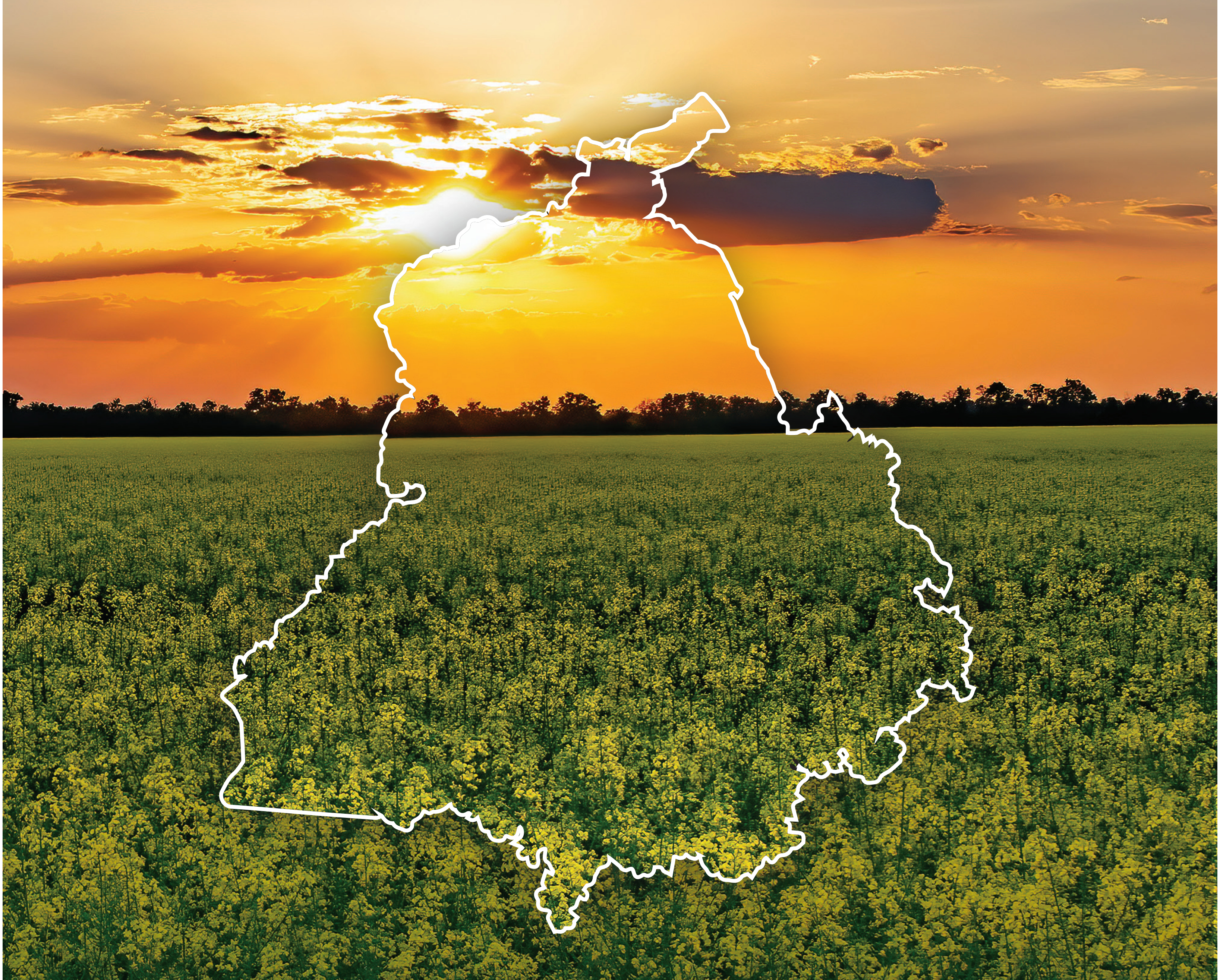

PATHWAYS TO NET ZERO IN PUNJAB: THE CRITICAL ROLE OF NON-CO_2 POLLUTANTS

PATHWAYS TO NET ZERO IN PUNJAB: THE CRITICAL ROLE OF NON-CO_2 POLLUTANTS

Prepared by:

Punjab State Council for Science & Technology (PSCST), Department of Science, Technology & Environment, Govt. of Punjab, India, The Energy and Resources Institute (TERI) and Institute for Governance & Sustainable Development (IGSD).

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Disclaimer

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Message

Punjab stands at a defining juncture, poised to champion decisive and transformative measures to combat air pollution and climate change with unwavering commitment. As a state that plays a pivotal role in India's agricultural and industrial landscape, we must ensure that our progress is built on a foundation of environmental sustainability. The growing burden of air pollution not only endangers public health but also affects our economy, food security, and overall quality of life.

This report on Short-Lived Climate Forcers (SLCFs) marks a significant step toward understanding and addressing pollutants such as black carbon, methane, and tropospheric ozone-key drivers of both air pollution and climate change. These pollutants have far-reaching consequences on air quality, climate stability, and agricultural productivity. By targeting their reduction, we can achieve immediate and tangible benefits for public health, environmental sustainability, and economic resilience.

The Government of Punjab is committed to implement comprehensive strategies to ensure cleaner air and a healthier future for our citizens. The Punjab State Action Plan on Climate Change (SAPCC 2.0) provides a strong foundation for integrating air quality management with climate resilience. The insights and policy recommendations in this report will further strengthen our efforts to reduce emissions across key sectors, including agriculture, industry, transport, and urban development.

I commend the Punjab State Council for Science & Technology (PSCST), for their collaborative efforts with IGSD and TERI, in compiling this vital study. I firmly believe that this report will serve as a guiding document for policymakers, researchers, and stakeholders, enabling decisive action toward a cleaner and more sustainable Punjab.

Let us work together to make Punjab a leader in environmental stewardship, setting an example for the rest of the country in combating air pollution and climate change.

(K A P Sinha)

Priyank Bharti, IAS
Secretary, Department of Science,
Technology & Environment Punjab

Message

The Department of Science, Technology & Environment underscores the critical importance of addressing environmental degradation and climate change, with a particular focus on Non-CO_2 pollutants, such as Short-Lived Climate Forcers (SLCFs). These pollutants, including methane, black carbon, and hydrofluorocarbons, have a potent impact on climate change, air quality, and public health. In Punjab, where agriculture, industry, and urbanization are significant economic drivers, SLCFs contribute to both environmental challenges and health risks, while also threatening food security and economic resilience. Mitigating these pollutants offers a unique opportunity to achieve rapid climate benefits, improve air quality, and advance sustainable development goals, aligning with the state's commitments under the Punjab State Action Plan on Climate Change (SAPCC 2.0) and the National Clean Air Programme (NCAP).

We are pleased to announce the release of the report titled "Pathways to Net Zero in Punjab: The Critical Role of Non-CO_2 Pollutants." This comprehensive study, prepared through a collaborative effort by the Punjab State Council for Science & Technology (PSCST), the Institute for Governance & Sustainable Development (IGSD), and The Energy and Resources Institute (TERI), provides an in-depth analysis of SLCFs in Punjab. The report examines their sources, trends, and actionable mitigation strategies, advocating for an integrated approach to air quality management and climate action. It identifies high-impact intervention areas that can deliver significant co-benefits for public health, agricultural productivity, and economic stability.

The insights from this report are poised to shape evidence-based policymaking, guiding the refinement and implementation of departmental strategies to enhance environmental quality and climate resilience across Punjab. We express our gratitude to PSCST, IGSD, and TERI for their technical expertise and commitment, which have enriched this study with robust data and strategic perspectives essential for informed decision-making. This report marks a significant step toward a sustainable and resilient future for Punjab.

(Priyank Bharti)

Pritpal Singh
Executive Director,
Punjab State Council for Science & Technology

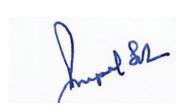
Message

The Punjab State Council for Science & Technology has prepared State Action Plan on Climate Change (SAPCC 2.0) on behalf of Department of Science, Technology & Environment, Govt. of Punjab in line with India's Nationally Determined Contributions (NDCs) and Sustainable Development Goals (SDGs). The report highlights trends of Climate Change adaptation and mitigation till 2030 and the impact of Non-CO_2 pollutants in the agriculture, livestock, transport and waste management sector.

Now this report on 'Pathways to Net Zero in Punjab: The Critical Role of Non-CO_2 Pollutants' has been prepared after taking inputs from all stakeholder departments and institutions. The report represents a significant endeavour to provide a comprehensive, data-driven assessment of Short Lived Climate Forcers (SLCFs) and their implications for the State's environmental landscape.

The report highlights baseline inventory of SLCF emissions for 2019 and projecting future trends under various mitigation strategies. This analytical work further highlights the emission reduction potential of both existing and proposed policies, thereby facilitating more effective environmental management. The report identifies priority sectors and policy interventions crucial for integrating climate and air quality actions across Punjab.

We extend our sincere appreciation to the collaborating organizations - the Institute for Governance & Sustainable Development (IGSD) and The Energy and Resources Institute (TERI) for their technical support for development of this report. I hope that the findings and recommendations contained herein will serve as a foundational reference for policymakers and stakeholders, enabling informed strategies and investments towards a cleaner and more sustainable Punjab.



(Er. Pritpal Singh)

Institute for Governance & Sustainable Development

Message from the Director, Institute for Governance & Sustainable Development (IGSD)

On behalf of the Institute for Governance & Sustainable Development (IGSD), I am pleased to present our report, 'Pathways to Net Zero in Punjab: The Critical Role of Non-CO2 Pollutants'.

IGSD has actively worked, over the years, to advance climate action, leading efforts to strengthen national and subnational strategies for addressing super pollutants, collaborating with partners across India, and other countries. A key focus has been building the necessary legal tools and institutional capacity to facilitate rapid mitigation of these pollutants. Furthermore, IGSD has championed equitable transitions in the crucial areas of cooling and energy efficiency and has played a vital role in creating awareness.

Countries worldwide, especially those in the Global South, are increasingly becoming cognisant of the need to have an alternate blueprint to tackle climate change bearing in mind its ongoing impacts. At IGSD, we have always believed it's essential to have a dual-pronged strategy to mitigate climate change. One which addresses the marathon of decarbonisation for the longer term and, crucially, takes on the sprint to decrease potent emissions in the form of Short-Lived Climate Forcers (SLCFs) for the shorter term. These SLCFs include Short-lived Climate Pollutants like methane (CH4), black carbon (BC), hydrofluorocarbons (HFCs), and tropospheric ozone (O3), in addition to nitrates and sulphates. Hence, it has become imperative to ensure focused, data-driven research that can support the government's efforts at ensuring a cleaner future for India.

This report aims to do just that for the state of Punjab — a critical state which, we must remember, experienced 128 heatwave days between 2010 and 2023. This is the same state which, in 2022, experienced an early season heatwave that contributed to wheat yield reductions of up to 25% in certain districts. The negative impacts of climate change on the Punjab landscape are very real and it's vital to have the right policies in place. Here, I'd like to congratulate and commend the state of Punjab for becoming a frontrunner in climate mitigation policies — by effectively integrating mitigation of non-CO2 pollutants into its Vision 2047 roadmap as well as its updated State Action Plan on Climate Change (SAPCC 2.0). However, to scale up mitigation efforts, we need further, nuanced technical research.

This report seeks to provide a sharper, data-led supportive framework for addressing SLCFs in the state. It outlines emission reduction potential of current as well as proposed policies so that the state has the tools to ensure precise policymaking in the future. The report assumes further significance as it provides a granular understanding of the emission landscape based on key contributing sectors such as transport, industry, agriculture and livestock, and residential.

Looking ahead, IGSD is firmly committed to ensuring continuity and fostering collaboration, supporting states in their implementation of commitments, and consistently championing equity and ambition in all climate initiatives.

SLCFs are a major hurdle in the state's journey toward a cleaner future. I hope this report - developed with invaluable support from TERI and PSCST - can help to remove all such hurdles and ensure a better tomorrow for the people of Punjab.

Zerin Osho

Director, Institute for Governance & Sustainable Development

Preface

Climate change poses an urgent and far-reaching threat, with profound implications for Punjab's agriculture, water resources, public health, and overall economic stability. The world is entering an era of unprecedented heat, with the state of Punjab expecting an average temperature rise of 2.1°C to 4.5°C by mid-century. In this background, decarbonisation alone is insufficient to slow warming, therefore a comprehensive dual-strategy is essential - combining the marathon to curb the longer living CO_2 with the sprint to mitigate shorter living non-CO_2 pollutants. As a climate-sensitive and rapidly developing state, Punjab must act decisively to strengthen its climate resilience and accelerate its mitigation efforts.

Parallelly, air pollution also poses a significant threat to Punjab's people and economy, increasing the possibility of adverse health impacts and development losses. The Government of Punjab recognizes the necessity of an integrated approach to curb climate pollutants and improve air quality through holistic strategies. This report focuses on Short-Lived Climate Forcers (SLCFs)—including black carbon, methane, and tropospheric ozone—which are potent climate pollutants with significant warming effects in the short-term and deteriorating air quality. Reducing these emissions not only helps slow near-term climate change but also enhances air quality, delivering tangible health and environmental benefits to communities across the state.

This study aligns with Punjab's broader climate and air quality policies, including the Punjab State Action Plan on Climate Change (SAPCC 2.0) and Punjab's Vision Document 2047. It identifies key emission sources, proposes targeted interventions, and provides a roadmap for integrating SLCF mitigation into state policies. Given the multi-sectoral nature of air pollution, the report underscores the need for cross-sector collaboration to maximize co-benefits for food security, public health, and economic sustainability.

The Punjab State Council for Science & Technology (PSCST), in collaboration with IGSD and TERI, has undertaken this study to support evidence-based policymaking and action. By providing robust data and strategic insights, this report aims to serve as a foundation for informed decision-making, guiding Punjab toward a cleaner, healthier, and more climate-resilient future.

It is our hope that this report will inform policy actions, strengthen institutional capacities, and encourage collaborative efforts across sectors to effectively reduce air pollution and its climate impacts.

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Glossary

Baseline Scenario (BAU): A Business-as-Usual (BAU) scenario that represents the sectoral growth projections for the state of Punjab under existing conditions, without considering the implementation of any specific mitigation actions or interventions to address SLCF emissions.

Alternate Scenarios (ALT): These scenarios assume the successful implementation of additional interventions aimed at reducing SLCF emissions. They assess the impact of these measures on both short-term (2030) and long-term (2047) policy targets. The interventions include specific sectoral policies planned by the state or similar measures being implemented in other parts of the country.

Global Warming Potential (GWP): An index to measure the potency of greenhouse gases to absorb infrared thermal radiation over a given time frame after their addition to the atmosphere.

Short-lived Climate Forcers (SLCFs): Chemically and physically reactive compounds with shorter atmospheric lifetimes, varying from a few weeks and months to a maximum of about two decades. These can have either net-warming or a net-cooling effect on the local environment. They include aerosols (sulphate, nitrate, ammonium, carbonaceous aerosols, mineral dust and sea spray), which are also called particulate matter (PM), and chemically reactive gases (methane, ozone, some halogenated compounds, nitrogen oxides, carbon monoxide, non-methane volatile organic compounds, sulphur dioxide and ammonia).

Short-lived Climate Pollutants (SLCPs): Short-lived climate pollutants (SLCPs) are a group of greenhouse gases and air pollutants that have a near-term warming impact on climate and can affect air quality. SLCPs include black carbon, methane, ground-level ozone, and hydrofluorocarbons (HFCs).

Emission Factors: A coefficient representing the amount of a specific pollutant emitted per unit of activity or fuel consumed in a sector.

Sectoral Emission Estimations: A comprehensive dataset that estimates emissions of different pollutants from various sources within a defined region and time period.

Direct Seeded Rice: Direct Seeded Rice is a viable alternative to conventional puddled transplanted rice, with strong potential to mitigate and adapt to climate change. This system empowers poor farmers to better cope with climate-induced changes by providing flexible rice establishment methods and reducing the water needed for both crop establishment and growth.

Crop Diversification: The practice of growing a variety of crops instead of relying on a single crop, helping to improve soil health, reduce dependency on water-intensive crops like rice, and lower emissions from agricultural activities.

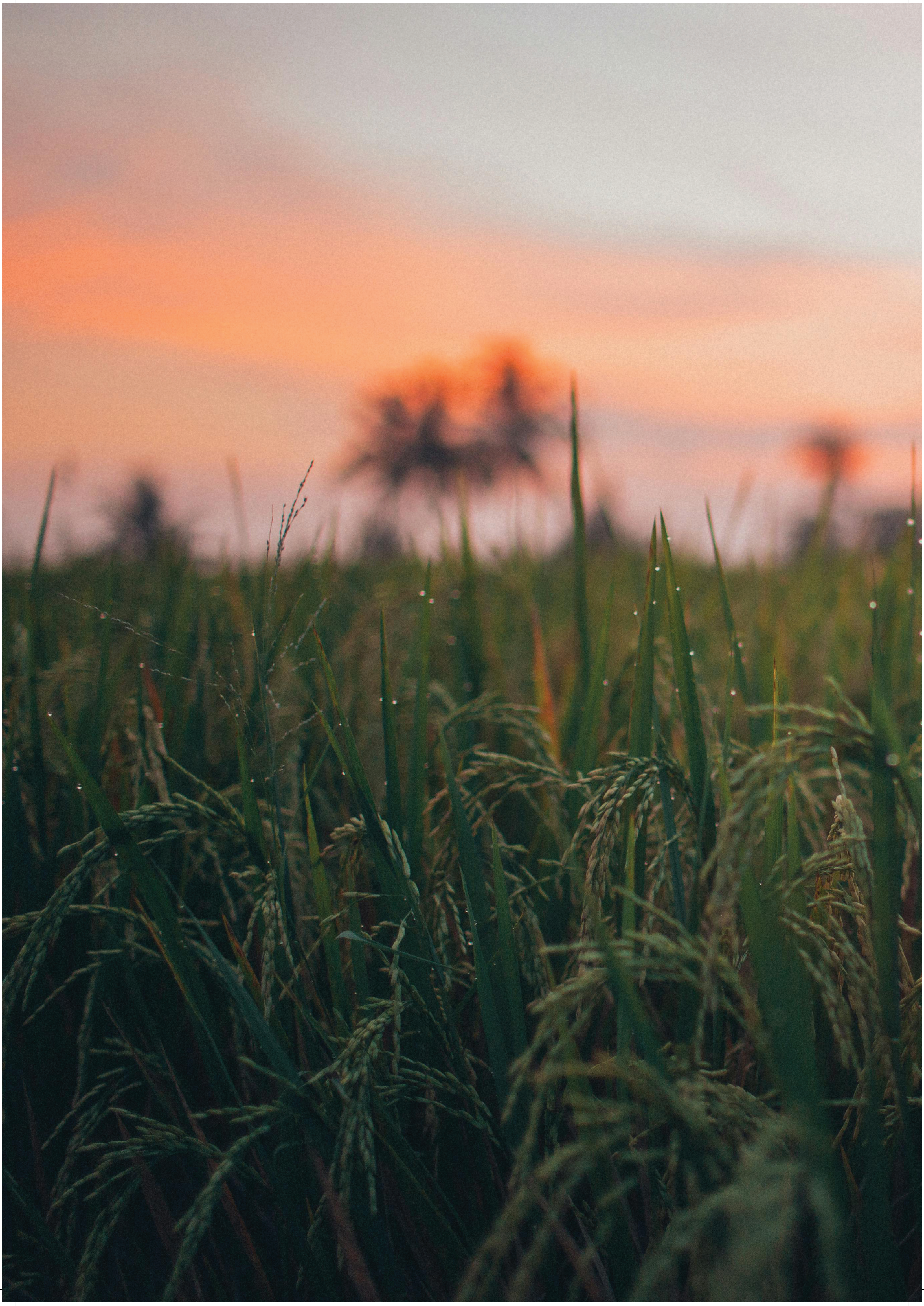
Heat Stress: A condition resulting from prolonged exposure to high temperatures, often exacerbated by climate change and urbanization. It can lead to adverse health effects such as dehydration, heat exhaustion, and heatstroke, particularly among vulnerable populations.

Co-benefits: Additional advantages gained from implementing climate and air pollution mitigation policies, such as improved public health, food security, and economic benefits.

List of Abbreviations

APCDs	Air Pollution Control Devices
AQI	Air Quality Index
BAU	Business-As-Usual
BC	Black Carbon
CAAQMS	Continuous Ambient Air Quality Monitoring Stations
CAFE	Corporate Average Fuel Efficiency
CAGR	Compound Annual Growth Rate
CCN	Cloud Condensation Nuclei
CEA	Central Electricity Authority
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CPCB	Central Pollution Control Board
DMS	Dimethyl sulphide
DSR	Direct Seeded Rice
FAME	Faster Adoption and Manufacturing of (Hybrid) and Electric Vehicles
GHG	Greenhouse Gas
GWP	Global Warming Potential
H-CNG	Hydrogen-Compressed Natural Gas
HAMP	Heat Action Management Plan
HFCs	Hydrofluorocarbons
ICAP	India Cooling Action Plan
IPCC	Intergovernmental Panel on Climate Change
ITMS	Integrated Traffic Management System
MoPNG	Ministry of Petroleum & Natural Gas
MoRTH	Ministry of Road Transport & Highways
NAAQS	National Ambient Air Quality Standards
NAMP	National Air Monitoring Programme
NCAP	National Clean Air Programme
NDDB	National Dairy Development Board
NH_3	Ammonia
NMVOCs	Non-methane Volatile Organic Compounds
NO_x	Nitrogen Oxides
NRRI	National Rice Research Institute
NSSO	National Sample Survey Office

O_3	Tropospheric Ozone
OH	Hydroxide
PM	Particulate Matter
PPCB	Punjab Pollution Control Board
SAPCC	State Action Plan on Climate Change
SLCFs	Short-lived Climate Forcers
SLCPs	Short-lived Climate Pollutants
SO_2	Sulphur Dioxide
UNEP	United Nations Environment Programme



1 / Executive Summary

The global climate system is undergoing unprecedented warming, with successive years setting new temperature records. In response, the Intergovernmental Panel on Climate Change (IPCC) has underscored the urgency of achieving substantial greenhouse gas reductions by 2030 to avert the most severe impacts of climate change. However, decarbonisation alone is insufficient. Mitigating short-lived climate pollutants (SLCPs)—such as methane (CH_4), black carbon (BC), tropospheric ozone (O_3) and hydrofluorocarbons (HFCs)—is critical, as these pollutants possess significantly higher global warming potentials (GWP) than carbon dioxide over a shorter timeframe ranging from a few days to about 20 years.

Short-lived climate forcers (SLCFs) is an overarching term referring to chemically and physically reactive compounds with shorter atmospheric lifetimes that can have either net-warming or a net-cooling effect on the local environment. Beyond SLCPs, they include aerosols and particulate matter as well. Addressing SLCFs offers immediate co-benefits, including improved air quality, enhanced public health, and increased agricultural resilience, thereby complementing long-term decarbonisation goals.

In the Indian context, Punjab presents both a unique challenge and a significant opportunity for SLCF mitigation. The state has experienced 128 heatwave days between 2010 and 2023, and in 2022; an early-season heatwave contributed to wheat yield reductions of up to 25% in certain districts. Agriculture remains a primary source of SLCFs in the state, notably through methane emissions from rice cultivation and particulate matter emissions from seasonal crop residue burning. Additionally, diesel-dependent transportation, with 90% of public buses running on diesel, and a high concentration of energy-intensive industries contribute to elevated SLCF emissions. Notably, Punjab has emerged as a frontrunner in climate governance by explicitly integrating mitigation of non-CO_2 pollutants into Punjab's Vision Document 2047 roadmap and its revised State Action Plan on Climate Change (SAPCC 2.0). This report represents the first of its kind effort to develop a strategic, data-driven framework for addressing SLCFs at the subnational level.

Presenting a novel emission estimation study of Short-lived Climate Forcers (SLCFs) for the state of Punjab for the baseline year 2019; this report highlights all the projected changes in these compounds by 2047 under a Business-As-Usual (BAU) scenario. It highlights the critical need to sharpen focus on SLCFs—which include Short-lived Climate Pollutants (SLCPs), i.e., methane (CH_4), black carbon (BC), hydrofluorocarbons (HFCs), and tropospheric ozone (O_3), in addition to nitrates and sulphates to mitigate short-term climate impacts, while maintaining the long-term momentum on CO_2.

To work towards this holistic strategy, the report analyses the projected trends in SLCFs and evaluates a set of policy-driven alternative scenarios (ALT) across sectors, identifying pathways to achieve maximum emission reductions. Two key insights emerge from this study:

It offers a sectoral emission estimations of SLCFs, highlighting the relative contributions of key sectors across the state.

It identifies priority sectors and policy interventions that are essential for integrating climate and air quality action, based on scenario-based analysis.

With rising global temperatures and increasing pollution, Punjab is vulnerable to the effects of climate change, heat stress, and air pollution.

Temperatures are breaking records year after year, highlighting the urgent need to reduce greenhouse gas emissions to avoid the worst impacts of climate change.[1] Punjab is experiencing an unprecedented temperature rise and more frequent, intense heatwaves; 2024 recorded 27 heatwave days – the highest in a decade.[2] Projections show an average temperature rise of 2.1°C to 4.5°C by mid-century, with major cities like Ludhiana and Amritsar already facing greater temperature rises due to the urban heat island effect.[3] These extreme temperatures have resulted in significant agricultural losses. For instance, climate projections predict crop yield reductions in Punjab by as much as 13% for maize, 6% for wheat, and 2% for paddy.[4]

At the same time, air pollution poses a severe threat to the state's economy and human health, it has been associated with various respiratory and cardiovascular diseases. All nine monitored cities in Punjab exceeded the National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$ in 2024, highlighting persistent and widespread air pollution across the state.[5]

Focusing on short-lived climate forcers allows Punjab to address air quality and manage unpredictability of weather in the short and medium term.

While CO_2 is the single largest contributor to global warming, short-lived climate pollutants (SLCPs) are responsible for nearly 45% of current temperature rise. Scientific research confirms that focusing solely on CO_2 reduction is insufficient; a dual strategy that focuses on both CO_2 and non-CO_2 mitigation is essential for meaningful climate action. Globally, cutting methane can lower temperature rise rates by 20% from 2010–2030, 25–40% from 2030–2050, and 20–30% over the full 2010–2050 period. Reducing black carbon (soot from burning fossil fuels) can lower near-term warming by an additional 10–20% by 2030.

This approach provides significant co-benefits, including improved air quality, reduced health impacts, and enhanced food security. For Punjab, reducing SLCF emissions is essential to combat its increasing vulnerability to climate change and mitigate projected temperature rise, as also highlighted in the State Action Plan on Climate Change 2.0 (SAPCC 2.0).[6] Notably, the state records high methane emissions during the rice-growing season, highlighting rice farming as a major source of methane.[7] Methane emissions from municipal landfills are also substantial due to unsegregated organic waste decomposition.[8] The Swachh Survekshan 2024 rankings[9] highlight the scope of improvement in the solid waste management infrastructure. As a part of the Indo-Gangetic Plain, Punjab also experiences high $PM_{2.5}$ and PM_{10} levels, with PM_{10} sometimes even exceeding national standards by about 1.5 times.[10]

This report creates a baseline for SLCFs, and projects their emissions for the near term under different alternate scenarios, thereby showcasing the emission reduction potential of effective policies.

Two key assessments have been undertaken in this study. First, a baseline inventory of SLCF emissions was established for 2019 using activity data from various government sources, complemented by academic literature. Second, emission scenarios were developed, including a Baseline Scenario and Alternate Scenarios aligned with the state's policy direction and overarching vision. These scenarios feature quantifiable targets for 2030, 2040, and 2047, in line with India's developmental aspirations. The study assesses sector-wise contributions to SLCFs, air pollutants, and their precursors in Punjab and projects the emission reduction potential of existing strategies during 2030 and 2047.

