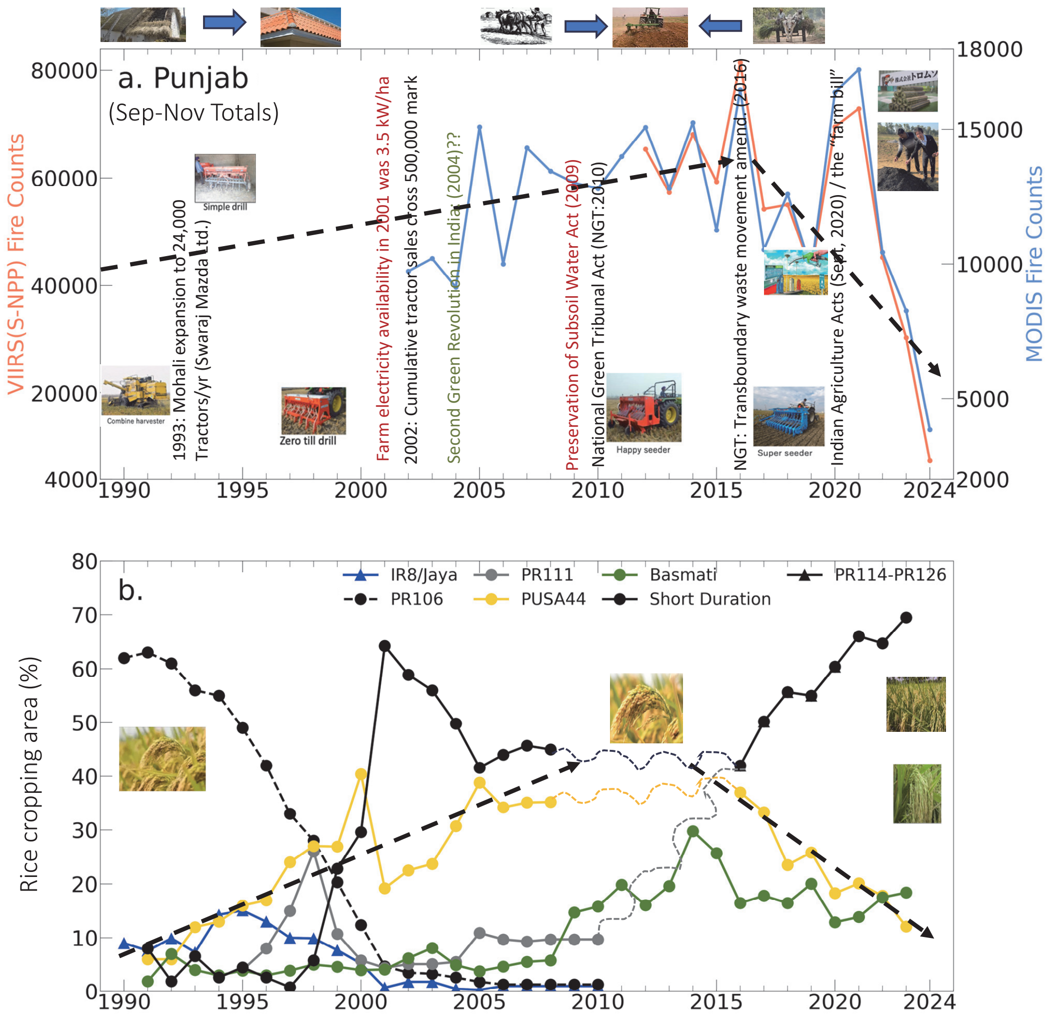

Figure 17. Evolution of CRB in Punjab, shown as FDCs from satellites (blue line: MODIS data; orange line: VIIRS data) in the top panel (a). The CRB time series should be placed within the context of government policies and socioeconomic developments in the region (marked approximately on the time axis). The lower panel (b) shows the adoption of various rice cultivars since the 1990s, which reveals an apparent link between fire counts and PUSA-44 rice variety cultivation (orange; data sources: Singh and Karla (2002), Grover (2013), Kurinji et al. (2022), and various newspaper articles). Short-duration PR cultivars have been promoted in recent years to reduce water use and rice straw production.