This report serves as a crucial guiding document for future policies and investments for the Government of Punjab not only for climate change and air pollution but also in sectors like agriculture, transport, industry, and waste. This report is grounded in the current landscape of implemented and planned policies in Punjab and reflects the best available data and discussions at the time of its preparation. However, as policies evolve, technologies advance, and sectoral shifts unfold, the findings and projections outlined here may require updates. The assessment is therefore intended as a dynamic framework, one that can be refined over time to remain aligned with emerging developments and priorities in climate and air quality action. It is envisioned as a living document, adaptable to the changing realities of emissions and environmental governance in the state.

The analysis reveals that Punjab is already positioned to achieve significant emission reductions through existing policies and ongoing initiatives, under certain BAU scenarios; while in other cases, significant policy shifts are critical.

Efforts such as increased LPG adoption in households, gradual electrification of the transport sector, and the implementation of emission controls in the industrial sector are expected to reduce SLCF emissions. The state's focus on transitioning households to LPG, promoting cleaner cookstoves, and enforcing crop residue management policies showcases its commitment to improving air quality. These measures set a strong foundation for further improvements in air quality and GHG mitigation. Additionally, strategies such as expanding transport electrification, improving waste diversion and sustainable waste management, adopting community boilers, increasing renewable energy penetration, and promoting crop diversification hold significant potential to deliver additional emission reductions beyond the BAU.

1.1 Key Findings

The report takes a deep dive into a wide spectrum of SLCF emissions that stand as a barrier to Punjab's climate and clean air goals. It delves into sectoral emission estimation of pollutants and thereon models alternate scenarios that represent potential changes in emissions. Based on the results, viable recommendations are provided, which can be implemented for reducing SLCF emissions.

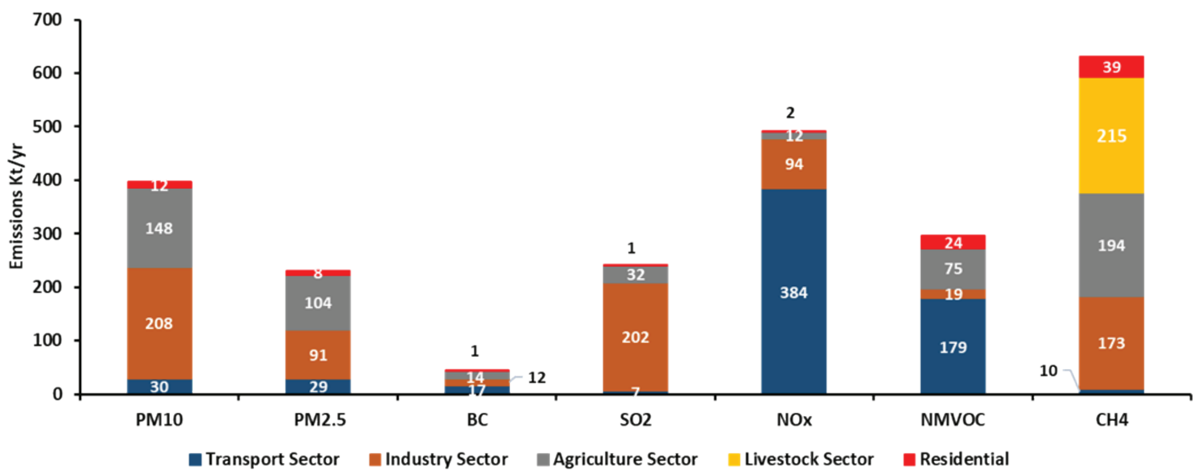


Figure 1: Sector-wise Emissions of Different Pollutants in Punjab for 2019

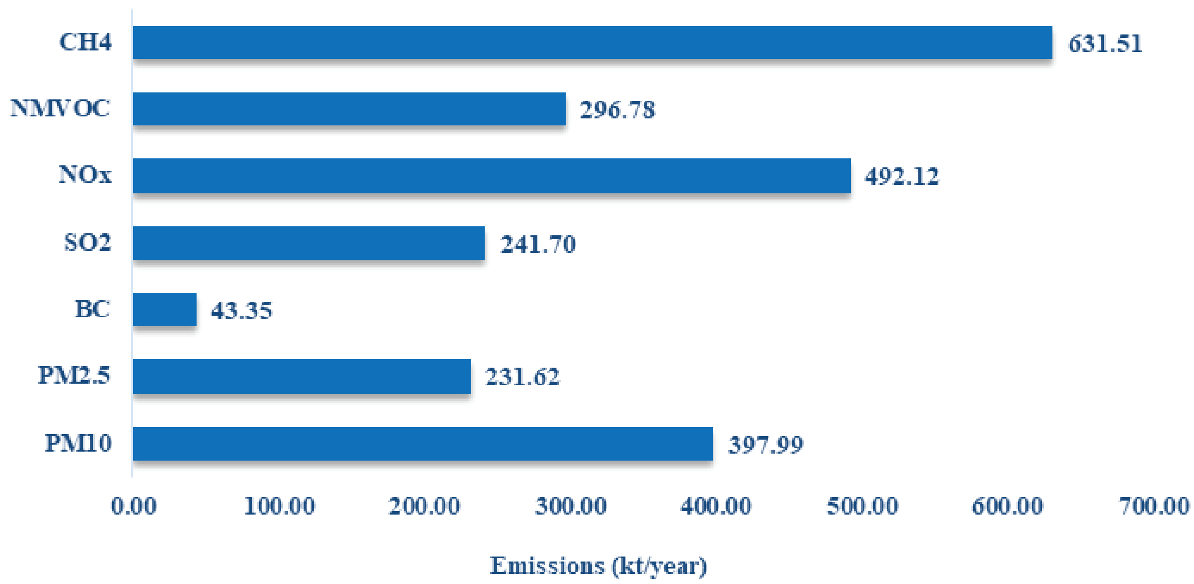


Figure 2: Total Baseline Emissions of PM_{10}, $PM_{2.5}$, BC, CH_4, SO_2, NO_x, NMVOC, and CH_4 in Punjab for 2019

Table 1: Total SLCF Emissions in Punjab for 2019 (in kt/yr) and Major Sectoral Contributions

SLCF	Total Emissions (kt/yr)	Major Emitting Sectors (with % contribution)
PM_{10}*	397.99	Industry (208 kt/yr, 52%), Agriculture (148.08 kt/yr, 37%), Transport (30 kt/yr, 7.5%)
$PM_{2.5}$*	231.62	Agriculture (103.52 kt/yr, 45%), Industry (91 kt/ yr, 39%), Transport (28.85 kt/yr, 12%)
BC	43.35	Transport (16.52 kt/yr, 38%), Industry (12 kt/yr, 27%), Agriculture (14.4 kt/yr, 33%)
SO_2	241.70	Industry (202 kt/yr, 84%), Agriculture (31.95 kt/yr, 13%)
NO_x	492.12	Transport (384.12 kt/yr, 78%), Industry (94 kt/yr, 19%), Agriculture (11.56 kt/yr, 2%)
NMVOC	296.78	Transport (178.99 kt/yr, 60%), Agriculture (75.02 kt/yr, 25%). Industry (19 kt/yr, 7%)
CH_4	631.51	Livestock (215.38 kt/yr, 34%), Agriculture (193.67 kt/yr, 31%), Industry (173 kt/yr, 27%)

**The assessment focuses on SLCF emissions; hence, dust from road and construction activities is excluded. Sectoral contributions to PM_{10} and $PM_{2.5}$ reflect only combustion-related sources, not total emissions from all sectors*

Table 2: Priority sectors for SLCF mitigation in Punjab based on ALT scenario findings

Priority Sectors for Punjab	Priority Policy Interventions
Transport	Phased implementation of ALT 2 - Vehicle Scrappage Policy, with improvements in assessment criteria and methods, in conjunction with ALT 1 - Phased Transition to EVs.
Industry	Transition to Natural Gas (ALT 1) offers the most substantial emission reductions, over 70% for PM_{10}, and $PM_{2.5}$ by 2047.
Agriculture	For methane mitigation, a combination of ALT 1 - Direct Seeded Rice (DSR) and ALT 2 - Crop Diversification provides the maximum emission reductions. The state must align targeted policy interventions with the aim to eliminate open burning of crop residues by 2030 to reduce emissions of particulate matter, black carbon, NO_x and SO_2.
Livestock	Combined strategy (ALT 3) of breed and fodder management yield maximum emission reductions per unit milk produced, thereby aligning productivity and sustainability in the sector.

*Note: Please refer to the sector-specific tables below for the underlying assumptions associated with each alternate (ALT) scenario.**

1.1.1 Transport

Punjab's transport sector is a major and growing contributor to both climate and air pollution. With over 1.2 crore registered vehicles and a heavy reliance on diesel, it is responsible for 87% of the state's NO_x emissions (384.12 kt/year), 40% of black carbon emissions (16.52 kt/year), and 32% of NMVOC emissions (178.99 kt/year). It also contributes over 28% of the state's PM_{10} and $PM_{2.5}$ emissions.

BAU AND ALT SCENARIOS:

The business-as-usual scenario (BAU) accounts for ongoing interventions in the state such as the adoption of BS-VI emission norms from 2020. In BAU, the following increase in emissions may be witnessed by 2047: (i) 37% in $PM_{2.5}$ emissions, (ii) 47% in NO_x emissions, and (iii) 43% in black carbon emissions compared to the 2019 baseline emissions. Despite this trajectory, emission intensity (emissions per vehicle) from the transport sector is expected to reduce. A primary reason is that over time the number of vehicles is expected to increase on account of a rising population and urbanization.

The study constructs four alternate policy scenarios to project reduction in emissions compared to the 2019 baseline. The policies are expected to be implemented in phases by 2047 (see Table 3).

Table 3: Targets Assumed Under Alternate Scenarios for the Transport Sector

Scenarios	2030	2040	2047
ALT 1: Electrification of Bus Fleet	25%	50%	100%
ALT 2: Vehicle Scrappage Policy	30%	60%	80%
ALT 3: Hydrogen Blending in CNG	0%	18%*	18%**
ALT 4: EV Policy for all Vehicles	50%	70%	100%

** in buses;*
*** in cars, autos, light commercial vehicles and buses*

RESULTS AND INFERENCE

Analysis reveals that Punjab's vehicle scrappage policy emerges as the most feasible strategy (See Table 4), in terms of emission reductions and practical implementations. While a comprehensive EV policy for all vehicle types—emerges as the most impactful, it also presents the greatest implementation challenges, including the need for widespread charging infrastructure, behavioural shifts, and affordability of EVs. A phased, well-incentivized rollout, particularly through infrastructure support and strong enforcement, will be essential for its success.

ALT-1 which focuses on electrification of the public bus fleet will be easier to implement, delivering modest emission reductions (12-26%) and rapid air quality benefits in urban areas.

Table 4: Transport Emissions Under Alternate Scenarios, Compared to 2047 Emissions Under BAU

Scenarios	$PM_{2.5}$	PM_{10}	SO_2	NO_x	CO	NMVOCs	BC	CH_4
ALT 1: Electrification of bus fleet	-12%	-15%	-17%	-13%	-24%	-16%	-14%	-26%
ALT 2: Vehicles scrappage policy	-31%	-39%	-19%	-26%	-41%	-22%	-25%	-52%
ALT 3: Hydrogen blending in CNG	-6%	-8%	-8%	-9%	-10%	-6%	-13%	-14%
ALT 4: EV Policy for all vehicles	-37%	-45%	-25%	-32%	-47%	-28%	-31%	-58%

However, for the scrappage policy to be successful, it should consider additional factors to improve efficacy. These include:

Distance Travelled: Instead of retiring vehicles solely by age, policies should account for total mileage and ensure compliance with emission standards through regular fitness tests and re-registration.

Fitness Tests & Vehicle Records: Mandatory fitness tests should align with up-to-date norms, integrating vehicle maintenance records to track conditions and enforce effective emission reductions.

Measuring Out-of-State Selling: After the vehicle has been deemed unfit in the State, the registered owner should not be allowed to sell the vehicle in or out of the State border. Proper scrappage procedure should be followed.

Life Cycle Analysis (LCA): Even newer vehicles should undergo LCA to assess environmental impact, with GPS-based real-time emissions monitoring enhancing policy enforcement.

It must also be noted that in urban areas—where the NOx/NMVOC ratio is high—cutting NOx emissions alone can paradoxically increase O_3 formation. Given that the transport sector is the dominant source of NO_x in Punjab, it plays a critical role in shaping the state's tropospheric ozone levels and must be a central focus of emission reduction strategies.

1.1.2 Industries

Punjab's industrial sector stands out as a major emitter of PM_{10} (208 kt/year), SO_2 (202 kt/year), NO_x (94 kt/year), $PM_{2.5}$ (91 kt/year), NMVOC (19 kt/year), and BC (12 kt/year). These emissions primarily stem from combustion of fossil fuels like coal, wood, charcoal, and pet coke across industrial units, power plants, brick kilns, and DG sets.

BAU AND ALT SCENARIOS:

In the Business-as-Usual (BAU) scenario, emissions for the year 2047 are projected to increase at a Compound Annual Growth Rate (CAGR) of 4%. SO_2 emissions are expected to decline following the mandatory implementation of Flue Gas Desulphurization (FGD) systems in thermal power plants by 2026, as directed by the MoEFCC, with a projected decrease at a CAGR of 5% by 2030, 2% by 2040, and 1% by 2047. Emissions of BC, CH_4, and NO_x are estimated to increase at a CAGR of approximately 5–6% by 2047. Consequently, by 2047 emissions of PM_{10}, $PM_{2.5}$, NO_x, NMVOCs, and CH_4 are estimated to be approximately three times higher than their levels in the base year 2019. Founded on guidelines from CPCB and NCAP, the alternate scenarios for this sector are constructed to assess the implementation of four distinct interventions, as shown in Table 5. Additionally, certain overarching measures are assumed to be implemented across scenarios to address the emission intensity of particular sectors, i.e., power, brick kilns, and DG sector.

Table 5: Targets Assumed Under Alternate Scenarios for the Industry Sector

Scenarios	2030	2040	2047
ALT 1: Transition of coal, wood, charcoal and pet coke to Natural Gas	25%	50%	100%
ALT 2: Implementation of community boilers	30%	30%	30%
ALT 3: Expansion of Green Hydrogen	-	5%	8%
Overarching Measures Taken in All Scenarios			
In the power sector, increasing energy generation from biomass and renewable sources to 40% by 2047			
In brick kiln sector, adoption of clean production practices and enhanced use of resource-efficient bricks is proposed			
Introduction of Retrofitting of Emission Control Devices (RECD) in DG sector			

RESULTS AND INFERENCE:

ALT 1 offers the most substantial emission reductions, 70% and above for PM_{10}, $PM_{2.5}$, and CO by 2047, through a transition to natural gas. This shift improves combustion efficiency, reduces water use, and minimizes solid waste, making it especially beneficial for Punjab's water-stressed and pollution-prone industrial landscape.

Among overarching measures, it must be noted that increasing energy generation from biomass and renewable sources to 40% by 2047 bring out the most significant SLCF reductions.

Table 6: Industry Emissions Under Alternate Scenarios, compared to 2047 Emissions Under BAU

Scenarios	PM_{10}	$PM_{2.5}$	SO_2	NO_x	CO	NMVOCs	BC	CH_4
ALT 1: Transition to Natural Gas	-82%	-76%	-54%	-43%	-70%	-25%	-37%	-23%
ALT 2: Implementation of community boilers	-16%	-17%	-8%	-34%	-10%	-18%	-34%	-22%
ALT 3: Expansion of Green Hydrogen	-14%	-15%	-9%	-34%	-9%	-21%	-35%	-26%

1.1.3 Residential Sector

This section covers emissions from two sources, waste and residential cooking from urban and rural households. Their contribution to overall SLCF emissions in the state is minimal, with the highest contribution to 7% methane (39.5 kt/year), 4% NMVOCs (23.7 kt/year), and 3% PM_{10} and $PM_{2.5}$ each (8.25 kt/year).

(A) Residential Cooking

Emissions from residential cooking remain a concern in rural areas where traditional biomass fuels like wood, and crop residues are still widely used. While the adoption of Liquified Petroleum Gas (LPG) has significantly improved over the years, around 16.1% of rural households still rely on biomass fuels due to economic and supply constraints.[11] Urban areas, on the other hand, have seen improvements, with LPG usage reaching 95%[12].

BAU AND ALT SCENARIOS:

Under all scenarios, emissions have been projected based on the consideration of growth pattern of LPG consumption in residential households. Indian Petroleum and Natural Gas Statistics report has been referred to estimate the growth trend of LPG consumption in residential households for the state of Punjab. Accordingly, household LPG usage was estimated to grow at 2.87% annually at urban and rural areas of Punjab; owing to which, biomass using households are expected to achieve 100% LPG penetration in urban and rural areas during 2030 and 2047 respectively.

All SLCF emissions are expected to be lower than 2019 levels from 2030 onwards, in all scenarios (including the BAU), owing to complete LPG penetration. However, a spillover of LPG expansion is NO_x emissions that rise over time.

Table 7: Description of Scenarios under Residential Cooking Sector

Scenario	LPG Adoption Rate	Alternate methods used by non-LPG households during transition (to LPG) period (2030-2047)		
		Improved Cookstove	Biogas	Solar Cooking Systems
ALT 1	2.87%	100%	0%	0%
ALT 2	2.87%	30%	30%	40%
ALT 3	2.87%	0%	0%	100%

RESULTS AND INFERENCE:

Under the BAU, NOx emissions are expected to increase by 7%, 11% and 18% in 2030, 2040 and 2047 respectively compared to baseline due to the increase of LPG consumption.

All scenarios converge in their resultant emissions by 2047. This highlights that Punjab is faring well at the current trajectory in terms of regulating the residential cooking sector and, provided LPG adoption continues per forecasted targets, the BAU scenario is also a viable outcome. The ALT scenarios help Punjab achieve lower emissions faster.

A transformative shift toward solar cooking beyond 2040 (ALT-3) shows the maximum reduction potential Even though solar cooking is supported by the MoPNG's "Surya Nutan" Solar Cooking Initiative, a 100% adoption in rate (for non-LPG households beyond 2040) would require larger policy support, investment, and 100% consumer behaviour change to be adopted. Thus, it is not the recommended strategy for the state. Punjab, with its significant organic waste from agriculture and livestock, would benefit most from a combination of biogas and solar cookstoves, i.e., ALT 2.

Moreover, adoption of these methods can accrue additional co-benefits; e.g., operationalizing large-scale Anaerobic Digestion plants will not only contribute to effective organic waste management but also reduce methane emissions and produce energy and bio-fertilizers that can benefit agriculture and residential sectors.

Table 8: Residential Cooking Emissions Under Alternate Scenarios Compared to BAU in 2030

Scenario	$PM_{2.5}$	PM_{10}	CO	BC	CH_4	SO_2	NO_x	NMVOC
ALT 1	-25.39%	-26.64%	-27.06%	-28.07%	-26.36%	-15.24%	-6.16%	-11.53%
ALT 2	-70.61%	-74.08%	-75.53%	-78.42%	-69.03%	-34.84%	-17.30%	-34.55%
ALT 3	-77.24%	-81.01%	-82.47%	-85.61%	-77.31%	-41.45%	-19.06%	-36.88%

Table 9: Residential Cooking Emissions Under Alternate Scenarios Compared to BAU in 2040

Scenario	$PM_{2.5}$	PM_{10}	CO	BC	CH_4	SO_2	NO_x	NMVOC
ALT 1	-20.38%	-23.52%	-24.72%	-28.07%	-22.74%	-7.22%	-2.39%	-4.86%
ALT 2	-56.37%	-65.21%	-68.88%	-78.42%	-59.35%	-15.81%	-5.66%	-13.54%
ALT 3	-66.99%	-77.40%	-81.59%	-92.81%	-72.36%	-20.95%	-7.22%	-16.03%

(B) Waste Management

Punjab's waste sector stood out as a major emitter of CH_4 in 2019 (35.025 kt/year), SO_2 (314 kt/year), and BC (230 kt/year). These result from the decomposition of waste at landfill sites, followed by open burning of waste by residents and spontaneous burning at landfill sites, and waste combustion plants.

BAU AND ALT SCENARIOS:

Currently, Punjab collects 99% of the total waste generated, and processes 25% of the collected waste by focussing primarily on recycling, composting, and waste combustion for treatment of waste[13]. This is modeled as the BAU, and analysis is done using the Solid Waste Emissions Estimation Tool (SWEET). Various alternate scenarios are built where increased levels of waste are diverted towards waste-to-energy, composting, anaerobic digestion, material recovery facilities (MRFs), refuse derived fuels (RDFs), and recycling (Table 10).

Table 10: Description of ALT Scenarios for Waste

Scenario	Treatment of Diverted Waste				Open Burning	
	Composting	Anaerobic Digestion	Combustion Plant	Recycling	At Residences	At Landfills
ALT 1: 31% diversion	50%	0%	11.67%	38.27%	3%	7%
ALT 2: 50% diversion	25%	25%	11.67%	38.27%	2%	4%
ALT 3: 70% diversion	10%	40%	11.67%	38.27%	2%	4%

RESULTS AND INFERENCE:

Landfill closure by 2025 as envisioned in the state policy contributes to a sharp decline in emissions. Assuming all the landfills close by the end of this year, methane emissions from the landfill are expected to decrease significantly, causing an overall reduction in emissions in the baseline scenario. For $PM_{2.5}$, PM_{10}, and SO_2, waste combustion is the primary source of emissions, followed by open waste burning. For BC, open waste burning is the main source, followed by waste combustion. A notable decrease in these emissions is observed starting from 2020s. The closure of landfills will reduce the amount of waste disposed of in the landfill, leading to a significant decline in spontaneous burning and an overall reduction in emissions in the baseline scenario.

Table 11: Emission Changes Under Alternate Scenarios Compared to BAU in 2047

Scenario	$PM_{2.5}$*	SO_2*	BC*	CH_4
ALT 1: 31% diversion	-0.8%	-0.5%	-8.3%	-0.5%
ALT 2: 50% diversion	+55.8%	+54.9%	-16.7%	-1.5%
ALT 3: 70% diversion	+116%	+114.6%	+25%	-2.8%

A salient observation in the emission changes is the positive difference in $PM_{2.5}$, SO_2, and BC emissions as compared to BAU. The increase can be primarily attributed to waste combustion activities resulting from the diversion of waste (away from landfills) to waste-to-energy plants where it can be converted into resource driven fuel – thus, not only assuring reduced methane emissions but adding to the economic output of the state. Moreover, it must be kept in mind that the absolute differences in the amount of these pollutants are marginal, while the reductions in methane emissions are significant. Therefore, these emissions are a necessary trade-off and may even be termed as positive emissions.

It must also be noted that Table 11 presents comparisons with BAU 2047 scenario; however, in their own trajectories, the pollutants continue to fall over time in all scenarios and are lower than their 2019 baseline values.

Methane emissions in 2047 are expected to be lower than the BAU projections for 2047 ranging from 0.5-2.8%, depending on the proportion of waste diverted. A scenario with 31% (ALT-1) waste diversion may be best suited for Punjab. This scenario comprises the plants proposed to be developed by Punjab which include composting of 1,500 TPD, waste combustion plant of 350 TPD, and decentralized MRFs with a cumulative capacity of 1,147 TPD. The selection of this scenario aligns with and banks on efficient implementation of existent state plans, including a large dependence on landfill closure. The outcomes lead to the most significant and favourable emission reductions over the years for all pollutants.

CH_4 Emissions Across Scenario

Declining trend in all scenarios due to:

- reduced landfill deposition owing landfill closures in 2025
- diversion of organic waste to compositing and anaerobic digestion.

$PM_{2.5}$, PM_{10}, BC, and SOx Emissions Across Scenarious

Increasing compared to the baseline scenario, due to:

- consisent reliance on waste combustion for treatment of diverted waste (11.67% across ALT scenarious)
- open waste burining, which is expected to continue, albeit at lower rates
- emissions generated by waste transportation and handling equipment.

Key Insidghts

- it is vital to prioritize low-emission waste management methods such as composting, anaerobic digestion, and recycling. These approaches produce sustantially lower emissions compared to waste combustion.
- Landfill closures remain foundational to emission reductions from the waste sector.
- Improved and sufficient waste-handling equipment isa crucial. Without it, delays in waste processing, increased fuel consumption, and inefficiencies in waste diversion are likely to occur.

1.1.4 Agriculture & Livestock

(A) Agriculture

Punjab, which supplies approximately 12% of India's annual rice demand, plays a central role in national food security. However, rice cultivation remains a major contributor to methane (CH_4) emissions due to traditional water-intensive practices like continuous flooding. In 2019–20, methane emissions from rice cultivation in Punjab were estimated at 0.19 Tg/year, projected to rise to 0.22 Tg/year by 2030–31 under a Business-as-Usual (BAU) scenario.

BAU AND ALT SCENARIOS:

The BAU (Business-as-Usual) scenario assumes the continuation of existing cropping practices and trends, including a plateau in rice area expansion post-2030–31. While productivity is expected to rise, methane emissions will continue to increase modestly without additional interventions.

To assess enhanced mitigation potential, the study models three alternate scenarios (ALT 1–3) for rice cultivation: ALT 1: Gradual adoption of Direct Seeded Rice (DSR), aligned with Punjab's DSR Policy 2022, ALT 2: Diversion of rice area to other, less water-intensive kharif crops, supported by Punjab's Crop Diversification Programme and ALT 3: A combined scenario where crop diversification is implemented and non diversified rice area is transitioned to DSR, in line with Punjab SAPCC 2.0 and Vision 2047.

RESULTS AND INFERENCE:

Each scenario reflects a pathway towards reduced methane emissions while maintaining productivity. DSR (ALT 1) enhances water efficiency and aeration, with an estimated methane reduction of 36% by 2047. Crop diversification (ALT 2) demonstrates even greater potential, with methane reductions reaching 78% by 2047 as rice area transitions to less intensive crops. The combined ALT 3 scenario delivers the most substantial benefit—a 91% reduction in methane emissions by 2047, representing a comprehensive approach to sustainable agriculture.

These strategies not only curb emissions but also support long-term soil health, groundwater conservation, and economic resilience for farmers. Punjab's proactive policies, including substantial budget allocations for crop diversification (₹115 crore in 2025) and DSR promotion (₹40 crore for FY 2025–26), underscore the state's commitment to driving this transition.

Table 12: Description of ALT Scenarios for the Agriculture Sector

Scenario	Description	Reduction in CH_4 emissions compared to BAU for each year		
		2030	2040	2047
ALT 1	Implementation of Direct Seeded Rice (DSR)	3%	13%	36%
ALT 2	Implementation of Crop Diversification	8%	34%	78%
ALT 3	Combined implementation of ALT 1 and ALT 2	11%	46%	91%

Punjab's leadership in promoting sustainable practices through policy innovation, financial incentives, and on-ground support reflects its readiness to pioneer a low-emission agricultural model for India.

(B) Livestock

Punjab's livestock sector accounts for 34% (215.38 kt/year) of the state's total methane emission. Based on the annual milk production data of the state during 2019-20 (13.3 MMT) to 2023-24 (14 MMT),[14] milk production in the state has grown by about 1% annually.

BAU AND ALT SCENARIOS:

For this study, the milk production was converted to the total bovine population following the distribution of the total bovine population in the state during 2019-20 and reported annual increase of milk production of different cattle varieties. This led to reduction in methane emission as well as reduction in methane emission per Kg of milk (emission intensity) produced, while increasing the milk production in the country.

Alternative strategies to mitigate methane emissions are modelled based on existent state and central livestock policies such as The Rashtriya Gokul Mission, 2014 and National Dairy Research Programme. Their implementation leads to greater than 50% additional methane emission reductions, per unit of milk produced, by 2050-51 (Table 13).

RESULTS AND INFERENCE:

Results revealed a decline in methane emission intensity (emissions per unit of milk produced) across all scenarios. ALT-1 and ALT-2 each achieved approximately 30–40% additional reductions in emission intensity compared to the business-as-usual (BAU) scenario. The combined strategy (ALT-3) delivered the most significant benefits, with over 50% additional reduction in emission intensity, underscoring the potential of integrated interventions.

However, it is important to note that although absolute methane emissions only decreased under ALT-2 *(the scenario focusing solely on fodder management without changes in livestock breed composition),* this scenario also yielded the lowest increase in milk production and the least benefit per unit of emissions, as it did not incorporate population growth dynamics.

These findings highlight the critical need to balance productivity growth with emission reduction efforts in the sector. A strategic integration of breed improvement and fodder management not only enhances emission efficiency but also ensures economic viability and long-term sustainability of the dairy sector.

Table 13: Summary of ALT Scenarios and Findings for Livestock

Scenarios	Reduction in annual CH_4 emission per kg of milk production compared to BAU		
	2030	2040	2047
ALT-1: Breed Management Increase of cattle population under different state and central government schemes.	18%	39%	38%
ALT-2: Fodder Management It was assumed that all dairy cattle under the BAU scenario will be fed with advanced fodder such as maize-sorghum silage, soybean cake to reduce methane emission from enteric fermentation and increase milk production.	32%	31%	31%
ALT-3: Incorporating Breed Management with Fodder Management All livestock including those estimated to be produced under ALT-1 was estimated to be fed with advanced fodder and forages.	33%	50%	52%

2 / Context

The world is entering an era of record-breaking heat, with each year surpassing the previous as the warmest year on record. Anticipating this trend, the Intergovernmental Panel on Climate Change (IPCC) has stressed the need for drastic greenhouse gas reductions by 2030 to avert the worst consequences of climate change.[15] This urgency aligns with the Paris Agreement's objective of keeping global warming below 2°C while striving for a 1.5°C limit. However, decarbonisation alone is insufficient to achieve these targets—a comprehensive dual-strategy is essential, with holistic CO_2 and non-CO_2 mitigation approaches.[16] These developments reiterate the critical need for concerted, and accelerated, global action on short-lived climate pollutants (SLCPs).

Within this context, the role of India is vital. While the policy landscape on SLCPs is still evolving, India remains one of the top five global emitters of SLCPs and currently lacks a dedicated national strategy to address them. Although India's Biennial Update Reports (BUR) to the UNFCCC,[17] only addresses methane emissions among all SLCPs, its methane emissions alone accounted for 13.32% of India's total greenhouse gas emissions in 2020, or 324 Mt CO_2e. Addressing these emissions—particularly within the context of India's demographic and development priorities—poses a significant policy challenge. However, the potential benefits of early action far outweigh the costs. In India, SLCF mitigation can deliver rapid gains: reducing air pollution-related illnesses, boosting agricultural productivity and food security, and accelerating the shift to sustainable energy sources.

For an agricultural state like Punjab, tackling these pollutants effectively is both an urgency and opportunity. While the Green Revolution transformed the state into an agricultural powerhouse, it now faces an unintended challenge—mitigating emissions from the agricultural sector, a consequence that was not foreseen during the agricultural boom. The state is witnessing a surge in the frequency and intensity of heatwaves, with 128 heatwave days recorded between 2010 and 2023.[18] These extreme temperatures have resulted in significant agricultural losses. For instance, climate projections predict reduction crop yield in Punjab by as much as 13% for maize, 6% for wheat, and 2% for paddy.[19] Additionally, livestock suffer from reduced productivity and higher mortality during heat spells.[20]

By addressing SLCFs, Punjab can unlock immediate and high-impact benefits, such as mitigating urban heat island effects, improving air quality, and boosting agricultural resilience. Its dual-strategy approach to tackling both CO_2 and non-CO_2 emissions offers a strong foundation to integrate SLCF mitigation into state policies. With sectoral interventions already underway—from EV policy and crop residue management to sustainable agriculture policies—targeted measures to tackle SLCFs can accelerate the state's climate goals, strengthen economic resilience, and serve as a replicable model for other states in India.

2.1 Beyond Decarbonization: What are SLCFs?

Short-lived climate forcers (SLCFs) are chemically and physically reactive compounds with atmospheric lifetimes typically shorter than two decades. They include aerosols which are also called particulate matter (PM), and chemically reactive gases such as methane and ozone.[21] While decarbonizing the energy system is a crucial long-term goal, a more holistic understanding of GHGs is essential for effective climate mitigation.

The IPCC Sixth Assessment Report also highlights the importance of mitigating SLCFs to achieve short-term climate goals and address the mitigation gap.[22] Furthermore, recent research indicates that focusing solely on decarbonization may inadvertently exacerbate near-term warming due to the masking effect of sulphate aerosols.

Table 14: SLCFs and their Global Warming Potential (GWP)

SLCF	Global Warming Potential (GWP)
Methane	More than 80 times that of CO_2 over a 20-year horizon
Black Carbon	Thousands of times greater than CO_2 on a per-mass basis (remains in the atmosphere for only a few days to weeks)
Hydrofluorocarbons	GWPs of HFCs vary widely but some HFCs can have GWPs ranging from hundreds to thousands of times that of CO_2 over 20 years
Tropospheric Ozone	Indirect GWP since it is not emitted directly but contributes to warming through its formation

Note: *Global Warming Potential (GWP) is an index to measure the potency of greenhouses gases to absorb infrared thermal radiation over a given time frame after their addition to the atmosphere. Essentially, the higher the GWP of a gas, the more that given gas warms the planet when compared to CO_2 over that period. This time for GWP is typically 100 years.*[23]

Some critical SLCFs which are major contributors to warming and air quality generally include:

1. **Methane (CH_4):** Methane is a highly potent greenhouse gas. Over 20 years, one kilogram of methane has more than 80 times the warming impact of the same amount of carbon dioxide (CO_2).[24] Approximately 45% of today's net global warming is driven by methane emissions from human activities.[25] Sources of methane include both natural processes, such as wetlands, and human activities. Anthropogenic sources, including agriculture (e.g., rice paddies, livestock digestion), landfills, and fossil fuel extraction, account for about 60% of global methane emissions.[26] It is not only a potent greenhouse gas but also a key precursor to tropospheric ozone (O_3), a major pollutant linked to reduced agricultural yields and severe health impacts. Methane reacts with hydroxyl radicals (OH) in the atmosphere, forming methyl radicals (CH_3), which subsequently oxidize to produce ozone in the presence of nitrogen oxides (NO_x).

2. **Tropospheric Ozone (O_3) and Its Precursors:** Tropospheric ozone is the third most important greenhouse gas after CO_2 and CH_4.[27] It absorbs infrared radiation (heat) from the Earth's surface, reducing the amount of radiation that escapes to space. It is not emitted directly but forms through reactions between precursor gases—such as CO, NO_x, and VOCs (including methane)—which result from both natural and human activities. Ozone interacts with both shortwave and longwave radiation, contributing to climate warming.[28]

3. **Black Carbon (BC):** Black carbon is a powerful climate-forcing aerosol with a short atmospheric lifetime of just a few days to weeks.[29] It is a key driver of global warming and is the light-absorbing component of particulate matter (PM). Primarily emitted from the incomplete combustion of fossil fuels and biomass-based fuels, its climate impact depends on its location in the atmosphere. At ground level, black carbon directly warms the air by absorbing solar radiation and emitting heat. It also impacts cloud microphysics, altering precipitation patterns posing as a hazardous air pollutant with severe health consequences. Alternatively, when deposited on ice and snow, black carbon particles reduce surface albedo (the ability to reflect sunlight and heat the surface; making high-altitude glaciated regions such as the Himalayas particularly vulnerable to melting as a result.[30]

4. **Sulphates:** Sulphate aerosols form in both gaseous and aqueous phases, primarily from sulphur dioxide (SO_2) emissions (from human activities and volcanic eruptions) and dimethyl sulphide (DMS) from biogenic sources. DMS also has a short atmospheric lifetime ranging from 11 min to 46h. This occurs due to the high reactivity of these compounds leading them to get oxidized quickly in the atmosphere, causing aerosol formation and acid deposition.[31] A major component of PM, sulphates contribute significantly to atmospheric cooling. These aerosols typically measure between 0.3 to 0.7 μm in diameter. They also serve as cloud condensation nuclei (CCN), playing a crucial role in cloud formation and influencing precipitation patterns[32] The largest source of SO_2 in the atmosphere is the burning of fossil fuels in power plants and other industrial facilities. India is one of the largest emitters of SO_2 in the world, owing to coal burning, cement, iron, and steel contribute significantly to SO_2 emissions[33].

5. **Nitrates:** Nitrate aerosols form through the oxidation of nitrogen oxides (NO_x), which are mainly emitted by vehicles and power plants. Their atmospheric lifetime is only a few hours, making them shorter-lived than sulphates, which persist for days to weeks.[34]

6. **Hydrofluorocarbons (HFCs):** HFCs are synthetic greenhouse gases primarily used as refrigerants, solvents, and in foam production. Some HFCs have global warming potentials (GWP) hundreds to thousands of times greater than CO_2 over a 20-year period. HFC emissions mainly result from leakage during the use and disposal of products containing these gases.

2.2. Punjab's need to focus on SLCFs

Punjab is among the few Indian states that has adopted an agriculture-based model of development. While this growth-driven approach has enabled the state to achieve self-sufficiency in food grains, it has also led to the depletion and pollution of natural resources, posing serious risks to public health.[35] Since 2011, the state has been witnessing a series of extreme climate events, ranging from unexpected snowfall in Pathankot after 55 years[36] to 28% less than normal level rainfall during the monsoon season of June-September 2024.[37]

Climate change studies reveal that rise in temperature, and unpredictable extreme weather events are expected to impact Punjab significantly, with expected yield reduction of wheat by 6% to 6.5%, rice by 2% to 8%, and maize by 13% by mid and end century respectively.[38] All nine monitored cities in Punjab exceeded the National Ambient Air Quality Standard (NAAQS) for $PM_{2.5}$ in 2024, highlighting persistent and widespread air pollution across the state.[39] The state's vulnerability to heat waves is also starkly evident. Between 2010 and 2023, Punjab experienced 128 heatwave days[40], with 2024 alone recording a decade-high of 27 heatwave days.[41] Temperature projections show a rise of 2.1°C to 4.5°C by mid-century, with urban centers like Ludhiana and Amritsar already experiencing amplified heat due to the urban heat island effect.[42]

Punjab's N_2O emissions[43] stem from its status as the third-largest consumer of chemical pesticides and largest per hectare consumption of fertilizers (NPK) for a state in India.[44,45] Given the significant health and environmental risks associated with intensive chemical agriculture, Punjab's Vision Document 2047, suggests a transition to integrated agricultural practices as a necessary step to mitigate these challenges.[46]

Punjab, facing extreme climate events that impact its growth and economy, has opted for a dual-strategy approach, addressing both CO_2 and non-CO_2 emissions. The state faces significant non-CO_2 challenges, primarily due to its agriculture sector that contributes to methane and BC emissions. With nine cities exceeding emission standards due to high PM_{10} concentrations, the state lags in its National Clean Air Programme (NCAP) targets[47] The State and central governments have made tremendous efforts to utilize stubble in various ex-situ and in-situ applications, which has led to reduced stubble burning in Punjab.[48] Punjab, occupying a central position in maintaining the food security of the country, contributes 21% of rice and 53% of wheat to India's central pool.[49] This achievement is largely driven by the dominance of the wheat-rice rotation system, which spans nearly the entire cultivated area of the state. While this system ensures high productivity, it also generates substantial crop residue and leaves farmers with limited turnaround time between harvest and sowing. Consequently, managing this biomass efficiently is a critical challenge. The State and Central Governments have made significant strides in promoting in-situ and ex-situ stubble management, leading to a notable reduction in stubble burning in recent years. At the same time, Punjab continues to strive toward mitigating its methane emissions, a large portion of which originates from rice cultivation. Sustained and scaled-up efforts will be essential to build on this progress and realize long-term environmental and agricultural gains.[50]

Although agriculture is a major source of non-CO_2 emissions in the state, sectors like transport industry, livestock and household also contribute to SLCF emissions.

Transport: The state has 12.2 million registered vehicles, accounting for 4.3% of India's total. With 90% of its buses running on diesel, these vehicles contribute to black carbon emissions and ozone formation. To address this, the state's revised Electric Vehicle policy, which expects to convert 25% vehicle registrations to EVs by 2027.[51]

Industry: The manufacturing sector accounts for 27% of Punjab's economy, with a projected annual growth rate of 7.9%.[52] Industrial combustion contributes 47% of PM_{10} emissions in the state. This challenge is compounded by the uneven distribution of industries, with a heavy concentration in Ludhiana, Jalandhar, and Amritsar—regions already facing significant environmental stress.[53] Notably, 57% of the state's industries fall under the red category (i.e., industries with a pollution index score of over 60, which is the most severe category according to CPCB Taxonomy), indicating high levels of pollution and significant environmental impact.[54]

Livestock: Punjab is India's fifth largest milk-producing state, contributing about 6% to the national milk supply.[55] Even though India's milk production is rising, milk production in Punjab has been rising by 1% annually. The state is focusing on policies that improve yield per cattle, thereby improving productivity of the sector[56] to meet increasing demand and contribute to rising methane emissions from the sector.

Fuel use in Residential Areas: While emissions from this sector are minimal, around 16.1% of rural households still rely on biomass fuels due to economic and supply constraints contributing to the air pollution problem of the state.[57] Urban areas, on the other hand, have seen improvements, with LPG usage reaching 95% by 2018[58].

Reducing SLCFs can have immediate and significant climate benefits with additional co-benefits on food security, livelihood, and human health.

For Punjab, reducing emissions is crucial for stabilizing the state's increasing vulnerability to extreme climate events and mitigating the projected temperature rise, as highlighted in the SAPCC 2.0[59]. By addressing these emissions, the state can strengthen its resilience among its identified climate-vulnerable areas. Effective strategies can help prevent temperature rise, curb the urban heat island effect, and safeguard agricultural productivity by preventing a decline in crop duration and grain yield. Additionally, these measures will aid in managing energy demands, preserving groundwater resources, and reduce the health burden on the state.

Due to enhanced surface ozone pollution, India may face an increased risk of yield losses of wheat, with regions of the Indo Gangetic Plains, being particularly vulnerable.[60] Punjab's agriculture is particularly vulnerable to climate change, with recent extreme weather events significantly impacting crop yields. In 2022, an intense March-April heatwave led to wheat yield reductions of up to 25% in several districts, as reported by the Indian Council of Agricultural Research (ICAR).[61] Other studies show a decline wheat yields by 5-6%, and maize yields by up to 13%, due to rising temperatures and altered rainfall patterns.[62]

Such disruptions to agriculture affect food security, rural livelihoods, and economic stability, reinforce the urgent need to mitigate SLCFs. Reducing SLCF emissions presents a dual opportunity: slowing near-term climate warming while improving air quality and public health. Given their short atmospheric lifespan, aggressive mitigation efforts can yield rapid and tangible benefits. Addressing these pollutants is an essential step toward a more sustainable and resilient future.

3 / Report Methodology

Estimating SLCF emissions at the sub-national level is crucial for informed policymaking and effective resource allocation. This localized approach empowers regions to address their unique challenges and maximize the benefits of SLCF mitigation. Against the above backdrop, it becomes evident that the most effective strategy overall is to combine the marathon of decarbonizing the energy system with the sprint to rapidly reduce non-CO_2 SLCF emissions. This report provides a crucial analysis of SLCFs in Punjab, a state striving to improve air quality and mitigate climate change.

By meticulously examining SLCF emissions across various sectors, this study illuminates key mitigation opportunities that can pave the way for cleaner air, improved public health, and a more sustainable future. The findings and recommendations presented herein are poised to inform policy decisions, guide strategic investments, and empower stakeholders to take decisive action. Moreover, this report serves as a valuable model for other states in India and beyond, underscoring the pivotal role of sub-national action in addressing SLCFs and achieving a more sustainable future for all.

To effectively address SLCF emissions in Punjab, a comprehensive approach is essential. This includes assessing current emission levels, reviewing existing policies, and identifying additional strategies. In this study, two key assessments were undertaken. First, a baseline inventory of SLCF emissions was established for the year 2019 using activity data from various government sources, complemented by academic literature. Second, emissions scenarios were developed, including a Baseline Scenario and Alternate Scenarios aligned with the state's policy direction and overarching vision. These scenarios feature quantifiable targets for 2030, 2040, and 2047, in line with India's developmental aspirations leading up to its 100th year of independence.

3.1 Estimating Baseline Emissions

The baseline emissions for various pollutants—PM_{10}, $PM_{2.5}$, CO, SO_2, NO_x, BC, NMVOC, and CH_4—were estimated through the development of an emissions inventory for the year 2019. The year 2019 was selected as the base year for this assessment, as it aligns with the Punjab SAPCC 2.0 timeline (2020–2030). The analysis covers key sectors, including transportation (tailpipe emissions), industry (brick kilns, diesel generator sets, and power plants), residential (household cooking, as well as waste emissions from open burning and landfills), agriculture (open burning of agricultural residue and cultivation-related emissions), and livestock (enteric fermentation and manure management). Emission estimates were derived based on activity data, emission factors, pollution abatement technologies employed, and their control efficiencies.

The basic equation followed by the study is,

$$E_{p} = \sum_{R} \sum_{S} \sum_{F} A_{R,S,F} \times EF_{R,S,F} \times (1 - \alpha_{R,S,F}) \times X_{p,R,S,F}$$

where, Ep is the annual emission of a pollutant (p) (kt); R is the region/state; S is the sector; F is the type of fuel; A is the activity data (fuel consumption or other emission related data); EF is the emission factor (kt per unit of fuel use) of the pollutant (p); α is the removal efficiency (%) of pollutant (p) with the installed pollution control technology and X is the actual application rate of the control technology[63].

The activity data (A) for 2019 across various sectors was primarily sourced from published datasets provided by different ministries of the Government of India. Where data gaps existed, these were supplemented using information from peer-reviewed literature. Figure 3 outlines the overall framework for emission estimation employed in this study. Detailed sector-specific methodologies for developing emission inventories, along with comprehensive inventories for each sector, are included in Annexure 1. It is important to note that this sectoral smission estimations study provides a macro-level estimate and does not constitute a fully detailed bottom-up assessment due to the limited availability of disaggregated data.

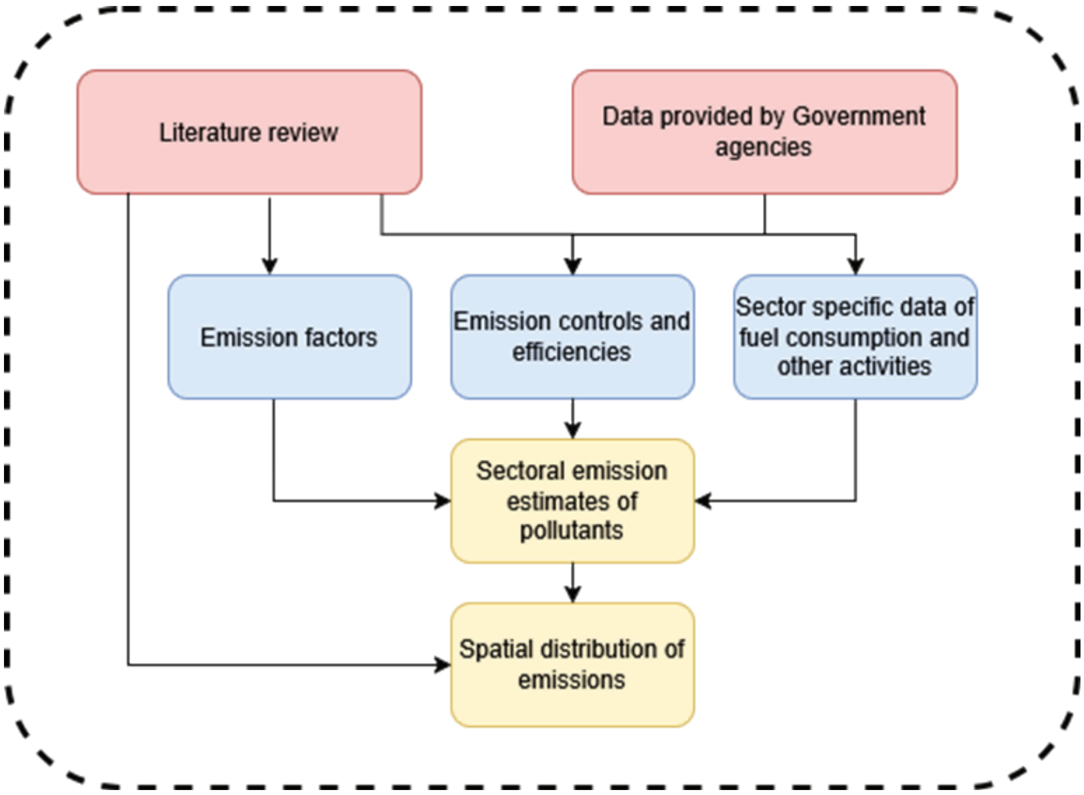


Figure 3: Emission Estimation Framework followed by the Study

3.2 Building Scenarios for the Study

To assess the potential of existing policies to reduce SLCF emissions, evaluate their ambition levels, identify gaps and additional strategies, and determine the emission reduction potential of various interventions, this study analyzed the emission growth trajectories of different SLCFs in Punjab. Two emissions scenarios—Baseline and Alternate—were developed, each representing distinct combinations of policy ambitions and strategies, with emission trajectories calculated for the milestone years 2030, 2040, and 2047. These scenarios are aligned with the State's Action Plan on Climate Change (SAPCC 2.0) and other relevant sectoral policies. The scenarios are as follows:

Baseline Scenario (BAU): This scenario reflects the sectoral growth projections for Punjab under current conditions. It takes into account certain interventions that have already been implemented to address SLCF emissions.

Alternate Scenarios (ALT): These scenarios assume the successful implementation of additional interventions aimed at reducing SLCF emissions. The year 2047 has been chosen as the long-term target as it aligns with the Government of India's 'Viksit Bharat by 2047' initiative, which envisions transforming India into a developed nation by its 100th year of independence. The interventions include specific sectoral policies planned by the state or similar measures being implemented in other parts of the country.

3.3 Baseline Scenario

The Baseline Scenario represents a Business-as-Usual (BAU) approach. It assumes that starting from the 2019 emission levels, sectoral activities grow according to the specified growth rates (as outlined in (Table 15) and no additional policy measures are implemented by the state government to specifically address emissions of SLCFs in these sectors. In this scenario, the state's emissions are expected to increase since the fuel mix for the state's total primary energy remains the same and other activities, such as agriculture, livestock rearing, and waste management, continue with their existing practices. Essentially, the BAU scenario serves as the reference point against which we compare the effectiveness of mitigation interventions in the Alternate scenarios. By contrasting the BAU emissions with those in the Alternate scenarios, we can assess the efficacy of various mitigation strategies. These insights inform policymaking, helping the state make informed decisions to combat SLCF emissions and work toward a more sustainable future.

Table 15: Reference Points for Sector-Wise Growth Projections

Sector	Growth Rate (y-o-y)	Rationale	Reference
Industry	4.05%	Based on the average annual growth rates of the industrial sector for the period of 2012- 13 to 2020- 21 Controls assumed Major industries are equipped with PM Controls as per the CPCB norms/guidelines.	Industrial Sector Growth, Punjab Economic Survey, 2023
Power	6.47%	The composite growth factor is calculated with a weighted ratio of 85% for GDP and 15% for population Controls assumed Full implementation of PM and SO_2 control measures.	Composite Growth Factor of Population and GDP, MoEF&CC Notification dated 05.09.2022
Transport	4.90%	Based on the average growth rate of the transport sector for the period of 2012- 13 to 2020-21. **Controls assumed** Light-duty vehicles (cars and vans), Gasoline: 70% of vehicles comply with Bharat Stage VI controls. Diesel: 56% of vehicles complying with Stage VI and 15% of vehicles with Stage IV controls	Transport Sector Growth, Punjab Economic Survey, 2023
Residential Cooking	2.87%	Emissions were projected based on the growth pattern of LPG consumption in residential households for the state of Punjab. The growth rate was estimated using LPG consumption data for 2019-20, 2020-21, and 2021-22.	Indian Petroleum & Natural Gas Statistics, Government of India
Waste	0.61%	Based on the waste collected data as per the Central Pollution Control Board (CPCB) Annual Reports on Implementation of Solid Waste Management Rules, 2016 (2014-21) and National Mission for Clean Ganga Monthly Progress Report for the Month of August 2024 the compound annual growth rate has been calculated.	Central Pollution Control Board (CPCB) Annual Reports on Implementation of Solid Waste Management Rules, 2016 (2014-21) National Mission for Clean Ganga Monthly Progress Report for August 2024 by Punjab Pollution Control Board, PPCB

Sector	Growth Rate (y-o-y)	Rationale	Reference
Agriculture	1.4% *[no increase in area beyond 2030-31]*	The domestic demand of rice in India is projected to be 197 Mt/annum during 2050-51 (NRRI, 2020). In addition, there is an expected increase in the export of rice to substantiate the projected economic growth of the country by 2050-51. Considering the export of rice, it was projected that the country requires about 227Mt/annum of rice during 2050-51. At present, Punjab produces about 12% of total annual rice demand of the country.[64] Keeping the present share of different states to the annual rice production of the country, it was estimated that the rice production in Punjab will reach about 26.7Mt/annum during 2050-51. However, there is no indication of increase in net sowing area (about 3.59 million ha during 2019-20) during the kharif season in Punjab. Following this, it was assumed that after converting about 95% of net kharif sowing area to rice cropping, there will be no further increase in rice cropping area in the state post 2030-31.	NRRI (2020); DoA&FW
Livestock	1%	The demand for milk in India is expected to rise dramatically due to population growth, income development, and changing dietary preferences. Based on the annual milk production data of the state during 2019-20 to 2023-24, milk production in Punjab has grown by about 1% annually. The milk production was converted to the total bovine population following the distribution of the total bovine population in the state during 2019-20 and reported annual increase of milk production of different cattle varieties - Cross breed cattle 5.7%, Indigenous cattle: 6.9% and buffello: 1.05%.	Basic Animal Husbandry Statistics (BAHS) 2024. Ministry of Farmers' Affairs and Animal Husbandry, Government of India

3.4 Alternate Scenarios

The Alternate Scenarios represent a blend of existing and planned sectoral interventions by the state, along with the anticipated emission reductions resulting from their implementation. Additionally, these scenarios analyse certain interventions that are either in the pilot stage or under discussion in other parts of the country. The implementation of these hypothetical policies could lead to achieving higher standards of SLCF reduction.

These scenarios assess the aggregate quantitative impact on activity levels across sectors for the years 2030, 2040, and 2047. Various sectoral policy documents were referenced to evaluate the potential impact. The selection of specific policy interventions for quantification was guided by two criteria: the direct impact of the policy on SLCF emission sources in the state and the feasibility of quantifying the policy through set targets to measure its direct mitigation benefits.

Policies Guiding Alternate Scenarios: Rationale

Across sectors, scenarios are designed to assess the impact of certain interventions on varied SLCF emissions, that the sector was emitting in the baseline. The selection of these interventions was guided by state policies, as detailed in Table 16. The assumptions for sectoral targets consider trends observed from 2020 to 2024, reflecting the anticipated full implementation of SAPCC policies for the 2020–2030 periods. Further insights were drawn from Punjab's sector-specific policies and regulations, supplemented by national policy targets where available.

The sectoral target assumptions are based on observed trends from 2020 to 2024, under the premise that these trends represent the effective implementation of sectoral policies for the 2020–2030 period—such as the expansion of LPG use, the introduction of BS-VI standards, a complete ban on open burning of agricultural residue, and increased milk production in line with national targets. Further assumptions are informed by the strategic directions outlined in Punjab's sector-specific policies and regulations, supplemented by national policy targets wherever applicable (Table 16).