PUSA-44 rice variety and replacing it with newer non-basmati PR varieties. This has resulted in a strong correlation between the decreases in the PUSA-44 cropping area and satellite fire counts during the period after 2016 (Fig. 17a, b), although the CRB time continued to be delayed even during 2023–2024 relative to the earlier periods (Fig. 3c,f). This situation has created a dilemma regarding the role of crop residue processing and the use of machinery, which are manufactured and distributed to farmers at subsidised costs. Which policy—phasing out the PUSA-44 rice variety or post-harvesting crop residue management practices—played a primary role in reducing satellite-based FDCs. Most recently, the media and scientists have been suspicious of behavioural changes among farmers to avoid the detection of CRB, with a more than 70% reduction in fire counts in just 2 years (2022–2024). These observations suggest that government policies have clear implications for behavioural changes among citizens and should be well paced on the basis of scientific evidence for achieving maximum benefits.

On the topics of sustainable agriculture and air pollution mitigation, we provide the following concluding remarks:

1. Crop diversification—fruits and vegetables with different timings could be grown in Punjab and Haryana. We already explored papaya and turmeric as crops. Nonperishable farm produce to the market at competitive pricing is a possibility and could be demonstrated by product manufacturing.
2. Income can be derived from the carbon trading system (CTS) under the global stocktake from crop residue management (biofuel production), and soil carbon restoration and GHG emission reduction can be achieved with the application of biochar in agricultural fields. Field experiments and a meta-data analysis generated a positive outlook for the CTS.
3. New land management policies in support of marginal farmers (e.g., less land holding, greater renting) should be formulated so that they can participate in governmental policy tools (subsidy on machineries) without affecting their livelihood. Socioeconomic studies revealed the constraints on farmers in avoiding paddy straw burning (even after the PUSA-44 cultivar is almost banned).
4. The health benefits of reducing air pollution due to short- and long-term exposure to $PM_{2.5}$ (outpatient visits, hospitalisation, and medical bills) and restricting the spread of viral/bacterial infection (biome studies) are being studied. A further increase in awareness of health issues is needed, and effects are becoming increasingly obvious as information is disseminated by media outlets.
5. The establishment of an air pollution measurement network covering rural and urban regions using low-cost sensors is strongly recommended. Promotion of integrated studies through national and international forums for long-term monitoring and managing air pollution in South

Asia is possible and highly desirable.

6. Stringent actions are also needed within the Delhi-NCR for reducing emissions from major industrial sources (e.g., vehicles, power plants, dust suspension, and the chemical industry), accounting for ~80% of $PM_{2.5}$ in air from October–November.

Data availability

The datasets generated and/or analysed during the current study are available in the RIHN Aakash database [https://aakash-rihn.org/en/data-set/], RIHN Academic Information Repository [https://chikyu.repo.nii.ac.jp]. The corresponding author will help establish contact with the person responsible for following up any requests that are not listed in the online database.