Table 16: Sector-wise Alternate Scenarios – Policy Rationale, Selected Interventions, and Quantified Targets

Sector	Scenario	Policy Rationale behind Selected Intervention(s)	Description of Interventions and Targets Assumed
Transport	ALT-1	Punjab Electric Vehicle Policy, 2022	Bus Fleet Electrification ▪ 25% conversion of all bus fleets in all districts to EVs in 2030. ▪ 50% conversion of all bus fleets in all districts to EVs in 2040. ▪ 100% conversion of all bus fleets in all districts to EVs in 2047.
	ALT-2	National Vehicle Scrappage Policy, 2022 | Punjab Vehicle Scrappage Policy 2023	Vehicle Scrappage Policy ▪ 30% scrappage of all 15-year-old petrol and 10-year-old diesel vehicles in 2030. ▪ 60% scrappage of all 15-year-old petrol and 10-year-old diesel vehicles in 2040. ▪ 80% scrappage of all 15-year-old petrol and 10-year-old diesel vehicles in 2047.
	ALT-3	National Green Hydrogen Mission, MoPNG 2023, Punjab State Draft Hydrogen Policy 2023	Hydrogen Blending in CNG ▪ 0% blending of hydrogen in CNG (H-CNG) in 2030. ▪ 18% H-CNG blending in buses in 2040. ▪ 18% H-CNG blending in cars, autos, light commercial vehicles (LCVs), and buses in 2047.
	ALT-4	Punjab Electric Vehicle Policy, 2022	Comprehensive EV Policy for All Vehicles ▪ 50% conversion of newly registered buses, two- and three-wheelers, and cars to EVs in 2030. ▪ 70% conversion of newly registered buses, two- and three-wheelers, and cars to EVs in 2040. ▪ 100% conversion of newly registered buses, two- and three-wheelers, and cars to EVs in 2047.

Sector	Scenario	Policy Rationale behind Selected Intervention(s)	Description of Interventions and Targets Assumed
Industry (including power plants, brick kilns, and DG sets)	For all Scenarios	▪ For RECDs: NCAP Industrial Emission Guidelines (MoEFCC, GoI), CPCB Guidelines ▪ For Resource Efficient Bricks: Energy Efficiency Improvements in Indian Brick Industry (India Brick EE) Project, (MoEFCC, GoI, PSCST) ▪ For renewable energy expansion: New and Renewable Sources of Energy Policy (NRSE), 2012; Punjab State Energy Action Plan; Punjab SAPCC 2.0, 2024 & Punjab Vision 2047.	▪ The Retrofit Emission Control Device (RECD) is estimated to cut particulate matter (PM) and black carbon (BC) emissions by 70% in the years 2030, 2040, and 2047, relative to their respective BAU emissions. ▪ Adoption of clean production practices and enhanced use of resource-efficient bricks (REB). By 2030 10% of the total brick produced will be REBs, by 2040 it will be 25% and by 2047 REBs penetration will reach 50%. ▪ Energy generation from renewable energy and biomass. 20%, 30% and 40% of power generation from Biomass and Renewable energy by 2030, 2040 and 2047 respectively.
	ALT-1	▪ NCAP Industrial Emission Guidelines (MoEFCC, GoI) ▪ City Action Plans (Ludhiana, Dera Bassi, Patiala)	The transition of Coal, Wood, charcoal and pet coke to Natural Gas is assumed to reach 25%, 50% and 100% in industries by 2030, 2040 and 2047, respectively.
	ALT-2	CPCB Guidelines on Community Boilers, 2024	The implementation of community boilers is expected to result in a 30% reduction in fuel consumption in the years 2030, 2040, and 2047.
	ALT-3	Draft Punjab Green Hydrogen Policy, 2023	The introduction of Green Hydrogen is assumed to reach 5% and 8% in industries by 2040 and 2047, respectively.
Residential Cooking	ALT-1	▪ LPG consumption growth rate is based on Ministry of Petroleum and Natural Gas (MoPNG) reports. National Biomass Cookstove Programme (NBCP), MNRE.	▪ Annual LPG consumption growth of 2.87% at state level ▪ After LPG adoption, the remaining households that still use biomass will switch to improved cookstoves that are 28% efficient in burning fuel. This change will happen gradually by 2030, 2040, and 2047.

Sector	Scenario	Policy Rationale behind Selected Intervention(s)	Description of Interventions and Targets Assumed
	ALT-2	▪ LPG consumption growth rate is based on Ministry of Petroleum and Natural Gas (MoPNG, GoI) reports. ▪ New National Biogas and organic Manure Management Programme (NNBOMP), Govt. of Punjab ▪ "Surya Nutan" Solar Cooking Initiative (Indian Oil and Ministry of Petroleum & Natural gas)	▪ Annual LPG consumption growth of 2.87% at state level ▪ Between 2030 and 2040, it is projected that rural households in Punjab that currently do not use LPG will adopt cleaner cooking alternatives as follows: 30% will switch to improved cookstoves, 30% to biogas-based systems, and the remaining 40% to solar-powered cooking solutions. ▪ This takes note of the substantial progress made by the state of Punjab in improving LPG penetration through targeted susbidies and awareness campaigns.
	ALT-3		▪ Annual LPG consumption growth of 2.87% at state level during 2030, 2040. Beyond 2040 no further LPG penetration is assumed in rural Punjab and accordingly the estimated increased households (from 2040 to 2047) along with existing ICS and biogas dependent households in rural Punjab will shift to solar based cooking. ▪ 20%, 20% and 60% of non-LPG using households in rural Punjab will shift to improved cookstove, biogas and solar based cooking respectively during 2030 ▪ During 2040, 70% of non-LPG using households in rural Punjab will shift to solar based cooking whereas, remaining 20% and 10% will use biogas and improved cookstove respectively ▪ 100% of non-LPG households during 2047 will shift to solar based cooking
Waste	ALT-1	▪ Punjab State Solid Waste Management Policy 2018 ▪ Solid Waste Management, Cleanliness, and Sanitation Bye-Laws, 2024 ▪ Punjab Mission on Sustainable Habitats, 2014	31% is the total diverted waste, out of which: ▪ 50% is diverted for composting ▪ 11.67% is diverted to waste combustion plant ▪ 38.27% for recycling Open burning is taken at 7% at landfill and 3% at residential level.
	ALT-2		50% is the total diverted waste, out of which: ▪ 25% is diverted to composting ▪ 25% for anaerobic digestion ▪ 11.67% for waste combustion ▪ 38.27% for recycling. Open burning is taken at 4% at landfill and 2% at residential level.
	ALT-3		70% is the total diverted waste, out of which: ▪ 10% is diverted to composting ▪ 40% for anaerobic digestion ▪ 11.67% for waste combustion ▪ 38.27% for recycling. Open burning is taken at 4% at landfill and 2% at residential level.

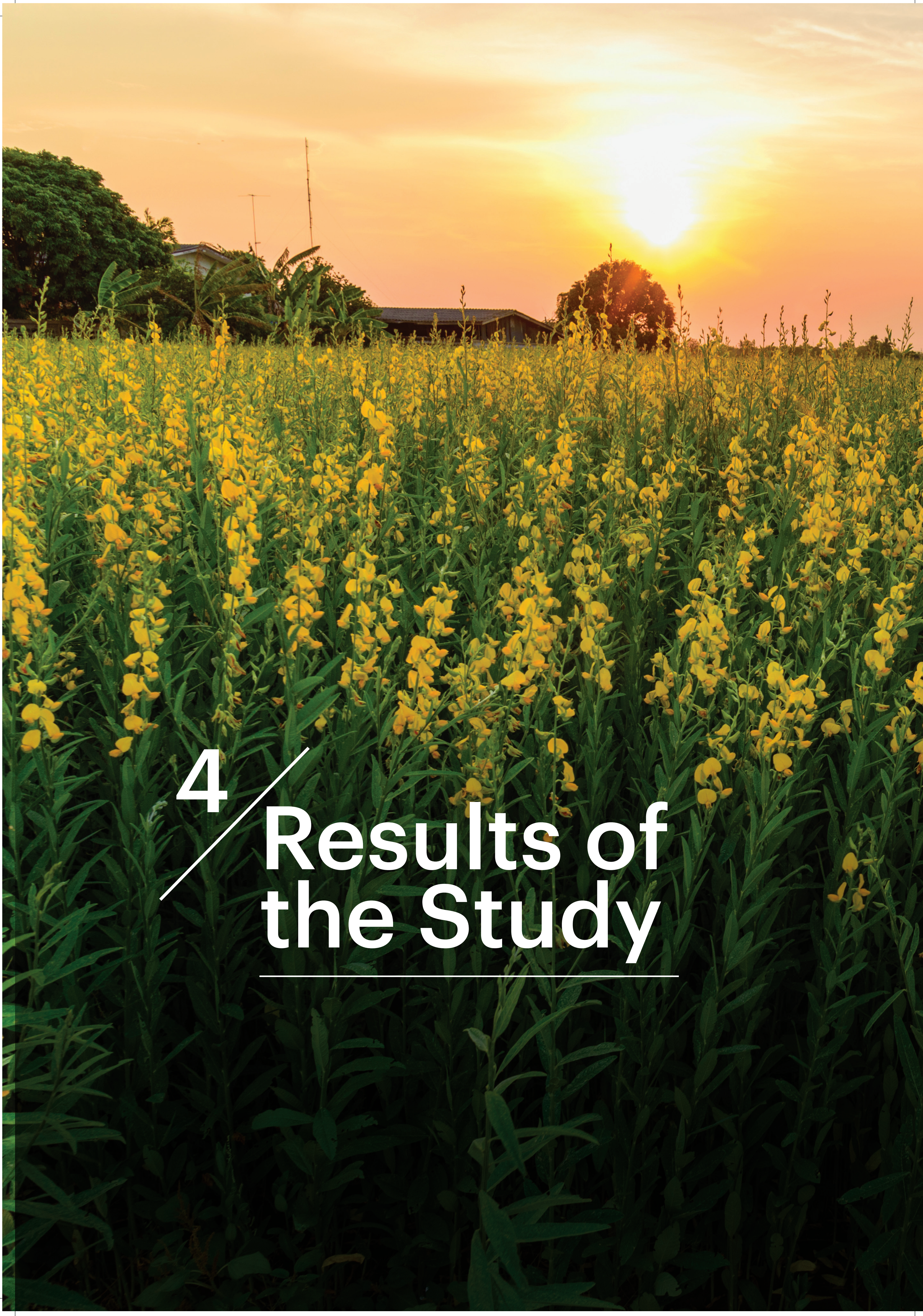
Sector	Scenario	Policy Rationale behind Selected Intervention(s)	Description of Interventions and Targets Assumed
Agriculture	ALT-1	Punjab DSR Policy 2022	Implementation of **System of Rice Intensification** (SRI) – with a targeted 500000 ha DSR in 2035, 1000000 ha DSR in 2040 and 100% DSR by 2050.
	ALT-2	Joint program of Government of Punjab and Central Government on Crop Diversification	Conversion of rice area to other crops – with a target of 300000 ha by 2030, 600000 ha by 2040, 1200000 ha by 2045.
	ALT-3	Combined strategy	Diversification and DSR
Livestock	ALT-1	Punjab Livestock Breeding Program; The Rashtriya Gokul Mission, 2014.	Selective Breed Control Increasing population of cross-breed cattle constant while the buffalo population is kept constant to keep up with milk production requirement
	ALT-2	National Dairy Research Programme.	Advanced Fodder for Dairy Cattle (e.g., maize-sorghum silage, soybean cake) fed to all dairy cattle.
	ALT-3	Combined Strategy	Improved Fodder for all Livestock.

3.5 Data Limitations & Resolution

Due to the absence of region-specific emission factors (EFs), emission factors from similar regions have been used as proxies.

- Where state-specific targets are still evolving, national-level goals have been adopted as a directional benchmark. These offer valuable guidance for policymakers and can be further refined to align with Punjab's local context and priorities.
- Certain small sectors, such as roadside eateries, are not included in the study due to a lack of compiled state-level data and reliance on primary surveys. However, their contribution to overall state emissions is expected to be negligible.
- Data on household fuel consumption for cooking in the residential sector is collected every ten years. Recent changes in usage patterns have been estimated using the 76th NSSO report by the Ministry of Statistics and Programme Implementation.
- In the base year emission estimates, emissions from industrial wastewater were not included in the industrial sector analysis because of insufficient data.
- Due to limited district-level data on vehicle de-registration, it is assumed that the central government's directive is being implemented uniformly across the state.
- The extent of policy implementation across different regions or industries is not fully known. Therefore, uniform assumptions—such as control efficiency—have been applied across similar industries based on government directives.

Despite data limitations, this assessment reflects the best available evidence and standardized assumptions to support informed decision-making. It also underscores the significant strides Punjab has made in advancing climate and air quality action—setting a strong foundation for continued leadership and progress.



4 Results of the Study

4.1 Baseline Emissions

The results of estimations and emission contributions from different sectors for Punjab in 2019 are shown in Figure 4

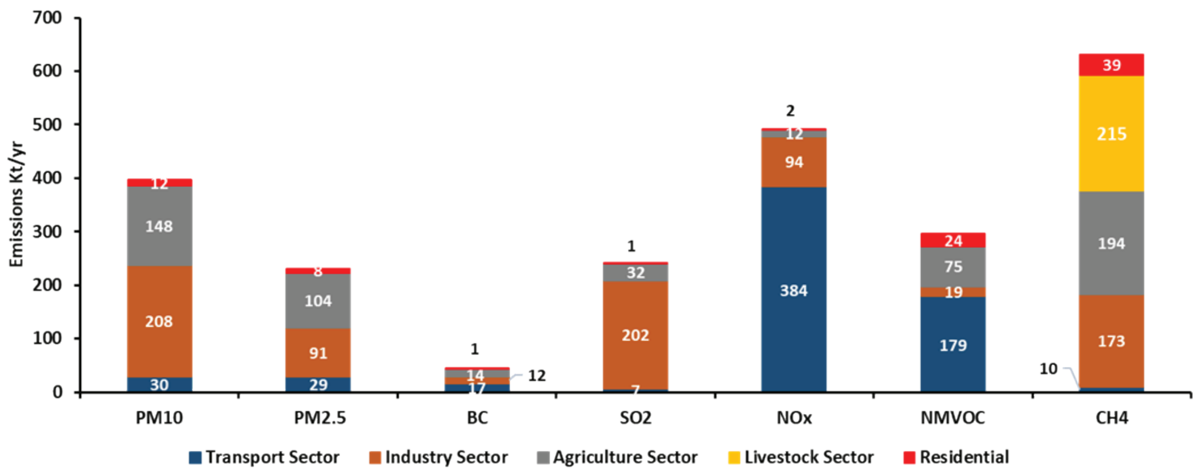


Figure 4: Sector-wise Emissions of Different Pollutants in Punjab for 2019

For informed analyses, it's essential to have both sectoral understanding of predominant SLCFs and pollutant-based insights in order to develop potential mitigation scenarios. Figure 4 above shows the proportional contribution of each sector to various pollutants, along with total absolute emissions (in kt/year) for each sector and pollutant. Figure 5 below provides a comprehensive overview of the percentage contributions of different sectors to the emissions of key pollutants. Understanding these contributions and the range of pollutants emitted by a sector's activities is crucial for selecting a priority sector for targeted interventions for emission reduction of different SLCFs.

Analysis highlights that transport, industry, and agriculture sectors are priority areas for reducing emissions of black carbon, particulate matter, sulphur dioxide, nitrogen oxides, volatile organic compounds, and methane. Mitigation efforts in these sectors

offer significant potential for achieving substantial reductions in SLCFs. In the transport sector, reducing NOX and NMVOC emissions would also help lower secondary pollutants such as ozone and nitrates. However, emissions from the residential sector (cooking and waste), particularly NMVOCs and methane, must not be overlooked. A comprehensive, multi-sectoral approach is essential for achieving holistic improvements in air quality and emission reductions across Punjab.

Table 17 provides a pollutant-wise overview of total emissions in 2019, as well as identifying sectoral priorities and key observations that will inform subsequent scenario analysis.

Table 17: Pollutant-wise analysis of pre-dominant SLCF emissions in Punjab in 2019

Pollutant	Total Emissions (kt/year)	Major Contributing Sectors	% Share by Sector	Noteworthy Insights
PM_{10}	397.99	Industry, Agriculture	Transport: 7% Industry: 52% Agriculture: 37% Livestock: 0% Residential: 3%	▪ The industrial sector emerges as the largest contributor to PM emissions. These emissions primarily result from fossil fuel combustion in industries, brick kilns, and thermal power plants. ▪ The agriculture sector contributes to emissions largely due to crop residue burning. ▪ The transport sector emissions reflect the influence of diesel vehicle exhaust on fine particulate pollution. ▪ The residential sector's contributions to PM_{10} and $PM_{2.5}$ emissions are relatively minor, attributable to the use of solid fuels for cooking and heating and open burning of waste.
$PM_{2.5}$	231.62	Industry, Agriculture, Transport	Transport: 12% Industry: 39% Agriculture: 45% Livestock: 0% Residential: 4%	
Black Carbon (BC)	43.35	Transport, Agriculture, Industry	Transport: 38% Industry: 27% Agriculture: 33% Livestock: 0% Residential: 1%	▪ Transport, agriculture and industry including the power sector are the predominant sources of BC emissions in Punjab ▪ Industrial emissions mainly result from the use of fossil fuels in brick kilns, power plants, and other industries. The overall emissions from this sector are relatively low due to the adoption of Air Pollution Control Devices (APCDs) in the state.
Sulphur Dioxide (SO_2)	241.70	Industry, Agriculture	Transport: 3% Industry: 84% Agriculture: 13% Livestock: 0% Residential: 0%	▪ The industrial sector is the dominant source, primarily due to the extensive use of coal as fuel. ▪ The transport sector's share is attributed to diesel-powered vehicles.

Pollutant	Total Emissions (kt/year)	Major Contributing Sectors	% Share by Sector	Noteworthy Insights
Nitrous Oxides (NO_x)	492.12	Transport, Agriculture	Transport: 78% Industry: 19% Agriculture: 2% Livestock: 0% Residential: 1%	Emissions are overwhelmingly driven by the transport sector, followed by the industrial sector.
Non-Methane Volatile Organic Compounds (NMVOCs)	296.78	Transport, Agriculture, Industry, Residential	Transport: 60% Industry: 7% Agriculture: 25% Livestock: 0% Residential: 8%	▪ NMVOC emissions are predominantly from the transport sector, followed by agriculture and the industrial sector. ▪ Residential sector contributes moderate amounts, largely from residential cooking activities.
CH_4	631.51	Livestock, Agriculture, Industry	Transport: 2% Industry: 27% Agriculture: 31% Livestock: 34% Residential: 6%	▪ Emissions are primarily attributed to livestock's enteric fermentation and manure management practices. ▪ Agriculture contributes primarily from widespread paddy cultivation. ▪ The industrial sector emissions, including power plants, are majorly due to coal, coke, and charcoal use. ▪ Waste management in residential areas accounts for 6% of methane emissions, mostly from landfill activities.

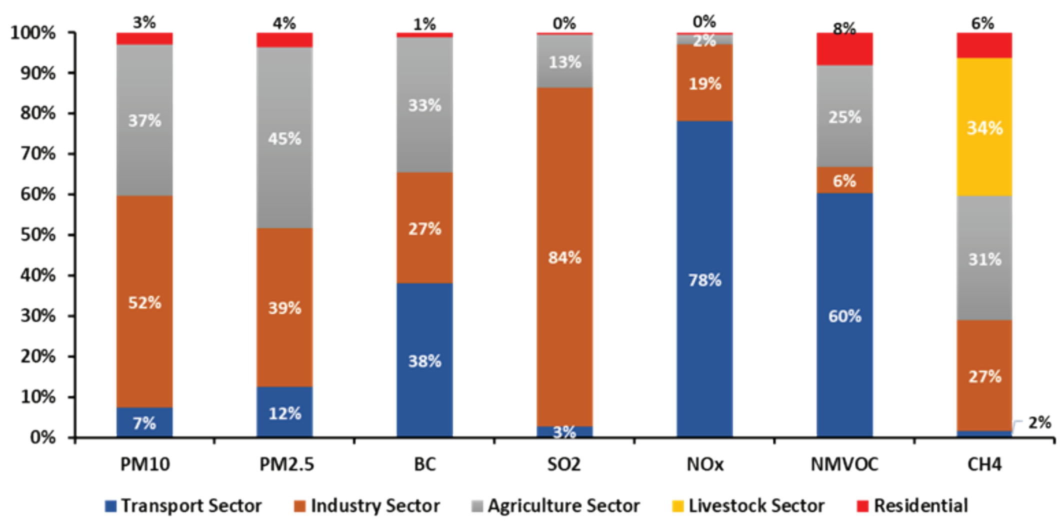


Figure 5: Proportional Contributions of Sectors to Emissions of PM_{10}, $PM_{2.5}$, BC, SO_2, NO_X, NMVOC and CH_4 in Punjab

4.2 Sectoral Assessments: A Deep Dive

4.2.1 Transport

The transport sector plays a critical role in propelling India's economic growth and fulfilling its developmental ambitions. However, it also poses a substantial challenge due to its role as a major polluter at local, state, and regional levels. Primarily relying on fossil fuels, the transport sector significantly contributes to air pollution and climate change along with related health impacts. Similarly, in Punjab as well, the transportation sector plays a vital role in supporting the state's agricultural and industrial economy. However, it is also a significant contributor to air pollution, primarily due to an increasing number of registered vehicles—estimated at over 1.2 crore as of 2023[65]—and heavy reliance on diesel-powered vehicles for both passenger and freight transport. Vehicular emissions are a major source of $PM_{2.5}$, NO_x, and black carbon, affecting both urban and rural air quality.

To address these challenges, the Government of Punjab has adopted several measures aimed at reducing transport-related emissions (Figure 6). Through these concerted efforts, Punjab aims to mitigate the environmental impacts of its transport sector and contribute to the national goals of cleaner air and reduced greenhouse gas emissions.

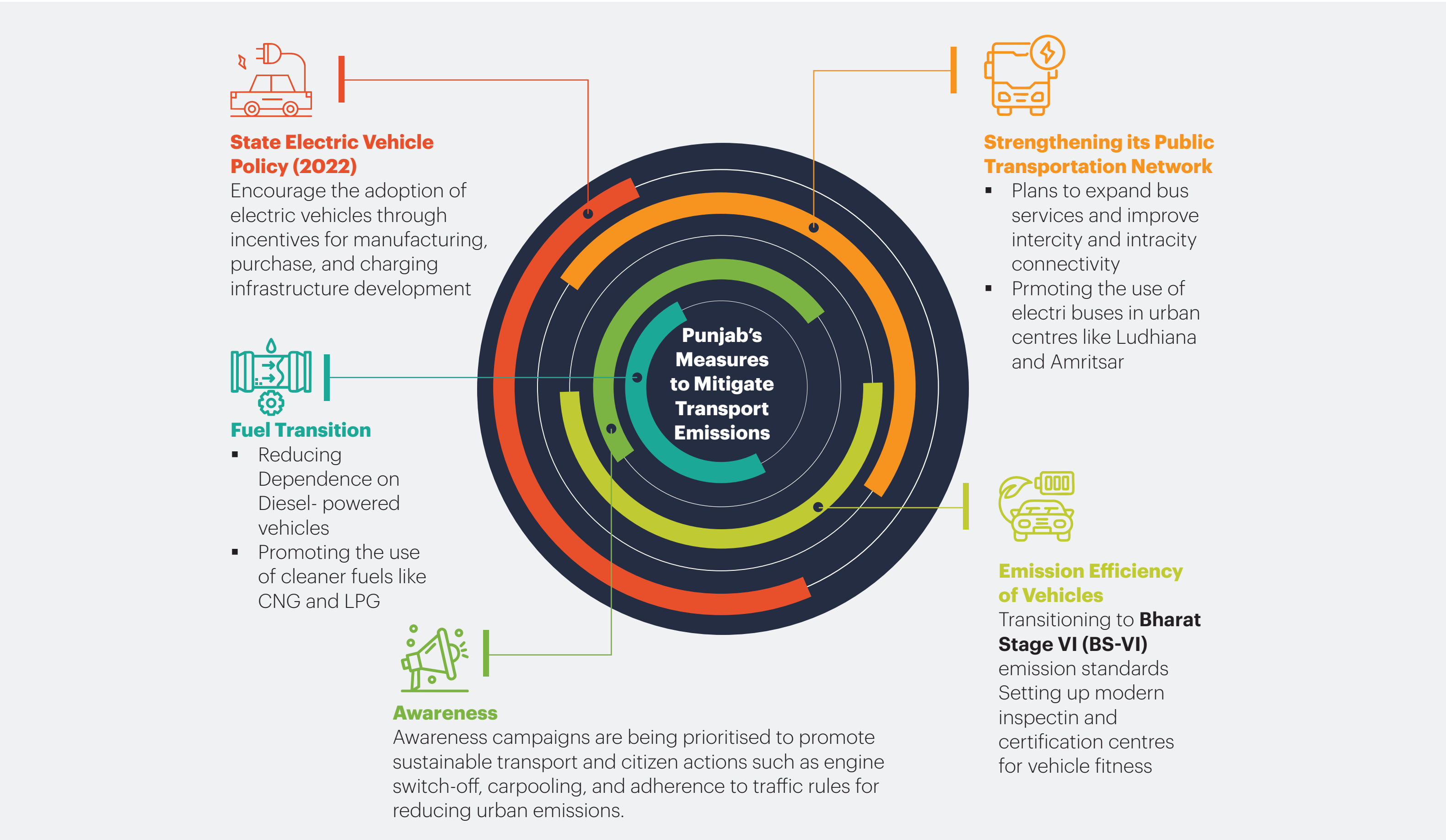


Figure 6: Punjab Government's Efforts to Address Pollution and Emissions from Transport Sector

BAU Scenario of the Transport Sector

Punjab, with its rapidly growing population and a robust agricultural-industrial economy, faces significant environmental challenges stemming from its transport sector. The continuous rise in vehicular numbers, coupled with a heavy reliance on fossil fuels, has led to escalating emissions. Addressing these challenges is critical for the state to achieve its climate and clean air goals.

The study utilized vehicle registration growth rates from the VAHAN database[66] and the Ministry of Road Transport and Highways (MoRTH) 2019 Statistical Yearbook[67] to project transport emissions under a Business-as-Usual (BAU) scenario. The projections assume that vehicle numbers will grow at 4.90% growth rate annually, reflecting no additional interventions beyond those already planned. The adoption of BS-VI emission norms, introduced in 2020, has been incorporated into the analysis, with emissions estimated for the years 2019, 2030, 2040, and 2047. Under the BAU scenario, emissions from Punjab's transport sector are expected to rise substantially over the coming decades, with over 100% increases over the years (Table 18). Notably, NMVOC emissions fall reflecting some benefits of improved fuel efficiency and BS-VI norms.

Table 18: Transport Sector Emissions in BAU Scenario

Pollutant	2019 Emissions (kt/yr)	2047 Emissions (kt/yr)	% Change
PM_{10}	29.7	42.7	+43.52%
$PM_{2.5}$	28.9	38.6	+33.72%
NO_X	384.1	553.0	+43.97%
CO	460.0	946.6	+105.78%
CH_4	10.0	29.2	+192.88%
BC	16.5	23.0	+38.98%
SO_2	6.7	17.0	+151.89%
NMVOCs	179.0	128.9	-27.98%

While the planned adoption of BS-VI norms and improved fuel efficiency measures are expected to reduce the emission intensity of the transport sector, these gains are insufficient to counterbalance the impact of vehicle growth. The BAU scenario underscores the urgent need for Punjab to adopt additional measures, such as accelerating electric vehicle penetration, strengthening public transportation networks, and promoting non-motorized transport, to curb emissions and mitigate their adverse impacts on air quality and public health.

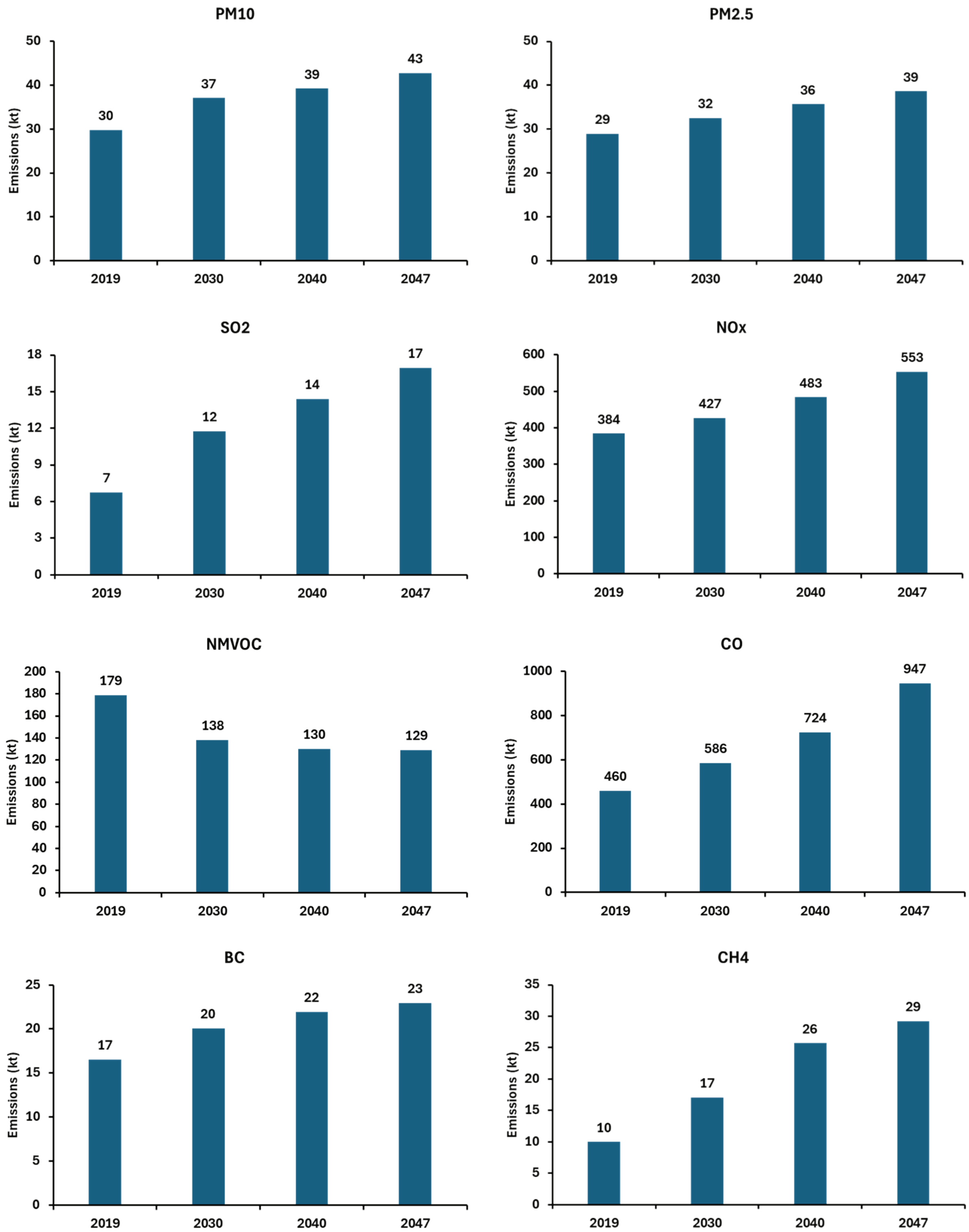


Figure 7: Emissions of PM_{10}, $PM_{2.5}$, CO, NO_X, CH_4, SO_2, NMVOCs and BC during 2019, 2030, 2040 and 2047 from the transport Sector under the BAU scenario

Alternate Scenarios of the Transport Sector

Intervention analysis has been performed to estimate the emissions reduction potential of different control strategies in the transport sector and construct alternative scenarios. The study has evaluated four alternate scenarios which include electrification of the bus fleet (ALT 1), vehicle scrappage policy (ALT 2), hydrogen blending in CNG (ALT 3), and a comprehensive EV policy for all vehicle types (ALT 4). These interventions align with the existing policies of the government and would aid the government in quantifying the impacts of different policies. A summary of alternate scenarios is provided in Table 19, while their details (including the policies they are based on) are discussed in the following sub-sections.

Table 19: Targets Assumed Under Alternate Scenarios for the Transport Sector

Scenarios	2030	2040	2047
ALT 1: Electrification of bus fleet	25%	50%	100%
ALT 2: Vehicle scrappage policy	30%	60%	80%
ALT 3: Hydrogen blending in CNG	0%	18%*	18%**
ALT 4: EV Policy for all vehicles	50%	70%	100%

* in buses;
** in cars, autos, light commercial vehicles and buses

ALT 1: Bus Fleet Electrification

[Punjab Electric Vehicle Policy 2022]

The Punjab Electric Vehicle Policy 2022 aims to electrify public and shared transport, including buses, to achieve substantial emission reductions. Under this scenario, it is assumed that 25% of all bus fleets across Punjab will transition to electric vehicles (EVs) by 2030, 50% by 2040, and 100% by 2047. These targets align with Punjab's broader goal of promoting EV adoption through incentives for EV purchases, battery manufacturing, and the establishment of charging infrastructure. The policy also emphasizes the electrification of buses in key cities such as Ludhiana, Jalandhar, Patiala, Amritsar, and Bathinda—identified as significant contributors to vehicular emissions.

The projected reductions in pollutants under this scenario compared to the Business-as-Usual (BAU) baseline demonstrate significant environmental benefits. In particular, over 20% reductions are observed in 2047 for CO (22%), CH_4 (26%), and NO_X (24%) emissions as compared to the BAU of 2047. Other SLCFs also showcase promising reductions, ranging from 12-17% as compared to BAU-2047.

ALT 2: Vehicle Scrappage Policy

[National Vehicle Scrappage Policy 2022 | Punjab Vehicle Scrappage Policy 2023]

In the ALT-2 scenario for Punjab, the vehicle scrappage policy is evaluated for its potential to reduce emissions from ageing vehicles. Punjab's approach mirrors the framework introduced under India's National Vehicle Scrappage Policy (2022) and is further strengthened by the state's own Punjab Vehicle Scrappage Policy (2023). This state-level policy operationalizes the national guidelines with localized incentives and mandates to retire older, high-emitting vehicles.

Under the Punjab policy, vehicles targeted for scrapping include petrol vehicles older than 15 years and diesel vehicles older than 10 years. The phased implementation aims to achieve 30% scrappage by 2030, 60% by 2040, and 80% by 2047.

This intervention is projected to deliver significant emissions reductions by 2047 relative to the BAU scenario: PM_{10} (-39%), $PM_{2.5}$ (-31%), NOX (-26%), CH_4 (-52%), BC (-25%), and NMVOCs (-22%). The policy supports Punjab's broader objectives of improving air quality and advancing sustainable transportation by accelerating the transition to cleaner and more efficient vehicle technologies.

Moving beyond vehicle age as a criterion for scrappage eligibility, the policy can incorporate additional factors to enhance its effectiveness and better target high-emission vehicles for scrappage:

Distance Traveled

Instead of solely retiring vehicles based on age (e.g., 15 years), scrappage policies should account for total distance covered and assess whether a vehicle continues to meet emission standards beyond this timeframe for a more sustainable approach. To assess the vehicle for its emissions standards, regular fitness tests and re-registration becomes crucial.

Fitness Tests & Vehicle Records

Re-registration and mandatory fitness tests should be integrated with vehicle maintenance records from service centres. As the policy aims to scrap the vehicles failing fitness test, a rigorous testing procedure that is up to date with the latest testing norms is required. Theses records can serve as a valuable tool for tracking vehicular conditions and ensuring effective emission reductions.

Life Cycle Assessment

Even newer vehicles should undergo a comprehensive life-cycle assessment to evaluate their overall environmental impact. Incorporating GPS-based real-time emissions monitoring can further enhance policy implementation.

Cheek on Out of State Selling

After the vehicle has been deemed unfit in the State, the registered owner should not be allowed to sell the vehicle in or out of the State border. Proper scrappage procedure should be followed.

While these factors can make the policy an effective approach to vehicle scrappage and emission reduction, it is crucial to monitor the implementation of these measures. Similar recommendations have been made in a discussion paper on the Vehicle Scrappage Policy by TERI[68]. Faltering on these measures can render the policy ineffective, while following mandated tests and strict compliance checks can significantly enhance the policy's success rate.

ALT 3: Hydrogen Blending in CNG

[National Green Hydrogen Mission | Punjab State Draft Hydrogen Policy 2023]

The ALT-3 scenario analysed Hydrogen-Enriched CNG (H-CNG) blending in Punjab's transport sector. This scenario envisions the progressive integration of H-CNG, beginning with no hydrogen blending in 2030, expanding to an 18% blend in buses by 2040, and extending to a similar 18% blend in cars, autos, Light Commercial Vehicles (LCVs), and buses by 2047. This approach aligns with the emphasis on hydrogen as a cleaner, more sustainable energy alternative and the policy momentum for its adoption in India.

Hydrogen, being light, highly combustible, and environmentally benign, plays a pivotal role in India's clean energy transition, particularly through Green Hydrogen (GH) initiatives under the National Green Hydrogen Mission. This mission aspires to position India as a global hub for GH production, utilization, and export, fostering innovations in the transportation sector among others. In alignment, Punjab's Draft Hydrogen Policy (2023) outlines the state's commitment to encouraging hydrogen production, distribution infrastructure, and end-use applications in transport and industry. The draft policy includes incentives, regulatory facilitation, and public-private partnership models to support H-CNG integration in urban fleets and commercial transport.

By adopting this H-CNG blending pathway, Punjab could realize significant emission reductions by 2047 compared to the BAU scenario, including reductions of 8% in PM_{10}, 6% in $PM_{2.5}$, 9% in N_2O, 12% in NO_2, 10% in CO, 14% in CH_4, 13% in BC, 8% in SO_2, and 6% in NMVOCs.

ALT 4: Comprehensive EV Policy for all Vehicles

[Punjab Electric Vehicle Policy (PEVP)]

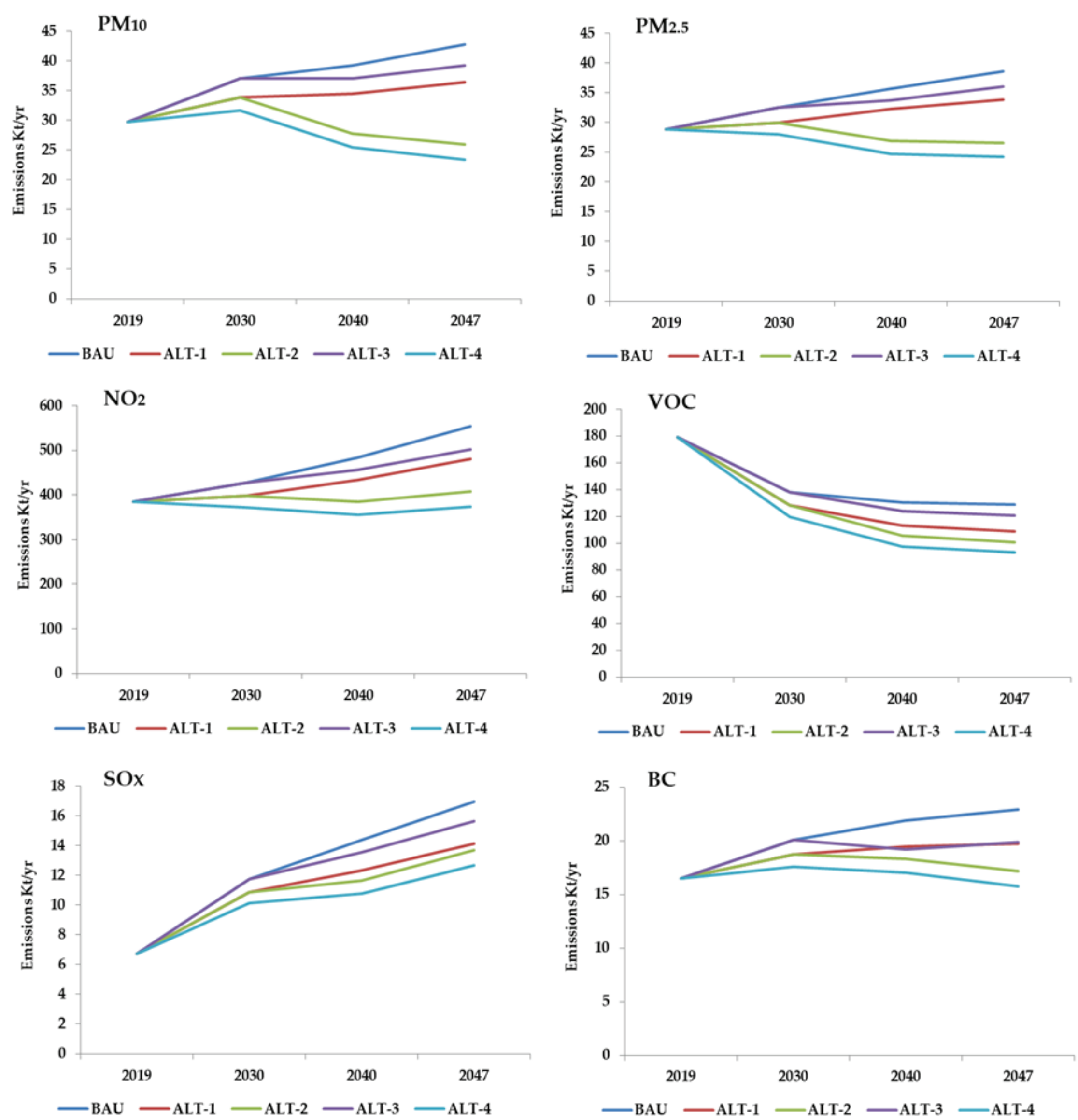
The ALT-4 scenario for Punjab envisions the comprehensive electrification of the vehicular fleet in alignment with the objectives of the Punjab Electric Vehicle Policy (PEVP). This scenario incorporates phased targets for the conversion of newly registered buses, two- and three-wheelers, and cars to EVs: 50% by 2030, 70% by 2040, and 100% by 2047. The policy emphasizes fostering sustainable mobility by providing incentives, tax exemptions, and the development of robust EV infrastructure. By implementing this comprehensive approach, Punjab aims to significantly mitigate vehicular emissions. Projected reductions by 2047, compared to the Business-as-Usual (BAU) scenario, include PM_{10} (-45%), $PM_{2.5}$ (-37%), NO_x (-32%), NO_2 (-45%), CO (-47%), CH4 (-58%), BC (-31%), SO_2 (-25%), and NMVOC (-28%). These initiatives underscore Punjab's dedication to achieving cleaner air, better public health, and a sustainable energy transition.

Table 20: Transport Emissions Under Alternate Scenarios, Compared to 2047 Emissions Under BAU

Scenarios	$PM_{2.5}$	PM_{10}	SO_2	NO_x	CO	NMVOCs	BC	CH_4
ALT 1: Electrification of bus fleet	-12%	-15%	-17%	-13%	-24%	-16%	-14%	-26%
ALT 2: Vehicles scrappage policy	-31%	-39%	-19%	-26%	-41%	-22%	-25%	-52%
ALT 3: Hydrogen blending in CNG	-6%	-8%	-8%	-9%	-10%	-6%	-13%	-14%
ALT 4: EV Policy for all vehicles	-37%	-45%	-25%	-32%	-47%	-28%	-31%	-58%

While the alternative scenarios modelled as part of this study highlight the four key policy interventions to be strengthened in Punjab to address emissions from the state's transport sector, need to be supported by a holistic assessment of how these policies are transformed into implementation on ground. In the context of ALT 1 and ALT 4, it would be crucial to bear in mind that a complete transition to electric vehicles on ground, under the current scenario, might not be feasible. Instead, a phased approach to transition must be adopted. Since 2019, Punjab has proactively developed and implemented a range of sector-specific policies aimed at transforming its transport sector. Notably, the state introduced its EV policy in 2022, followed by comprehensive vehicle scrappage and hydrogen policies in 2023. The impact of these initiatives, as modeled in this study, demonstrates substantial emission reductions—up to 58%. These results underscore Punjab's exemplary commitment to setting ambitious targets and regulating the transport sector, effectively minimizing its environmental footprint.

Further, the transport sector continues to evolve, the emergence of technologies such as green hydrogen-powered vehicles, strong hybrids, and intelligent mobility systems will offer new opportunities for emission reductions. While the present study provides a roadmap for state-level interventions, further granular, city-specific assessments are necessary to guide practical implementation. These should include analyses of current modal shares, travel demand, and existing public and private transport infrastructure in each major city. Such diagnostics will help evaluate context-appropriate solutions, including metro systems, Bus Rapid Transit Systems (BRTS), Light Rail Transit (LRT), monorail, or commuter rail, tailored to local travel behaviour and urban form, thereby enhancing the effectiveness of sustainable mobility transitions across Punjab's cities.



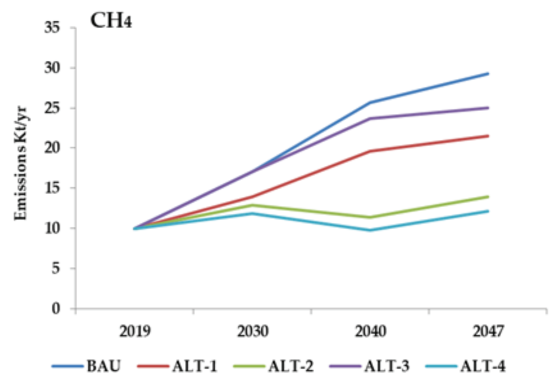


Figure 8: Emissions of PM_{10}, $PM_{2.5}$, NO_X, NMVOCs, SO_2, BC and CH_4 during 2030, 2040 and 2047 from the Transport sector under BAU, ALT-1, ALT-2, ALT-3 and ALT-4 scenario

4.2.2 Industry

Punjab is renowned for its entrepreneurial spirit, which propelled the Green Revolution and established the state as a hub for small and medium enterprises (SMEs). With a robust industrial base encompassing textile, auto components, bicycle parts, agricultural implements, brick manufacturing, and more, Punjab remains a vital driver of India's economic growth. The state accounts for a significant share of national production in key sectors, including 95% of woollen knitwear, 85% of sewing machines, and 75% of sports goods. Approximately 1.78 lakh MSME units in Punjab employ over 11.66 lakh people, underscoring their critical role in the state's development.[69]

However, Punjab's rapid industrialization has led to significant environmental challenges, particularly regarding air quality. The reliance on coal-fired energy for industrial and residential demands has resulted in elevated emissions of PM_{10} and $PM_{2.5}$, SO_2, nitrogen oxides (NO_x), and SLCFs such as CH_4 and BC. These pollutants pose serious public health risks, degrade air quality, and contribute to climate change.

Coal-fired thermal power plants (TPPs) serve as a pivotal energy source in Punjab, significantly contributing to the state's economic development while also imposing a considerable environmental burden. In 2019, these plants consumed approximately 12.1 million tons (Mt) of coal,[70] sourced both domestically and through imports, as documented by the Central Electricity Authority (CEA) and the Punjab State Council for Science & Technology (PSCST). With a combined installed capacity of 5,680 MW, coal continues to dominate Punjab's energy mix.

In addition to coal-based power generation, Punjab has also made strides in renewable energy. The state hosts 11 operational biomass power plants with a cumulative installed capacity of 97.5 MW. These facilities collectively utilize 8.8 lakh metric tons of paddy straw annually as feedstock.[71]

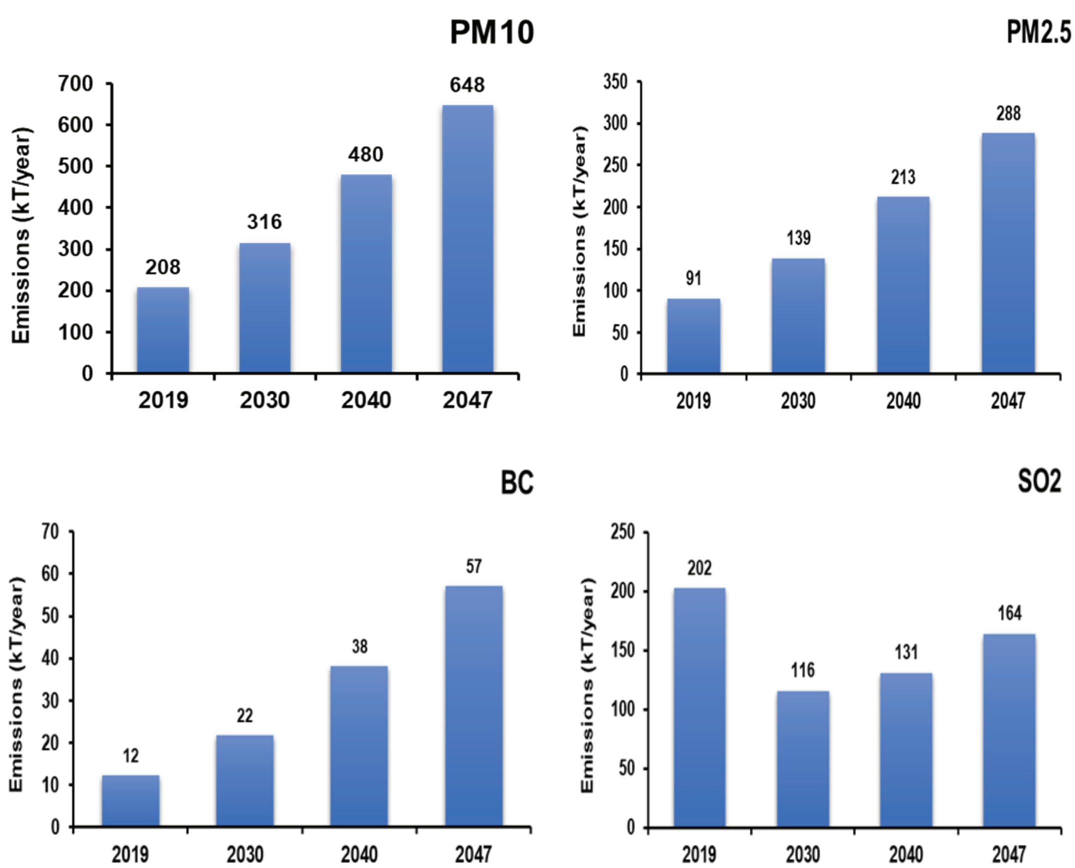
Although all coal-based TPPs in Punjab are equipped with Electrostatic Precipitators (ESPs) to control particulate matter emissions, the high ash content (30–40%) in Indian coal contributes significantly to PM emissions, while its sulphur content (<0.6%) results in substantial SO_2 emissions.[72] Emissions from these plants depend on fuel quality, specific fuel consumption, and the efficiency of pollution control technologies.

This report provides a comprehensive analysis of Punjab's industry and power sector emissions profile from 2019 to 2047, examining the scale, sources, and projections of various pollutants. Through an integrated perspective, the study aims to support evidence-based policymaking and promote cleaner, more sustainable industrial and energy practices, steering Punjab toward a resilient future. Note that the City Action Plans in Punjab, including Amritsar's, highlight the need to transition from coal to cleaner fuels like PNG. This shift is part of their technology interventions aimed at reducing emissions of PM, SO_2, and NO_x.[73]

BAU Scenario of the Industrial sector (Industries, Power, DG sets, and Brick Kilns)

A Business-as-Usual (BAU) scenario for emissions from the industrial sectors has been projected for the years 2030, 2040, and 2047, using growth rates derived from literature reviews. These include an industrial sector growth rate of 4.05% based on the Punjab Economic Survey, 2023, a Composite Growth Factor of 6.47% reflecting both population and GDP growth for the power sector, and a production growth rate of 0.41% calculated from the past four years. This BAU scenario assumes that current trends and patterns will continue through 2047 without significant policy or technological interventions.

Using the specified growth rates, the BAU scenario was developed to estimate emissions for the years 2019, 2030, 2040, and 2047, as presented in Figure 9. Under the BAU scenario, emissions of PM_{10}, $PM_{2.5}$, CO, and NMVOCs are projected to increase at a compound annual growth rate (CAGR) of 4% through 2047. In contrast, SO_2 emissions are expected to decline due to the mandatory implementation of FGDs in power plants by 2026, with a projected decrease at a CAGR of 5% by 2030, 2% by 2040, and 1% by 2047. Emissions of BC, CH_4, and NO_x are estimated to increase at a CAGR of approximately 5–6% by 2047. Consequently, emissions of PM_{10}, $PM_{2.5}$, NO_x, NMVOCs, and CH_4 are estimated to be approximately three times higher than their levels in the base year 2019.



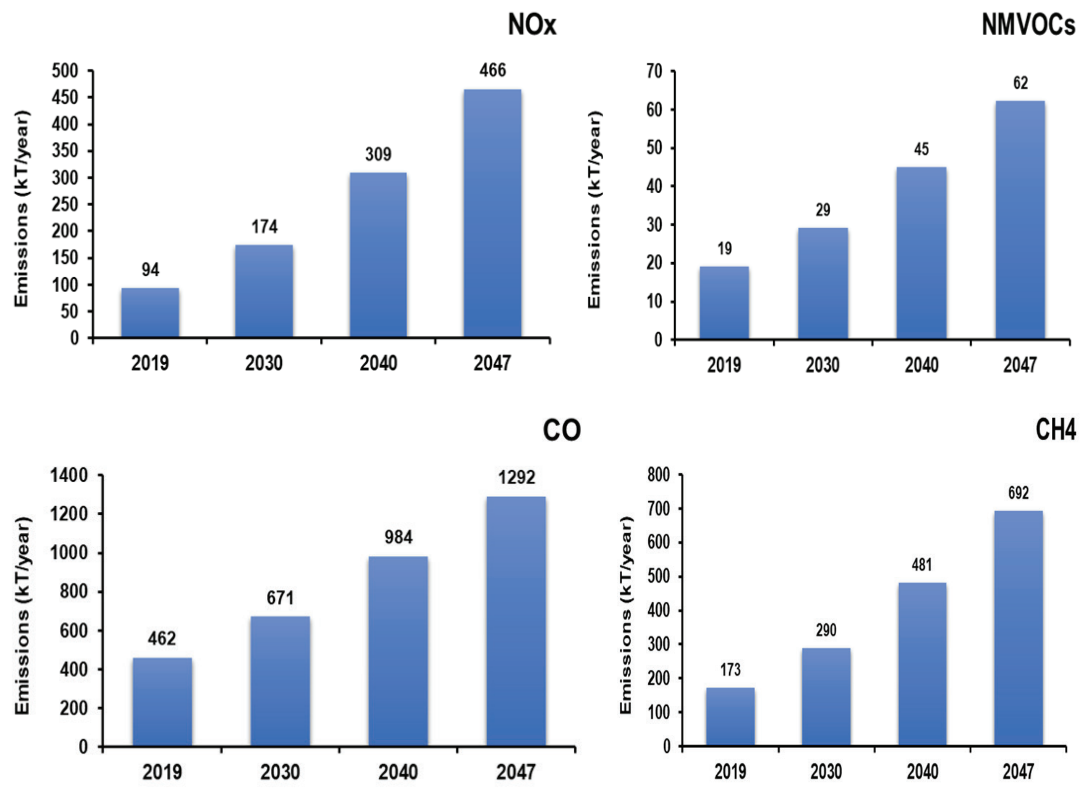


Figure 9: Emissions of PM_{10}, $PM_{2.5}$, BC, SO_2, NO_X, NMVOCs, CO and CH_4 during 2019, 2030, 2040 and 2047 from the Industry Sector under BAU scenarios

Alternate Scenarios

The Alternate Scenarios evaluate emissions from Punjab's industrial, power, brick kiln, and diesel generator (DG) sectors, focusing on the impact of various mitigation strategies. These sectors are significant contributors to air pollution and GHG emissions, making targeted interventions critical for achieving cleaner and more sustainable operations. The analysis considers a range of strategies, including transitioning to cleaner fuels, enhancing technology adoption, and integrating renewable energy sources.