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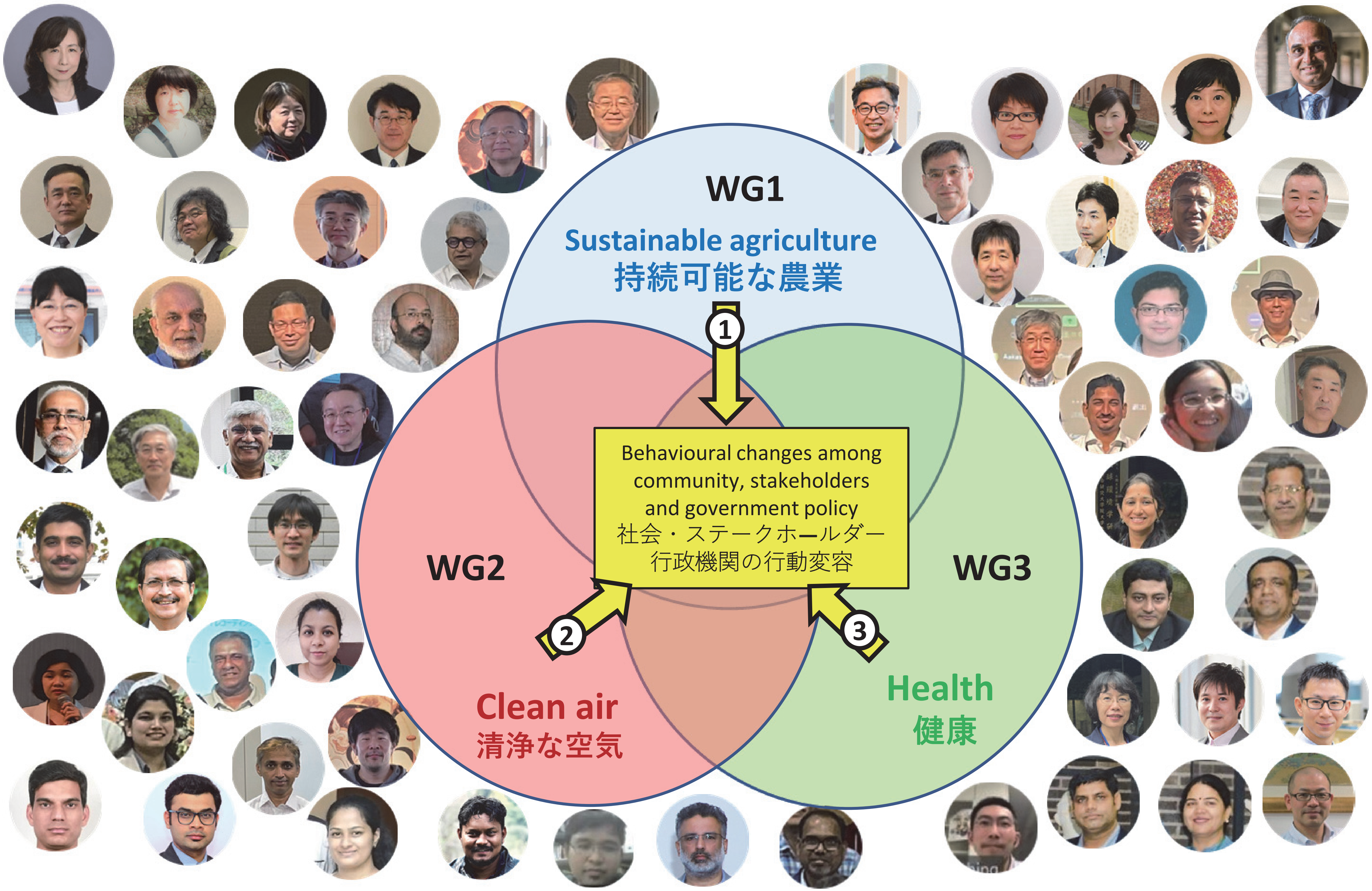

The front cover is designed by Kaede Ohashi using photographs taken by Rumiko Murao (Punjab agriculture), Prabir K. Patra (Delhi pollution) and Haruhisa Asada (field burning)

Aakash Project - An Interdisciplinary Study Toward Clean Air, Public Health and Sustainable Agriculture: The Case of Crop Residue Burning in North India

A large amount of rice straw is burned after the kharif crop season in the northwest India region. This practice of crop residue burning releases large amounts of pollutants into the atmosphere, causing severe conditions for human health and economic activities. The Aakash project is delineating the science of air pollution in the region (including the national capital of Delhi), raising social awareness, and exploring ways for sustainable agriculture.

Photograph by Sachiko Hayashida