In the industrial sector, three key measures are explored (See Table 21). Under all scenarios, the following has been assumed: (i) for DG sets, the installation of Retrofit Emission Control Devices (RECDs) is expected to achieve a 70% reduction in PM and BC emissions, (ii) in brick kilns, adoption of clean production practices and enhanced use of resource-efficient bricks in a phased manner is examined, and (iii) for the power sector focus is on increasing energy generation from biomass and renewable sources to 40% by 2047.

These interventions collectively aim to significantly reduce emissions, enhance energy efficiency, and support Punjab's transition to a low-carbon economy. The selection of said interventions is founded on key national and state level policies, regulations, and strategies (Table 21). The following section delves into the detailed analysis of emissions trends and the projected impact of these measures under alternate scenarios.

Table 21: Targets Assumed Under Alternate Scenarios for the Industry Sector and Policy Rationale

Scenarios	2030	2040	2047	Policy Rationale behind Intervention Selected
ALT 1: Transition of coal, wood, charcoal and pet coke to Natural Gas	**25%**	**50%**	**100%**	NCAP Industrial Emission Guidelines (MoEFCC, GoI), City Action Plans (Ludhiana, DeraBassi, Patiala, Gobindgarh, Khanna, Amritsar)
ALT 2: Implementation of community boilers	**30%**	**30%**	**30%**	CPCB Guidelines on Community Boilers, 2024
ALT 3: Expansion of Green Hydrogen	**-**	**5%**	**8%**	Punjab Green Hydrogen Policy, 2023
Overarching Measures Taken in All Scenarios	**Policy Rationale behind Measure**			
In the power sector, increasing energy generation from biomass and renewable sources to 40% by 2047	New and Renewable Sources of Energy Policy (NRSE), 2012; Punjab State Energy Action Plan; SAPCC 2.0, 2024 & Punjab Vision 2047.			
In brick kiln sector, adoption of clean production practices and enhanced use of resource-efficient bricks	Energy Efficiency Improvements in Indian Brick Industry (India Brick EE) Project, (MoEFCC,GoI, PSCST)			
Introduction of Retrofitting of Emission Control Devices (RECD) in DG sector	NCAP Industrial Emission Guidelines (MoEFCC, GoI), CPCB Guidelines			

ALT 1 – Phased Transition to natural gas

[NCAP Industrial Emission Guidelines (MoEFCC, GoI), City Action Plans (Ludhiana, DeraBassi, Patiala, Patiala, Gobindgarh, Khanna, Amritsar)]

In ALT 1 Scenario, the transition from solid fuels (Coal, Wood, charcoal and pet coke) to natural gas as a fuel for combustion in industrial boilers/furnaces is evaluated. This shift offers several significant benefits. Natural gas combustion leads to lower emissions of particulate matter (PM), sulphur dioxide (SO_2), nitrogen oxides (NO_x), and carbon dioxide (CO_2), thereby improving air quality. However, it is important to note that natural gas, while generally cleaner than coal in terms of conventional pollutants, has a higher methane (CH_4) emission potential due to its composition. Methane leaks during extraction, transport, and combustion can offset some of the climate benefits typically associated with natural gas use.[74]

The transition also enhances combustion efficiency due to the higher energy content of natural gas, leading to better heat generation and reduced maintenance requirements compared to coal. Furthermore, natural gas boilers require less water for cooling, which is particularly advantageous in water-scarce regions, such as Punjab. This shift supports industries in meeting stringent environmental regulations while reducing the need for costly pollution control measures. Natural gas boilers offer greater operational flexibility, with faster start-up times and more efficient emission control, enabling industries to adjust to changing demands quickly. Additionally, natural gas combustion produces minimal solid waste, reducing the environmental impact associated with ash disposal. By 2047, transitioning from coal to natural gas is expected to result in substantial emission reductions compared to the BAU scenario for the same year.

By 2047, emissions are projected to decrease significantly compared to the business-as-usual (BAU) scenario: PM_{10} by 82%, $PM_{2.5}$ by 76%, SO_2 by 54%, NO_x by 43%, NMVOCs by 25%, BC by 37%, CO by 70% and CH_4 by 23%. These reductions stem solely from combustion-related emissions, driven by the shift from solid fuels to natural gas. However, an increase in CH_4 emissions is expected due to methane leaks during extraction, transportation, and processing.

ALT 2 – Implementation of Community Boilers

[CPCB Guidelines on Community Boilers]

In ALT 2 scenario, which involves the implementation of community boilers, these centralized systems supply steam or heat to multiple industrial units within a community, offering significant advantages over individual boilers by centralizing the boiler operations, these systems are expected to reduce operational and maintenance costs, enhance fuel efficiency, and minimize downtime. Additionally, they improve environmental outcomes by consolidating emissions, which allows for more effective pollution monitoring and control and reduces overall coal consumption. When individual boilers are replaced with community boilers in an industrial cluster, fuel consumption is projected to decrease by 30%.

By 2047, this reduction in fuel use is anticipated to result in a decrease in emissions of PM_{10} by 16%, $PM_{2.5}$ by 17%, SO_2 by 8%, NO_x by 34%, NMVOCs by 18%, BC by 34%, CO by 10% and CH_4 by 22% compared to the BAU scenario for the same year.

ALT 3 – Transition to Green Hydrogen

[Draft Punjab Green Hydrogen Policy, 2023]

In ALT3 scenario, the transition to green hydrogen as a fuel is evaluated. Green hydrogen is produced via electrolysis, which uses renewable energy sources—such as wind, solar, or hydropower to split water into hydrogen and oxygen, making it a clean alternative to conventional hydrogen production. This scenario proposes that green hydrogen will replace existing industrial fuels by 5% by 2040, and 8% by 2047. The adoption of green hydrogen is expected to significantly reduce emissions by 2047, achieving a 14% reduction in PM_{10}, 15% in $PM_{2.5}$, 9% in SO_2, 34% in NO_X, 21% in NMVOC, 35% in BC, 9% in CO and 26% in CH_4 compared to the BAU scenario for the same year.

The overarching transition from coal-fired thermal power plants to renewable energy sources and biomass-based generation is also considerable. By 2047, this transition in the power sector is projected to reduce emissions of PM_{10}, $PM_{2.5}$, SO_2, NO_2, NMVOCs, BC, and CH_4 by 40% compared to the BAU scenario for the same year.

Beyond the modelled policies related to green hydrogen, community boilers, and natural gas, Punjab has also ensured that low-emission industrial development in centric to its Industrial and Business Development Policy (2022)[75], including the following aspects:

- Facilitation of supply of Natural gas to the Industrial Parks through proper connectivity
- Special fiscal incentives to existing industries to switch over to Paddy Straw fuel based boilers

- Financial & Fiscal Assistance to Renewable Energy Projects, including facilitation for setting up of Green Hydrogen Projects

Moreover, the state in 2022 also mandated 20% coal replacement with paddy straw pellets in brick kilns.[76]

Key Industrial Air Pollution Mitigation Policies in Punjab

Multiple steps are being considered at the national level to curb emissions from agricultural residue burning and industrial fuel use. One such initiative is the central government's directive, effective August 1, 2023, mandating the use of paddy straw in biomass-based power generation and encouraging its use in the production of bioethanol, biogas, briquettes, pellets, and torrefied charcoal.

Punjab has taken proactive, first-of-its-kind initiatives to operationalize and build on these goals, emerging as a national leader in ex-situ crop residue management and clean industrial fuel transitions. Key state-level actions include:

- Brick Kiln Fuel Diversification: A state notification mandates that all brick kilns in Punjab use at least 20% paddy straw pellets as fuel from May 1, 2023, significantly cutting emissions from the sector.
- Promotion of Paddy Straw-based Boilers: Punjab is actively facilitating the switch to paddy straw as an industrial boiler fuel, supported by outreach efforts from the Punjab Pollution Control Board. Paddy straw consumption in boilers is projected to rise to 3.1 million tonnes in 2024
- Capital Subsidy for Straw-based Boilers: Under the Punjab Bureau of Investment Promotion (PBIP) policy, eligible industries—such as sugar and paper mills—can claim SGST reimbursement on straw-fired boiler installations. The state is also considering additional capital subsidies to accelerate adoption
- Cleaner Industrial Fuel Policy: Industries such as re-rolling mills and forging units are transitioning to PNG, electric, or induction-based heating, further contributing to air quality improvements

Through these integrated policies, Punjab is demonstrating how proactive, state-level action can drive national clean air goals while supporting sustainable agricultural and industrial practices.

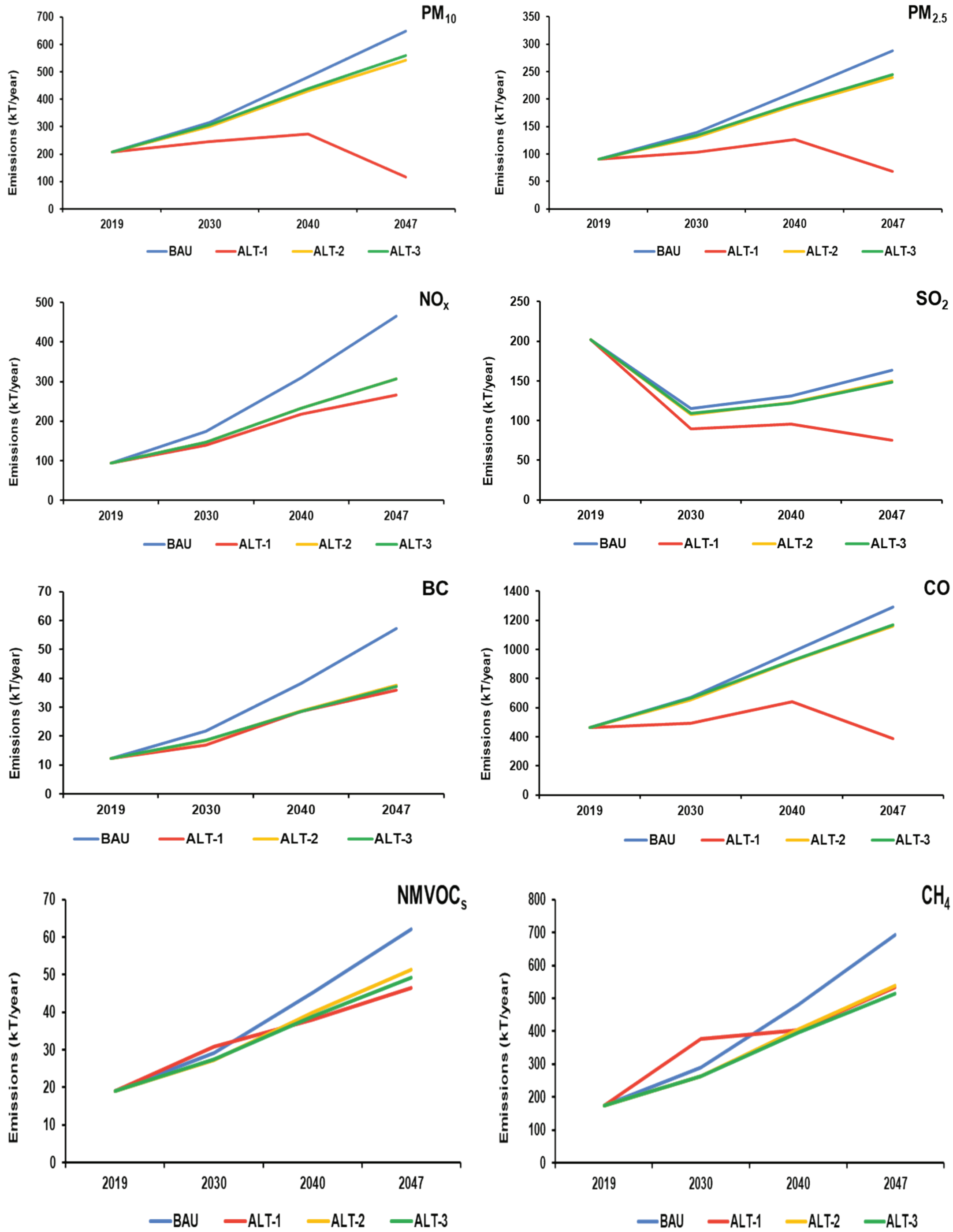


Figure 10: Emissions of PM_{10}, $PM_{2.5}$, NO_X, SO_2, BC, CO, NMVOCs and CH_4 during 2019, 2030, 2040 and 2047 from the Industry Sector under ALT scenarios

Table 22: Industry Emissions Under Alternate Scenarios, compared to 2047 Emissions Under BAU

Scenarios	PM_{10}	$PM_{2.5}$	SO_2	NO_x	CO	NMVOCs	BC	CH_4
ALT 1: Transition to Natural Gas	-82%	-76%	-54%	-43%	-70%	-25%	-37%	-23%
ALT 2: Implementation of community boilers	-16%	-17%	-8%	-34%	-10%	-18%	-34%	-22%
ALT 3: Expansion of Green Hydrogen	-14%	-15%	-9%	-34%	-9%	-21%	-35%	-26%

4.2.3 Residential Sector

The residential sectors contribute to environmental degradation and public health challenges, primarily through emissions from waste management and residential cooking activities.

Waste Management

In urban areas, rapid population growth and urbanization have led to increased waste generation, overwhelming existing waste management systems. While Punjab achieves approximately 99% waste collection efficiency[77], limited treatment capacity means a substantial portion of waste is inadequately processed and ends up in municipal dumpsites[78]. These dumpsites act as sources of significant methane emissions, when organic waste decomposes in anaerobic conditions typically within a year of deposition.[79] Beyond methane, SLCFs (PM_{10}, $PM_{2.5}$, Black Carbon, etc.) from waste primarily are emitted due to open burning activities.

To address these challenges associated with waste management, the Government of Punjab has implemented initiatives such as converting dumpsites into sanitary landfills and remediating legacy waste while adopting a decentralized and cost-effective waste management approach. This approach emphasizes 100% source segregation, door-to-door collection, and the processing of wet and dry waste through composting, bio-methanization, and material recovery facilities. Despite these efforts, gaps persist, particularly in achieving comprehensive waste treatment and reducing emissions from dumpsites and open burning.

Residential Cooking:

Emissions from residential cooking activities remain a significant concern, particularly in rural areas where traditional biomass fuels like wood, crop residues, and dung cakes are still being used – leading to SLCF emissions such as NMVOCs, Black Carbon, CH_4, SO_2, etc. While the adoption of LPG has significantly improved over the years, as highlighted by an increase in rural LPG usage from 18.1% in 2001 to 77.4% in 2018[80], around 16.1% of rural households still rely on biomass fuels due to economic and supply constraints.

This study's assessment of the residential sector focused specifically on cooking activities, as they represent the predominant use of both solid and gaseous fuels in the sector. Space heating, while present, is seasonal and limited to colder months, making it a negligible source of emissions.

Moreover, reliable and consistent data on space heating practices, fuel use patterns, and technology types is limited, making robust estimation challenging. Therefore, for this phase of the assessment, we prioritized cooking to ensure methodological consistency and broader applicability. However, future studies could consider including space heating, especially for areas in states where it forms a substantial portion of residential energy use.

Although Punjab has made commendable progress in reducing emissions from residential cooking and waste sectors, our analysis guides the prioritization of measures based on emission reductions and feasibility of implementation. The following sections present both BAU and ALT scenarios for the residential sectors, providing a detailed emission forecast through 2047 and highlighting the path toward sustainable and low-emission development.

BAU scenario for residential cooking

Under the BAU scenario, emissions have been projected based on the consideration of growth pattern of LPG consumption in residential households. Indian Petroleum and Natural Gas Statistics report has been referred to estimate the growth trend of LPG consumption in residential households for the state of Punjab. Ministry of Petroleum and Natural Gas (MoPNG) reports LPG consumption at state level and in absence of LPG consumption information at rural and urban level, LPG consumption during 2019-20, 2020-21 and 2021-22[81] was used to project the LPG growth for the entire state. Accordingly, household LPG usage was estimated to grow at 2.87% annually at urban and rural areas of Punjab; owing to which, biomass using households are expected to completely shift to LPG, achieving 100% LPG penetration in urban and rural areas during 2030 and 2047 respectively. Reliant on this, SLCF emissions for BAU scenario till 2047 have been estimated, Figure 11 presents the outcomes.

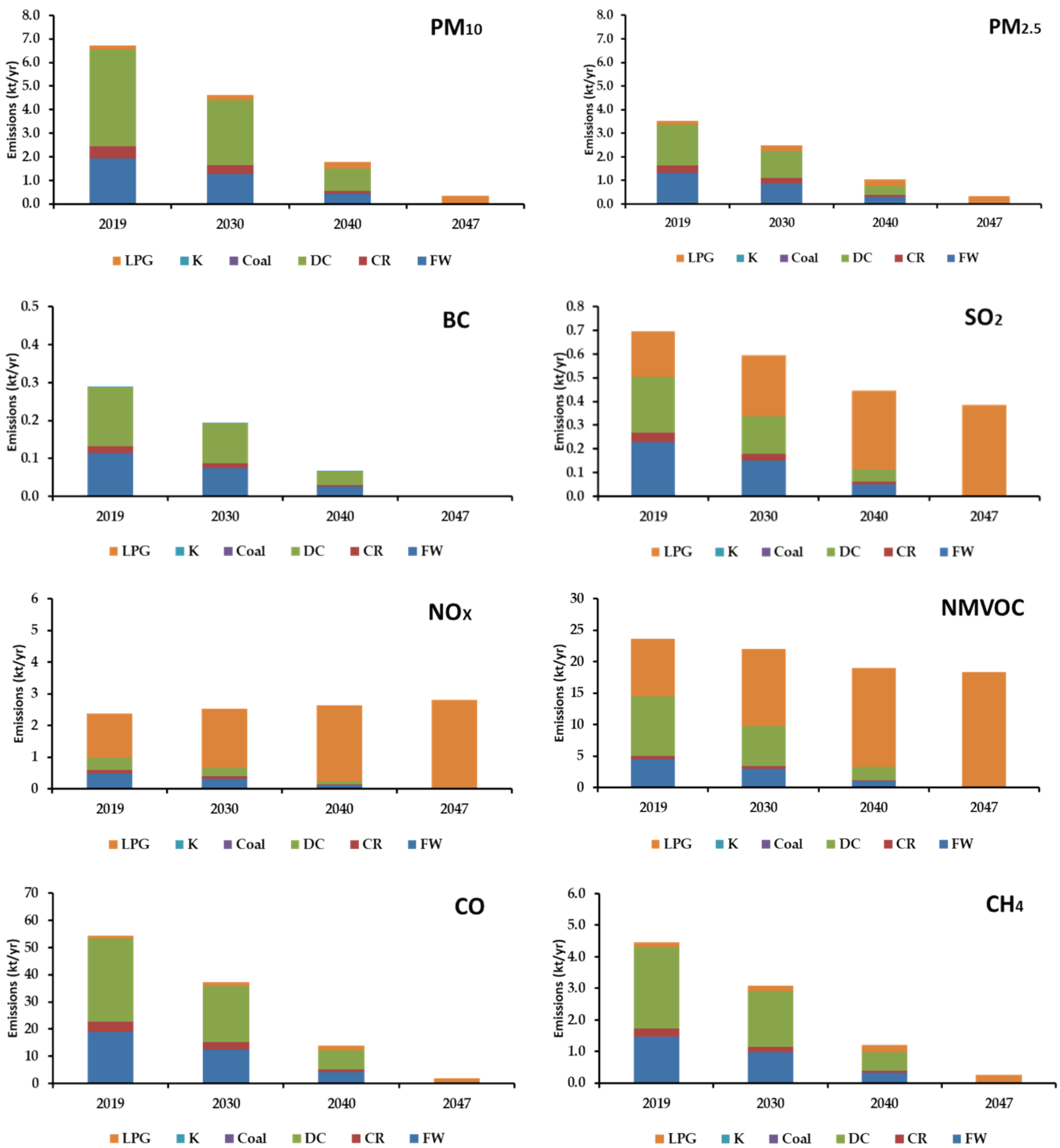


Figure 11: Fuel wise emission (kt/yr) of different pollutants from residential cooking activity in Punjab during 2019, 2030, 2040 and 2047 as per the Business as Usual (BAU) scenario

(FW: Fuelwood; CR: Crop Residue; DC: Dung Cake; K: Kerosene; LPG: Liquified Petroleum Gas)

From the Figure 11, various notable observations can be made. As the fuel ratio in the sector moves away from alternatives (fuelwood, crop residue, dung cake, and kerosene) towards LPG, emissions of almost all SLCFs reduce over. Most notable impacts are reductions in $PM_{2.5}$ by 0%, 70% and 90% respectively in 2030, 2040 and 2047 and PM_{10} by 31% in 2030, 73% in 2040. and 95% in 2047 compared to the baseline emission (2019). BC, CO, and CH4 also reduce by drastic amounts, reflecting almost 0 emissions from the sector by 2047. These trajectories reflect the environmental viability of LPG over its existent alternatives. However, an evident caveat is that NO_x emissions do increase over the years (by 7%, 11%

and 18% in 2030, 2040 and 2047 respectively compared to 2019) since LPG, although cleaner than other fuels, still emits pollutants and its expected widespread adoption in the state would lead to significant NO_x emissions.

Alternative Scenarios of the residential cooking sector

The study evaluates three alternative scenarios to explore pathways for reducing SLCFs in Punjab's residential cooking sector. These scenarios build upon the current levels of technology adoption and align with existing state and national policies aimed at promoting cleaner cooking solutions, such as increased LPG and biogas usage, while reducing reliance on traditional biomass cookstoves. Each scenario supports Punjab's long-term target of achieving 100% LPG adoption by 2047 and assesses how different interventions can maximize emission reductions during this transition.

Table 23: Description of Scenarios under Residential Cooking Sector

	Scenario Description	Policy Rationale Behind Chosen Interventions
ALT 1	Non-LPG households adopt improved biomass cookstoves.	▪ **National Biomass Cookstove Programme (NBCP), MNRE** – It promotes improved biomass cookstoves to reduce indoor air pollution and SLCP emissions. ▪ **New National Biogas and organic Manure Management Programme (NNBOMP), Govt. of Punjab -** Encourages adoption of improved cookstoves, biogas plants and solar cooking systems in rural households. ▪ **"Surya Nutan" Solar Cooking Initiative (Indian Oil and Ministry of Petroleum & Natural gas)** - Maximizing the share of clean indoor solar cooking in rural households by distributing "Surya Nutan" devices, along with biogas and improved cookstoves
ALT 2	Between 2030 and 2040, non-LPG rural households shift to: ▪ 30% to improved cookstoves, ▪ 30% to biogas, ▪ 40% to solar cooking systems.	
ALT 3	No further LPG penetration is assumed in rural Punjab, hence after 2040, the remaining non-LPG households will transition to solar-based cooking systems, aiming for 100% adoption by 2047.	

Note: An annual 2.87% growth of LPG consumption has been assumed under all scenarios.

These alternative scenarios demonstrate a range of possibilities for reducing emissions in Punjab's residential cooking sector. Figure 11 highlights their impacts on the total emission load compared to the business-as-usual (BAU) scenario, providing a comprehensive understanding of the potential benefits of adopting cleaner technologies.

ALT 1: Adoption of improved biomass cookstoves

[National Biomass Cookstove Programme (NBCP), MNRE]

Under ALT1 scenario, the emission load from residential sector is projected based on the assumption that LPG consumption will grow at 2.87% annually as considered under the BAU scenario. However, remaining households i.e. biomass and coal dependent households (remaining after LPG penetration) will gradually shift from traditional cookstove to improved less smoke solid fuel cookstove. According to a test report approved by Biomass Cookstove Test Centre under the Ministry of New and Renewable Energy (MNRE), improved biomass cookstove with thermal efficiency of 28% can achieve significant emission reduction.[82] Unless there is a sustainable supply of LPG for cooking activity in residential households particularly in rural and urban slums, implementation of improved solid fuel cookstove emits less smoke compared to traditional cookstove.

Accordingly, assuming co-implementation of LPG fuel and improved solid fuel cookstove, the emission load of particulate matter, CO, BC and CH4 is expected to reduce between 15% and 28% during 2030 and between 7% and 28% during 2040 with respect to corresponding emissions under the BAU scenario. Whereas NOx and NMVOC is expected to reduce between 5% and 12% during 2030 and 2040 compared to BAU emissions.

ALT 2: Adoption of improved cookstoves, biogas and solar cooking systems

[New National Biogas and organic Manure Management Programme (NNBOMP), Govt. of Punjab, "Surya Nutan" Solar Cooking Initiative (Indian Oil and Ministry of Petroleum & Natural gas)]

Considering the baseline situation and growing LPG usage at 2.87% annually, rural Punjab is achieving 100% LPG coverage in 2047. However, about 25% of rural households during 2030 and 10% of rural households during 2040 would still depend on biomass and other inefficient fuels to meet their cooking needs. Therefore, 30%, 30% and 40% of non-LPG using households in rural Punjab is assumed to shift to improved cookstove, biogas and solar based cooking respectively.

Accordingly, the emission load of different pollutants is expected to reduce between 17% and 78% during 2030 compared BAU2030 emissions. Similarly, assuming similar scenario during 2040, PM10 and PM2.5 emission is expected to decline by 65% and 56% respectively compared to BAU 2040 emission indicating significant air quality improvements.

ALT 3: Transition to solar cooking systems

[New National Biogas and organic Manure Management Programme (NNBOMP), Govt. of Punjab, "Surya Nutan" Solar Cooking Initiative (Indian Oil and Ministry of Petroleum & Natural gas)]

Under ALT3 scenario, the emission load from residential sector is projected assuming that 20%, 20% and 60% of non-LPG using households in rural Punjab will shift to improved cookstove, biogas and solar-based cooking respectively during 2030. Again, during 2040, 70% of non-LPG using households in rural Punjab is assumed to shift to solar-based cooking whereas, remaining 20% and 10% of non-LPG households will use biogas and improved cookstove respectively. However, beyond 2040 no further LPG penetration is assumed in rural Punjab and therefore, the estimated increased households (from 2040 to 2047) along with existing ICS and biogas dependent households in rural Punjab will shift to solar cookers as source of primary energy for cooking.

The emission load of different pollutants is expected to reduce between 19% and 86% during 2030 compared BAU 2030 emissions. Similarly, during 2040, the emission load of different pollutants is expected to reduce between 7% and 93% compared to BAU 2040 emissions indicating significant air quality improvements. This scenario achieves the most substantial emission reductions, particularly in particulate matter and methane, by avoiding combustion-based cooking entirely. However, despite the promising emission reductions, it must also note that ALT-3 represents a highly ambitious evolution in residential cooking habits and may not be attainable unless there is a transformative shift in consumer behaviour, supported by dedicated policies and widespread implementation.

Table 24: Residential Cooking Emissions Under Alternate Scenarios Compared to BAU in 2030

Scenario	$PM_{2.5}$	PM_{10}	CO	BC	CH_4	SO_2	NO_x	NMVOC
ALT 1	-25.39%	-26.64%	-27.06%	-28.07%	-26.36%	-15.24%	-6.16%	-11.53%
ALT 2	-70.61%	-74.08%	-75.53%	-78.42%	-69.03%	-34.84%	-17.30%	-34.55%
ALT 3	-77.24%	-81.01%	-82.47%	-85.61%	-77.31%	-41.45%	-19.06%	-36.88%

Table 25: Residential Cooking Emissions Under Alternate Scenarios Compared to BAU in 2040

Scenario	$PM_{2.5}$	PM_{10}	CO	BC	CH_4	SO_2	NO_x	NMVOC
ALT 1	-20.38%	-23.52%	-24.72%	-28.07%	-22.74%	-7.22%	-2.39%	-4.86%
ALT 2	-56.37%	-65.21%	-68.88%	-78.42%	-59.35%	-15.81%	-5.66%	-13.54%
ALT 3	-66.99%	-77.40%	-81.59%	-92.81%	-72.36%	-20.95%	-7.22%	-16.03%

Tables 24 and 25 summarise the emission reductions in 2030 and 2040 across the modelled scenarios. The most drastic reductions are observed in ALT-3, but as highlighted previously, this scenario may not be pragmatically viable. Considering the policy support and target for 100% LPG penetration, and the positive impact it has on SLCF emissions (Figure 12), BAU itself maybe be considered a viable and attainable trajectory. However, ALT-2 also represents a highly promising emissions scenario, and could be achieved with policy support for diversified cooking options (biogas, improved cookstoves, and solar cookstoves) in the transition years to all households adopting LPG. This support must be in the form of financial incentives and awareness building associated measures at local levels.

The state recognises the importance of emission reductions in the cooking sector and consequently has emphasised on provision of modern cooking solutions (LPG/PNG, biogas) to 100% rural/ urban population, as well as LPG penetration being a key aspect of slum upgradation in its SAPCC 2.0[83].

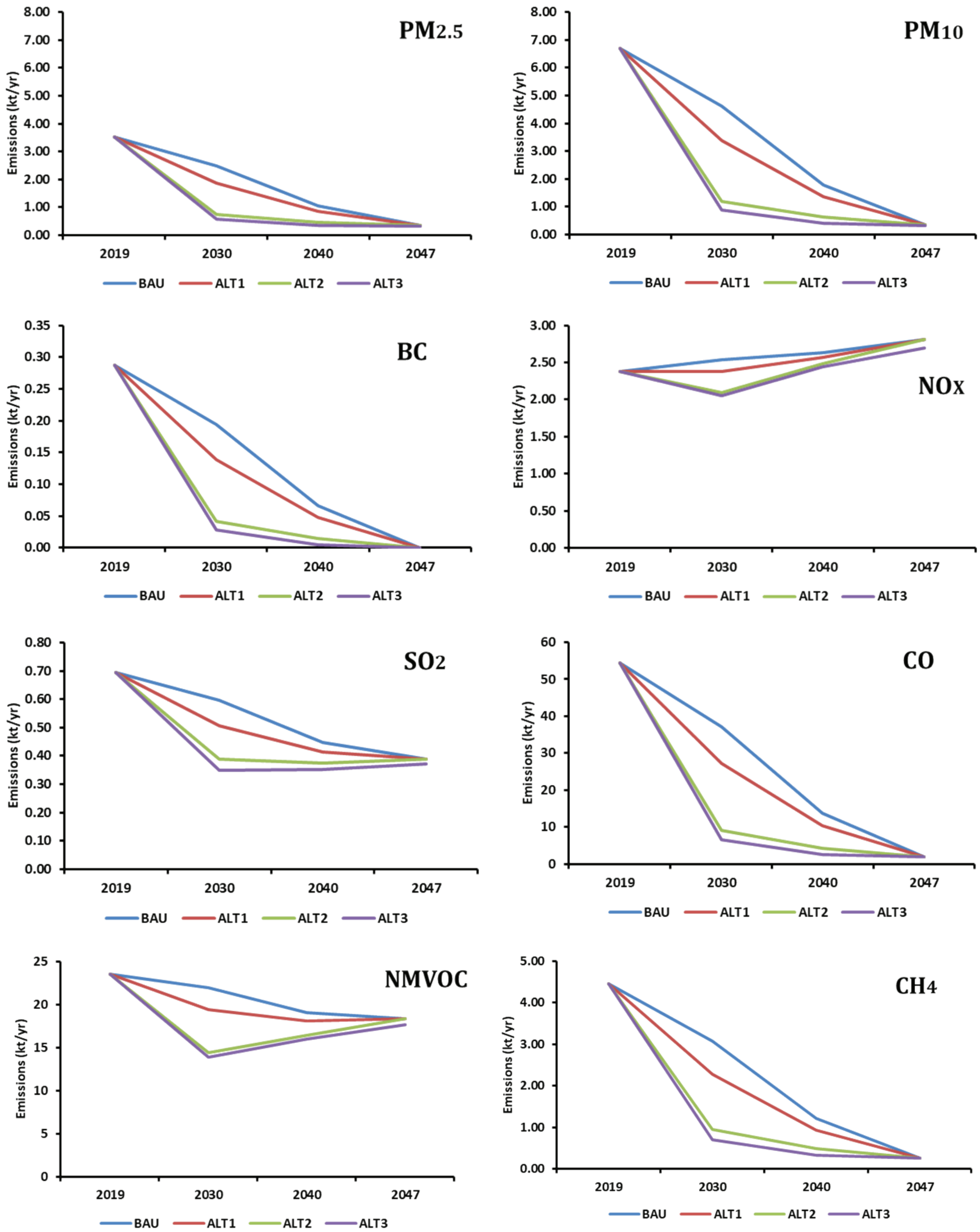


Figure 12: Emission (kt) of different pollutants from residential cooking activity in the state of Punjab during 2019, 2030, 2040 and 2047 under the BAU and ALT scenarios

BAU Scenario of the Waste Sector

With per capita waste generation of 0.31 kg per person per day and a population of 30,335,818, a BAU scenario for waste sector emissions has been developed which projected the emissions till 2047 in the Solid Waste Emission Estimation Tool (SWEET).

,[84], The BAU scenario represents[85] is being collected, with about 25% being processed. In this baseline scenario, the state focuses majorly on recycling, composting, and waste combustion for treatment of waste. Of the approximately 25% of waste being processed [86],[87] the majority is composted and recycled (42.5% each), while the remaining 15% is directed towards waste combustion. Regarding the assumptions considered for open waste burning, although it is banned in India, municipal solid waste (MSW) is still burned due to gaps in the waste management system. Based on findings from TERI's previous studies, this study includes open waste burning rate in the baseline scenario as 5% of uncollected waste being burnt by residents and 10% being burnt at landfill. Only municipal solid waste is considered in this analysis, excluding agricultural, construction, demolition waste, and other types of waste.

Based on the projected growth rates (Annual Average Growth Rate (AAGR) of 0.61%) for waste collection in this sector, the BAU scenario has been developed, and emission loads have been estimated. The estimates for the years 2020, 2030, 2040, and 2047 are shown in Figure 13.

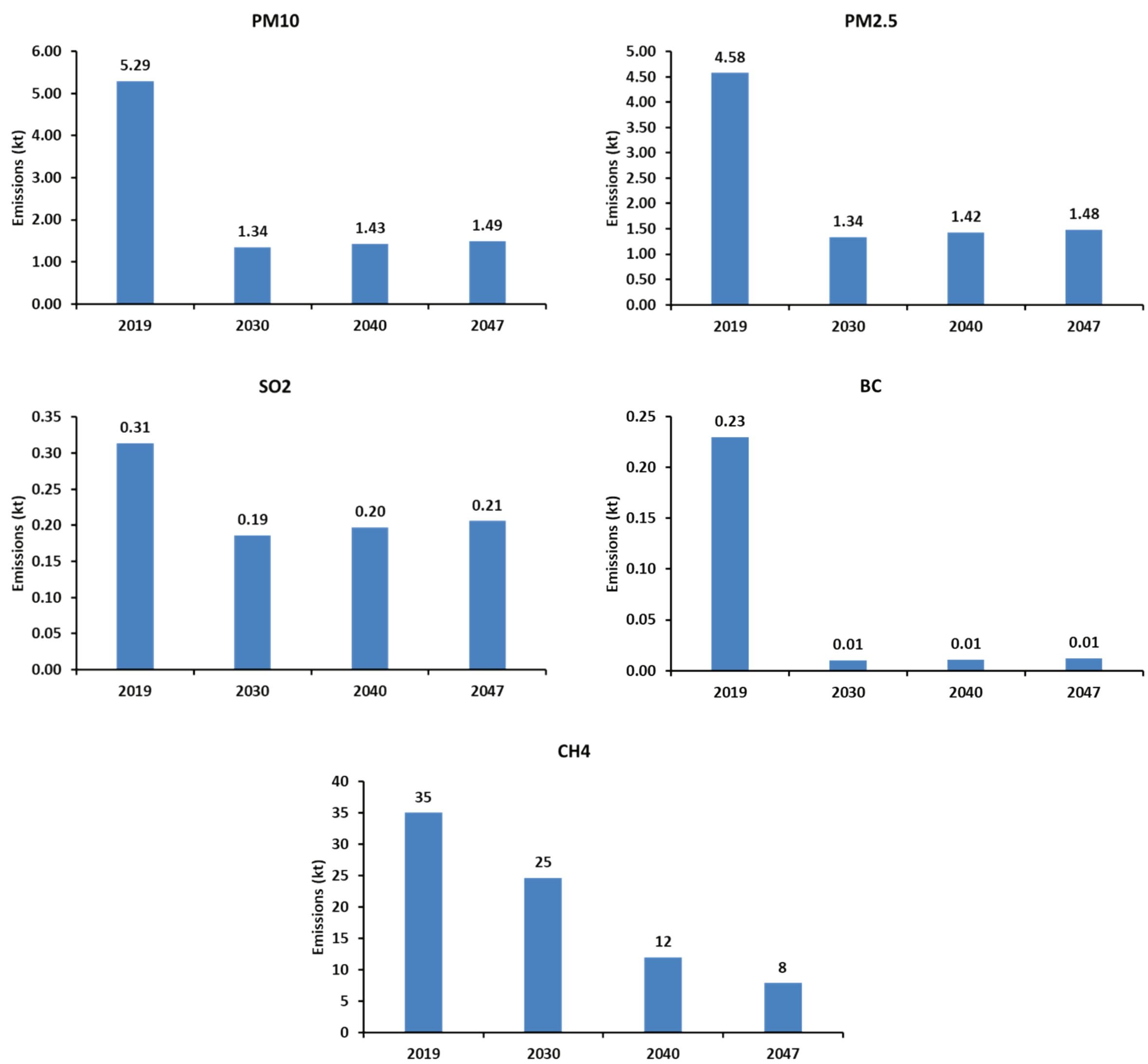


Figure 13: Emission (kt) of different pollutants from waste sector in Punjab during 2019, 2030, 2040 and 2047 as per the BAU scenario

Figure 13 outlines the BAU emissions projections for Punjab's waste sector, focusing on six key pollutants: CH_4, BC, SO_2, $PM_{2.5}$, and PM_{10}. The emissions in the baseline primarily result from the decomposition of waste at landfill sites, followed by open burning of waste by residents and spontaneous burning at landfill sites, and waste combustion at processing facilities. Amongst the various waste management activities, waste combustion plants the leading source of $PM_{2.5}$, PM_{10}, and SO_2 emissions; whereas open burning of waste by the residents and/or at the dumpsites is the second major contributor to these pollutants. Landfills in the largest Municipal Corporations – Amritsar, Ludhiana, Jalandhar, and Patiala have been considered in the study. Figure 14 represents salient observations from BAU of pollutants in the waste sector.

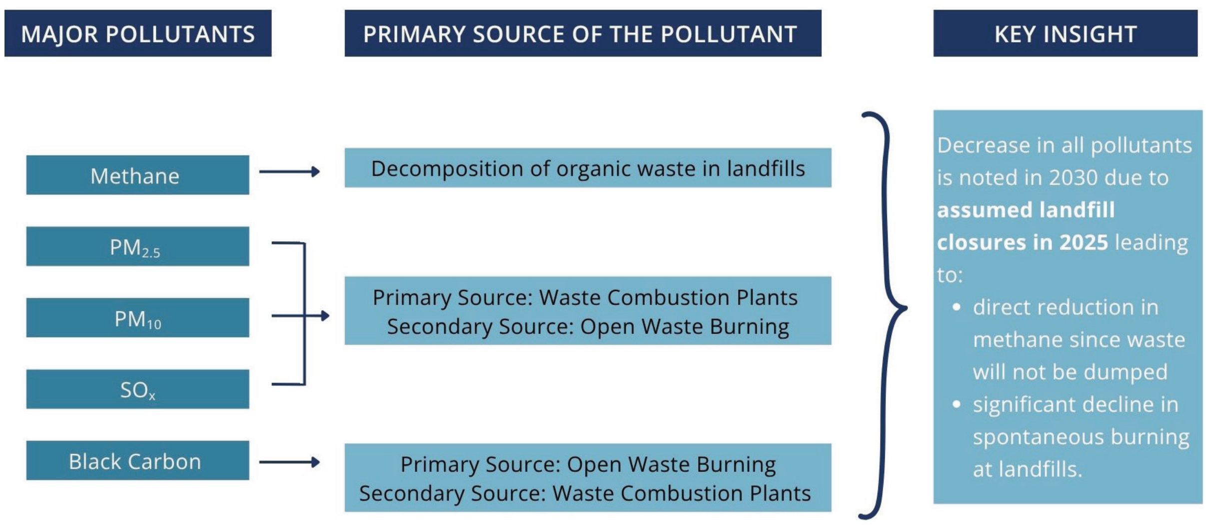


Figure 14: Pollutant-wise Insights from BAU of Waste Sector

Alternate Scenarios of the Waste Sector

The alternate scenarios are built upon the baseline using increasing level of waste diversion to the four processing facilities i.e., composting, anaerobic digestion, waste combustion, and recycling. The choice of processing facilities is based upon primary waste-centric policies of the state; namely, Punjab State Solid Waste Management Policy 2018, Solid Waste Management, Cleanliness, and Sanitation Bye-Laws, 2024, and Punjab Mission on Sustainable Habitats, 2014. The rates of total waste diversion, as well as distribution to various facilities, have been assumed by modelers based on their academic discretion. These estimates were guided by the intention to improve waste diversion ambition at progressive but realistic rates to assess the emission reduction impact as waste management improves. Across all scenarios, landfill closure of 2025 is kept intact (as in BAU), and pragmatic (but progressively ambitious) rates of open burning have been assumed. The three alternate scenarios begin from the year 2024.

Table 26: Overview of Modelled ALT Scenarios for the Waste sector

Scenario	Treatment of Diverted Waste				Open Burning	
	Composting	Anaerobic Digestion	Combustion Plant	Recycling	At Residences	At Landfills
ALT 1: 31% diversion	50%	0%	11.67%	38.27%	3%	7%
ALT 2: 50% diversion	25%	25%	11.67%	38.27%	2%	4%
ALT 3: 70% diversion	10%	40%	11.67%	38.27%	2%	4%

ALT 1: Of the collected waste, 31% is directed to composting, waste combustion, and recycling

[Punjab State Solid Waste Management Policy 2018, Solid Waste Management, Cleanliness, and Sanitation Bye-Laws, 2024, and Punjab Mission on Sustainable Habitats, 2014]

The scenario comprises the plants proposed to be developed by the State govt. which include composting of 1500 TPD, waste combustion plant of 350 TPD, and decentralized MRFs with a cumulative capacity of 1147 TPD. A 31% diversion of the collected waste is developed in this scenario where, of the total collected waste, 2997 TPD (31%) is diverted to composting of 1500 TPD (50%), waste combustion plant of 350 TPD (11.67%) and MRFs of 1147 TPD (38.27%). In the case of open burning, it is assumed that 3% of uncollected waste is burned by residents, while 7% is burned at the landfill sites as compared to the BAU level.

ALT 2: Of the collected waste, 50% is directed to composting, anaerobic digestion, waste combustion, and recycling

[Punjab State Solid Waste Management Policy 2018, Solid Waste Management, Cleanliness, and Sanitation Bye-Laws, 2024, and Punjab Mission on Sustainable Habitats, 2014]

Within this scenario, out of the total of 9560.66 TPD waste collected, 50% (4780.33 TPD) of the waste is diverted to diversion facilities. This diversion scenario assumes that anaerobic digestion (AD), which was not included in the baseline, has now been introduced. An equal amount of wet waste (50%) is allocated to both composting and AD facilities. Of the 4780.33 TPD sent for diversion, 1195.08 TPD (25%) is set for composting, 1195.08 TPD (25%) is set for anaerobic digestion, 557.86 TPD (11.67%) is set for waste combustion, and 1829.43 TPD (38.27%) is set for recycling. For open burning, the rate of open waste burning takes into account 2% of uncollected waste being burned by residents and 4% being burned at the landfill.

ALT 3: Of the collected waste, 70% is directed to composting, anaerobic digestion, waste combustion, and recycling

[Punjab State Solid Waste Management Policy 2018, Solid Waste Management, Cleanliness, and Sanitation Bye-Laws, 2024, and Punjab Mission on Sustainable Habitats, 2014]

Within this scenario, out of the total of 9560.66 TPD waste collected, 70% (6692.46 TPD) of the waste is diverted to diversion facilities. This diversion scenario assumes that AD, which was not included in the baseline, has now been introduced. It assumes a higher waste diversion rate for AD (40%) compared to composting (10%). Of the 6692.46 TPD sent for diversion, 669.24 TPD (10%) is set for composting, 2676.98 TPD (40%) is set for anaerobic digestion, 781.01 TPD (11.67%) is set for waste combustion, and 2561.20 TPD (38.27%) is set for recycling. For open burning, the rate of open waste burning takes into account 2% of uncollected waste being burned by residents and 4% being burned at the landfill. This is based on the assumption that with high collection efficiency and increased diversion of waste to treatment facilities rather than to the solid waste disposal sites will result in reduction of the open burning of waste, which will in return control air pollution emissions from the BAU levels

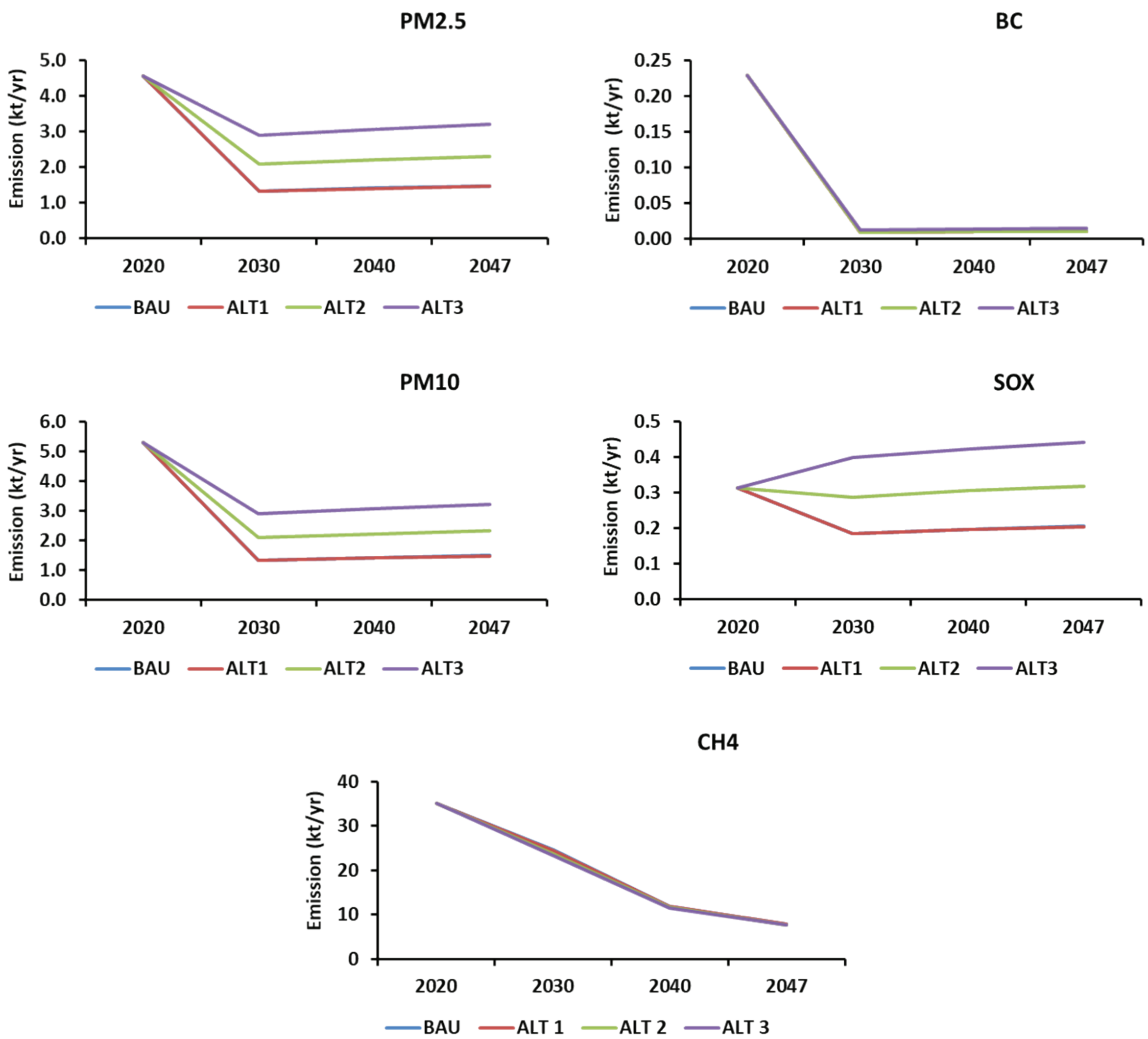


Figure 15: Emissions of CH_4, PM_{10}, $PM_{2.5}$, SO_2, and BC during 2020, 2030, 2040 and 2047 from the waste sector under BAU, ALT-1, ALT-2, and ALT-3 scenarios

Figure 15 highlights the trends in emissions for PM_{10}, $PM_{2.5}$, SO_2, BC, and CH_4 across the alternative scenarios. Over time, net CH_4 emissions, the largest contributor, significantly decrease. However, emissions of PM_{10}, $PM_{2.5}$, SO_2, and BC continue to rise, driven by heavy dependence on waste combustion and limited waste-handling infrastructure.

CH_4 Emissions Across Scenario

Declining trend in all scenarios due to:

- reduced landfill deposition owing landfill closures in 2025
- diversion of organic waste to compositing and anaerobic digestion.

$PM_{2.5}$, PM_{10}, BC, and SOx Emissions Across Scenarious

Increasing compared to the baseline scenario, due to:

- consisent reliance on waste combustion for treatment of diverted waste (11.67% across ALT scenarious)
- open waste burining, which is expected to continue, albeit at lower rates
- emissions generated by waste transportation and handling equipment.

Key Insidghts

- it is vital to prioritize low-emission waste management methods such as composting, anaerobic digestion, and recycling. These approaches produce sustantially lower emissions compared to waste combustion.
- Landfill closures remain foundational to emission reductions from the waste sector.
- Improved and sufficient waste-handling equipment isa crucial. Without it, delays in waste processing, increased fuel consumption, and inefficiencies in waste diversion are likely to occur.

Table 27: Emission Changes Under Alternate Scenarios Compared to BAU in 2047

Scenario	$PM_{2.5}$	SO_2	BC	CH_4
ALT 1: 31% diversion	-0.8%	-0.5%	-8.3%	-0.5%
ALT 2: 50% diversion	+55.8%	+54.9%	-16.7%	-1.5%
ALT 3: 70% diversion	+116%	+114.6%	+25%	-2.8%

A salient observation in the emission changes is the positive difference in PM2.5, SO2, and BC emissions as compared to BAU. The increase can be primarily attributed to waste combustion activities resulting from the diversion of waste (away from landfills) to waste-to-energy plants where it can be converted into resource driven fuel – thus, not only assuring reduced methane emissions but adding to the economic output of the state. Moreover, it must be kept in mind that the absolute differences in the amount of these pollutants are marginal, while the reductions in methane emissions are significant. Therefore, these emissions are a necessary trade-off and may even be termed as positive emissions.

It must also be noted that Table 11 presents comparisons with BAU 2047 scenario; however, in their own trajectories, the pollutants continue to fall over time in all scenarios and are lower than their 2019 baseline values (Figure 15).

The SWEET analysis identifies the primary sources of emissions in Punjab's waste management system as landfills, open waste burning, waste combustion, and inadequate waste-handling equipment. This underscores the urgent need to reduce landfill reliance, enhance waste-handling infrastructure, adopt alternative disposal methods to curb open burning, and prioritize waste diversion strategies with lower emissions than combustion plants.

The Punjab Municipal Infrastructure Development Company (PMIDC) is tasked with supervising waste management operations throughout the state. In alignment with the Solid Waste Management Rules, 2016, and the Punjab State Solid Waste Management Policy, the state has adopted a decentralized and cost-effective framework for the scientific and sustainable management of solid waste in urban areas. Furthermore, Punjab has developed and enacted Model Byelaws pertaining to Solid Waste Management, Cleanliness, and Sanitation. Urban Local Bodies (ULBs) have commenced the implementation of low-cost composting solutions via micro composting units and have established material recovery facilities to process dry waste. The state has also promoted the development and deployment of affordable solid waste management machinery, including mechanical separators for the remediation of legacy waste and composting machines, in collaboration with local manufacturers to support decentralized applications.[88]

Waste management efforts in Punjab

Following the general trend, waste management strategies and efforts (segregation, collection and processing) are more advanced in urban areas in Punjab while the rural waste sector still has a long way to go in strengthening waste management strategies. For example, while unsegregated plastic waste is difficult to dispose of, about 70% of the collected urban plastic waste is sold to and recycled by scrap dealers ("kabadiwalas") and the best plastic waste is picked up by cement industries. Plastic waste is broadly categorised into high-quality plastic, which is sold as pellets at around 40 Rs./kg, and mixed-plastic pellets, which is sold at 2 Rs./kg. On the other hand, in rural areas, legacy waste management and sanitary waste management (for example, appropriate disposal of sanitary pads) is significantly lacking. Appropriate policy interventions for the state must, therefore, reflect these differences in the location-specific characterisation of waste, acknowledging that distinctive policies might be required to address waste-sector emissions even at a district-level and further within the urban-rural split. The characterisation of waste is likely to differ between urban and rural areas in the state and policy interventions must correspondingly reflect these differences while targeting waste management efforts.

4.2.4 Agriculture & Livestock

Punjab's agricultural sector is a cornerstone of India's food production, contributing significantly to the nation's supply of rice, wheat, and dairy products. However, this vital sector is also a major source of SLCFs, which negatively impact regional air quality and contribute to climate change. Key activities such as rice cultivation, livestock rearing, and the open burning of agricultural residues release substantial quantities of CH_4, particulate matter (PM), and other air pollutants, highlighting the dual challenge of sustaining agricultural productivity while mitigating environmental harm.

The open burning of crop residues, particularly paddy straw, is a critical environmental issue in Punjab. This practice is widely adopted by farmers to quickly clear fields for the next crop cycle but results in significant emissions of PM and BC, which degrade air quality and amplify climate impacts. The widespread nature of this issue necessitates urgent action to promote alternative residue management practices such as in-situ incorporation, mulching, bioenergy conversion, or composting. These methods not only reduce emissions but also improve soil health and resource efficiency.

Similarly, livestock rearing, a crucial component of Punjab's agricultural economy, contributes to methane emissions through enteric fermentation and manure management. While dairy and livestock products remain central to the livelihoods of many, the associated emissions highlight the need for targeted interventions, including improved feed practices and manure management systems.

To address these challenges, this study developed BAU scenario to project the growth trends of Punjab's agriculture and livestock sectors and assess their environmental impacts. It also evaluates mitigation strategies, focusing on targeted interventions in rice cultivation and livestock management to curb methane and other SLCF emissions. These strategies demonstrate significant potential for emission reductions while ensuring that Punjab can continue to meet the growing demands for food and dairy products sustainably. Separate scenarios have been developed for crop cultivation and livestock activities, offering a comprehensive pathway toward a low-emission agricultural system in the state.

(A) Agriculture

BAU Scenario for crop cultivation activities

The domestic demand of rice in India is projected to be 197 Mt/annum during 2050-51 (NRRI, 2020)[89]. In addition, there is an expected increase in the export of rice to substantiate the projected economic growth of the country by 2050-51. Considering the export of rice, it was projected that the country requires about 227Mt/annum of rice during 2050-51. At present, Punjab produces about 12% of total annual rice demand of the country.[90] Keeping the present share of different states to the annual rice production of the country, it was estimated that the rice production in Punjab will reach about 26.7Mt/annum during 2050-51. Under the present crop yield scenario, the rice cropping area in the state need to be increased by 2050-51.

Data from the central government suggests that the rice cropping area in Punjab has increased by approximately 1.4% annually during 2014-15 to 2019-20 period.[91,92] If the rice cropping area in the state going to increase at the same rate, the methane emissions from the agriculture sector are going to increase. However, there is no indication of increase in net sowing area (about 3.59 million ha during 2019-20) during the kharif season in Punjab. Following this, it was assumed that after converting about 95% of net kharif sowing area to rice cropping, there will be no further increase in rice cropping area in the state post 2030-31. It was estimated that the methane emissions from rice crop land will increase from 0.19 Tg/annum in 2019-20 to 0.22 Tg/annum in 2030-31 (Figure 16).

The overuse of fertilizers, particularly urea, is another critical environment concern. However, it has been excluded from the modelling exercise as its primary emissions—N_2O (a long-lived GHG) and NH_3 (which forms secondary $PM_{2.5}$ but is not an SLCF)—do not directly contribute to near-term climate forcing. Additionally, fertilizer-driven NO_x emissions are minimal compared to transport and industry, making their impact on SLCF reduction negligible.

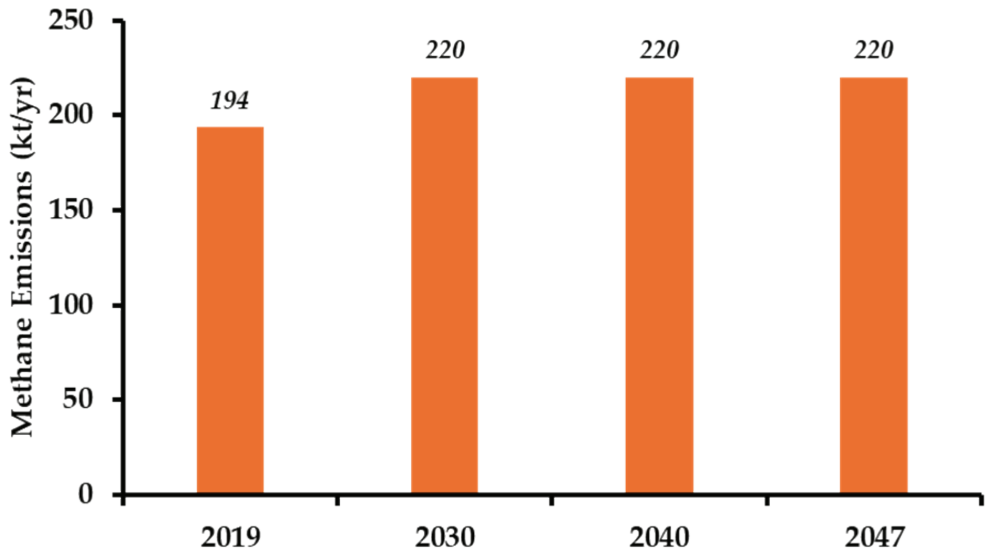


Figure 16: Agriculture Methane Emissions in Punjab over the years in BAU Scenario

However, to reduce the methane emission from the rice production in Punjab different scenarios were formulated and their impact on methane emission reduction from rice cropping was estimated.

Alternate scenarios for rice cultivation activities

Three alternative scenarios were tested to reduce methane emission from the rice cropping in Punjab, each focusing on sustainable agricultural practices tailored to Punjab's cropping systems. These scenarios aim to reduce methane emissions while maintaining or enhancing rice production levels, ensuring agricultural productivity and environmental sustainability.

Table 28: Description of ALT Scenarios for the Agriculture Sector

Scenario	Description	Policy/Guidance Supporting the Intervention
ALT-1	Implementation of System of Rice Intensification (SRI)-– with a targeted 500000 ha DSR in 2035, 1000000 ha DSR in 2040 and 100% DSR by 2050.	Punjab DSR policy 2022
ALT-2	Conversion of rice area to other crops – with a target of 300000 ha by 2030, 600000 ha by 2040, 1200000 ha by 2045.	Joint program of the Government of Punjab and the Central Government on Crop Diversification
ALT-3	Combined implementation of ALT 1, ALT 2, – Following diversification of rice cropping are to other crop, remining rice area was converted to DSR following the same growth rate of DSR under the ALT –1.	Punjab SAPCC 2.0, 2024 Punjab Vision 2047

ALT 1: Implementation of DSR

[Direct Seeded Rice Policy, 2022]

The DSR (Direct Seeding of Rice) policy in Punjab, introduced in 2022, aims to incentivize farmers to switch from transplanting to direct seeding, a method that potentially reduces water consumption and amount of in situ crop residues The state offers financial incentives, such as subsidies for DSR-specific machinery (e.g., seed drills) and technical support through agricultural extension services to encourage adoption. a financial incentive of ₹1,500 per acre for farmers adopting the DSR technique, as part of efforts to promote water conservation and reduce groundwater depletion. DSR's potential to cut methane emissions by up to 33% and water use by 15–53%.[93]

In 2023, there was about 32000ha was under DSR; however, the amount increased to about 2.72 lakh ha in 2024, although the government target was 7 lakh ha. Under this scenario the methane emission from rice cropping was estimated to decrease about 3%, 13% and 36% during 2030, 2040 and 2047 compared to the respective emissions under the BAU scenario.

ALT 2: Conversion of rice area to other kharif crops

[Crop Diversification Programme (CDP), Punjab]

The Crop Diversification Programme (CDP) in Punjab, in support of the Government of India, aims to shift farmers away from water-intensive crops like rice, particularly traditional transplanted rice, It was lunched in 2023 with a target to convert approximately 7 lakh rice area in 2023-24 to other kharif crop. The program provides financial incentives, such as INR 7,000 per hectare for alternative crops, along with subsidies for seeds, machinery, and technical support. An estimated 29,000 hectares were converted from rice or other crops in 2023-24; Additionally, basmati rice, which is less water-intensive, expanded to 6.5 lakh hectares from 5.96 lakh hectares, suggesting a shift of about 54,000 hectares within rice varieties. The Punjab government's CDP targeted 5 lakh hectares for diversification, but precise data on rice-to-other-crop conversion is limited. Under the ALT-2 scenario it was assumed that there will be approximately 14% change of rice area to less water intensive crops annually in Punjab, based on the present conversion rate and governmental push for crop diversification.

The estimation of methane emission under ALT-2 suggests reduction of 8%, 34% and 78% of methane emission from the rice fields during 2030, 2040 and 2047, respectively.

ALT 3: Additional Crop diversification

[Punjab SAPCC 2.0, 2024, Punjab Vision 2047]

Under this scenario, the remaining rice cropping area in each year after converting the estimated rice cropping area to other crop, was assumed to adopt DSR at the same rate as in ALT-1 i.e. the ALT-3 is a combination of ALT-1 and ALT-2.

This strategy not only reduces methane emissions but also supports soil fertility and sustainable crop rotation practices.

The methane emission from the rice field was estimated to reduce by 13%, 46% and 91% during 2030, 2040 and 2047, respectively.

Table 29: Livestock Methane Emission Reductions Under Alternate Scenarios, compared to Emissions Under BAU

Scenario	Reduction in CH_4 emissions compared to BAU for each year		
	ALT-1	ALT-2	ALT-3
2030	3%	8%	11%
2040	13%	34%	46%
2047	36%	78%	91%

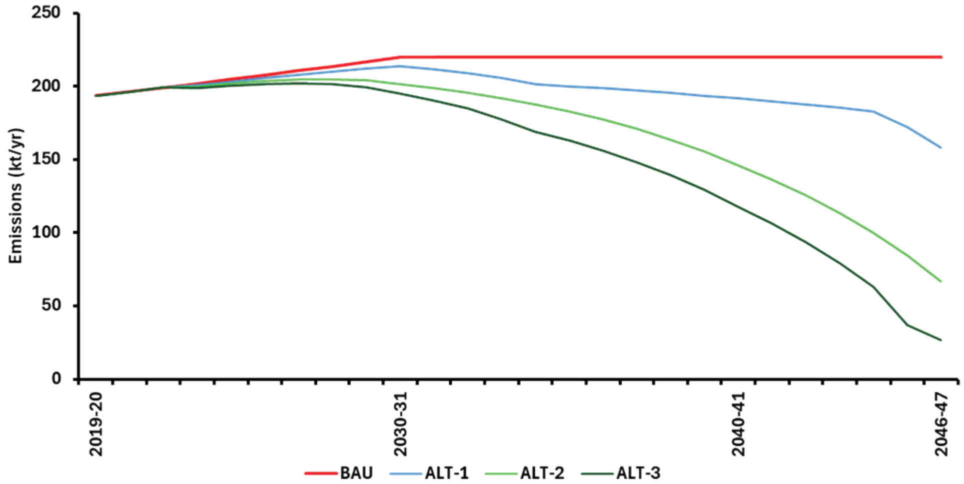


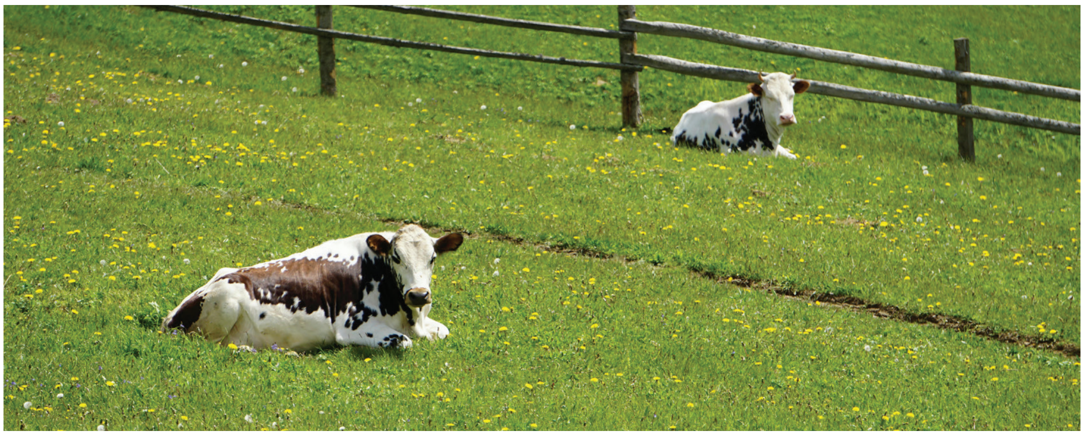
Figure 17: Annual changes in CH_4 emissions from rice cropland under different ALT scenarios in Punjab

The combined implementation of DSR and crop diversification, as under ALT3, demonstrates a progressive reduction in methane emissions from rice cultivation compared to the BAU scenario. These alternative scenarios illustrate a comprehensive approach to reducing methane emissions in Punjab's rice cultivation sector through sustainable farming practices and diversification, paving the way for a resilient and low-emission agricultural system.

The state of Punjab has long recognised the importance of crop diversification and continues to make efforts in promoting it. In 2025, the state budget allocated ₹14,524 crore to agriculture and allied sectors—a 5% increase over the previous year—with ₹115 crore specifically earmarked for crop diversification initiatives. Under this plan, a subsidy of ₹17,500 per hectare will be given to farmers shifting from paddy to Kharif maize in Bathinda, Kapurthala, and Gurdaspur, targeting around 30,000 farmers and covering 21,000 hectares. Similarly, the state has also allocated resources to promote DSR. For the 2025 Kharif season, the Punjab government has set a target of bringing 5 lakh acres under direct seeding of rice (DSR) and is offering a financial incentive of ₹1,500 per acre to participating farmers, with a total budget allocation of ₹40 crore for FY 2025-26.[94]

In reference to crop residue management, the Punjab Government has formulated an action plan worth ₹500 crore to provide farmers with the latest Crop Residue Management (CRM) machinery on subsidy and implement other strategies to efficiently manage the paddy straw. A 50 per cent subsidy has been offered to individual farmers and an 80 per cent subsidy to farmer groups, Cooperative Societies and Gram Panchayats for the purchase of CRM machines.[95]

(B) Livestock



BAU Scenario of Livestock Sector

The demand of milk in India is expected to increase dramatically due to factors like population growth, and changing dietary preferences. According to the National Dairy Development Board (NDDB) of India, the annual milk demand is expected to reach over 300 million metric tons by 2030. This indicates the requirement of a gain in milk production of about 6% every year. In addition to the expansion of rural milk infrastructure, sustained improvements in productivity, livestock population, and animal health will be necessary to meet this demand.

Punjab is the sixth largest milk producing state of the country, producing about 5.85% of total milk produced in the country.[96] The rural economy of the state is heavily reliant on the dairy sector.[97] Based on the annual milk production data of the state during 2019-20 (13.3 MMT) to 2023-24 (14 MMT),[98] milk production in the state has grown by about 1% annually. The milk production was converted to the total bovine population following the distribution of the total bovine population in the state during 2019-20 and reported annual increase of milk production of different cattle varieties - Cross breed cattle 5.7%, Indigenous cattle: 6.9% and buffalo: 1.05%. This led to reduction in methane emission as well as reduction in methane emission per Kg of milk produced, while increasing the milk production in the country.[99]

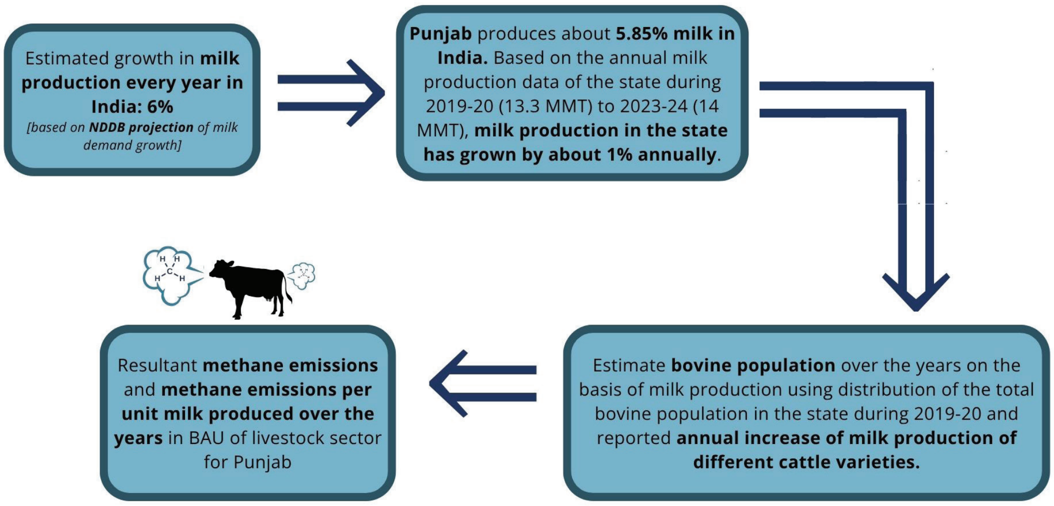


Figure 18: BAU Scenario Estimations for Livestock Methane in Punjab

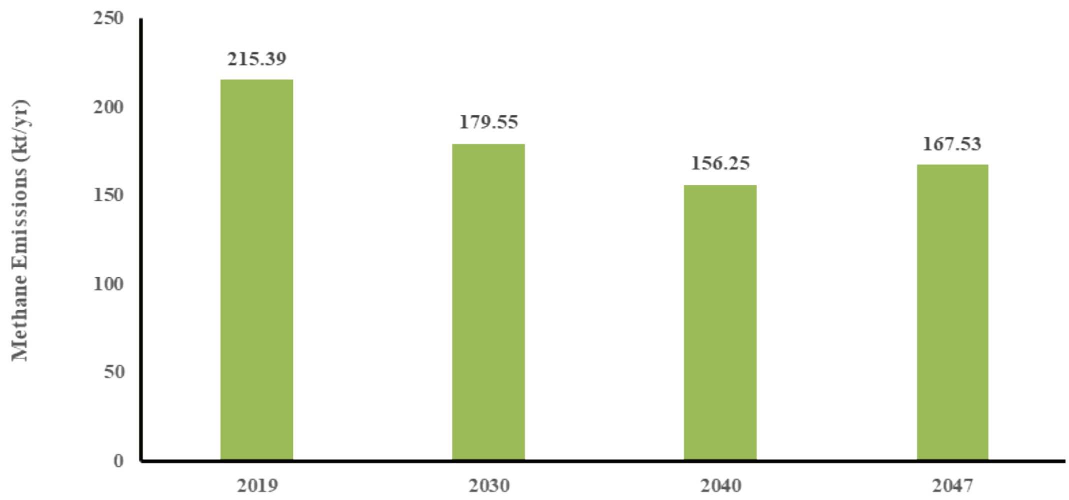


Figure 19: Estimated annual methane emission from livestock under BAU scenario

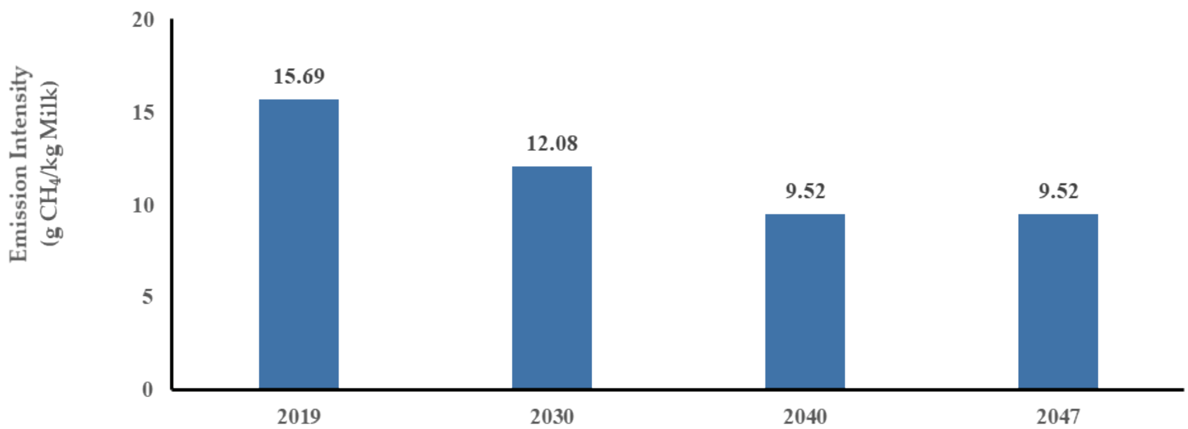


Figure 20: Estimated Annual Methane Emission per kg of Milk Produced under BAU Scenario

Alternate scenarios for Livestock sector

The State government supports different programs for the development of the dairy sector. The Crossbreed cattle breeding program (e.g. like Holstein-Friesian and Karan Swiss) is most advanced in the state under National Dairy Plan and Punjab Cattle Breeding Program followed by Buffalo breeding (e.g. Murrah and Nili Ravi) and indigenous cow breeding program like National Gokul Mission. This program helps to focus more on Crossbreed and Buffalo population in Punjab.

In addition to the cattle breeding programs, the state also supports the dairy industry by improving the availability, quality, and diversity of livestock feed. These programs aim to ensure a stable and nutritious supply of fodder for dairy animals, ultimately enhancing milk production. Some of these programs are National Fodder Development Program (NFDP), Rastriya Krishi Vikas Yojana (RKVY), Fodder Research and Extension of the Punjab Agriculture University, Kishan Fodder Development Program, Integrated Fodder Development Program etc. Different types of fodders have significant methane emission reduction potential from enteric fermentation of ruminants. Based on these, different scenarios to reduce future methane emission from the Livestock sector were designed.

ALT 1: Selective Breed Control

[Punjab Livestock Breeding Program, Rashtriya Gokul Mission (2014)]

Under the ALT-1 scenario, improved breed management is promoted by increasing the population of high-yielding cattle through initiatives such as the Punjab Livestock Breeding Program and the Rashtriya Gokul Mission (launched in 2014). The population of high-yeild cross-breed and indigenous cattle population was assumed to grow 2% annually in addition to BAU, while the growth of the buffalo population was kept as per of BAU. As per the changes in improved cattle population, total annual methane emissions were estimated to rise by approximately 13% in 2030, 42% in 2040, and 53% in 2047 compared to the BAU scenario (Figure 21 (a)). This increase is primarily due to the larger number of animals. However, the growth in cattle population also leads to a substantial rise in milk production, as the animals follow the breed-specific annual milk yield growth rates described earlier. As a result, total milk production is projected to reach approximately 43 MMT by 2047.

When methane emissions are evaluated relative to milk output, the emissions per kilogram of milk produced are notably lower under ALT-1 on account of better breed management (Figure 21 (b)). Specifically, compared to BAU, ALT-1 results in a reduction in methane emissions per kg of milk by 18% in 2030, 39% in 2040, and 38% in 2047 (Table 30).

ALT 2: Advanced Fodder for Dairy Cattle

[National Dairy Research Programme]

Fodder management is an important practice to reduce methane emissions from cattle while increasing milk production. The National Dairy Research Programme encourages cattle feeding with Advanced Fodder to reduce enteric methane emissions. Different types of fodders like legumes, maize-sorghum silage, mustard/soybean cake blended fodder, etc. can reduce the methane emission from enteric fermentation by about 15%. On the other hand, different studies related to milk production with livestock fodder management have established that the fodder management can increase milk production by 15-20%.[100,101] Thus, with the fodder improvement under ALT-2, it was assumed that the milk production in Punjab would reach 20.7 MMT by 2047. Accordingly, the annual methane emission per kg of milk production was estimated to decrease by about 30% under the ALT-2 scenario.

ALT 3: Improved Fodder for all Livestock

[Combined Strategy= ALT 1 + ALT 2]

The ALT-3 scenario represents an ambitious strategy aimed at maximising methane emission reductions by combining existing livestock management interventions. It builds on the ALT-1 scenario (which increases the high-yield cattle population through better breed improvement schemes) by additionally assuming that all cattle are fed improved fodder, as outlined in the ALT-2 scenario. This integrated approach reflects the maximum feasible adoption of current breed and fodder management policies.

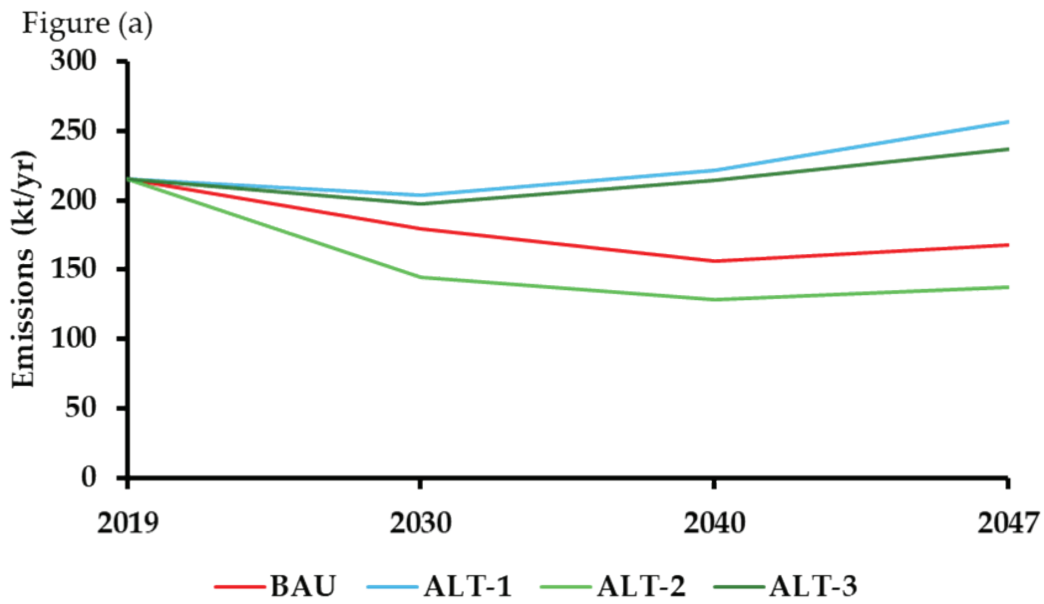
Under this scenario, methane emissions per kilogram of milk (emission intensity) are projected to decline significantly compared to the BAU scenario. Specifically, emission intensity reduces by 33% in 2030, 50% in 2040, and 52% in 2047 (Figure 21(b)), reflecting enhanced productivity from targeted interventions. There is tangible emission intensity reduction, however, the livestock population will increase, resulting in higher milk production, projected to exceed 50 MMT annually by 2047. Further, the growing livestock numbers also drive a rise in absolute methane emissions, by about 10% in 2030, 37% in 2040, and 41% in 2047 compared to the BAU scenario (Figure 21(a)). Nevertheless, due to the Punjab government's improved breed management initiatives, emission intensity would decline, helping to balance both emission control and food security for the state and the country.

It is also to be noted that there are challenges related to nutritive forage availability to all cattle breeds in Punjab, which might be a constraint to implement the ALT-2 and ALT-3 fully in the state. Some of the challenges are outlined below:

- **Fodder Deficit:** Punjab faces a 20–30% fodder shortage, limiting high-quality forage adoption. Silage and fodder banks require infrastructure investment.
- **Farmer Adoption:** Smallholders need training to optimise fodder management, as improper feeding can reduce yields or cause cattle health issues.
- **Land Competition:** Fodder crops compete with food crops. It necessitates efficient cultivation practices like intercropping.

Table 30: Description of ALT scenarios in the livestock sector and Projected Methane Emission Reductions

Scenarios	Reduction in annual CH_4 emission per kg of milk production compared to BAU		
	2030	2040	2047
ALT-1: Breed Management Increase in the population of high-yield cattle breeds	18%	39%	38%
ALT-2: Fodder Management It was assumed that all dairy cattle under the BAU scenario will be fed with advanced fodder such as maize-sorghum silage, soybean cake to reduce methane emission from enteric fermentation and increase milk production.	32%	31%	31%
ALT-3: Incorporating Breed Management with Fodder Management All livestock including those estimated to be produced under ALT-1 was estimated to be fed with advanced fodder and forages.	33%	50%	52%



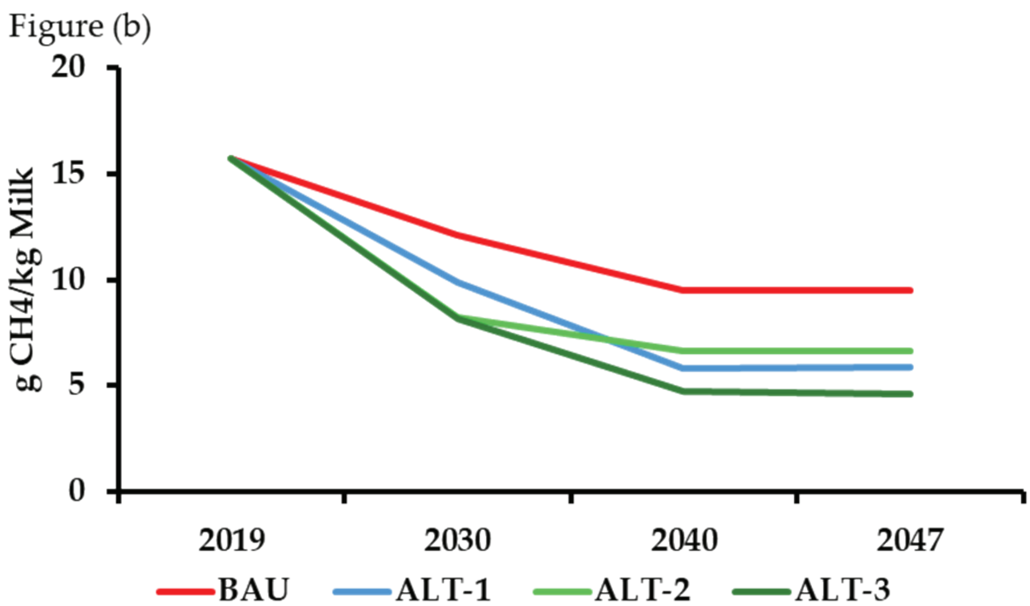
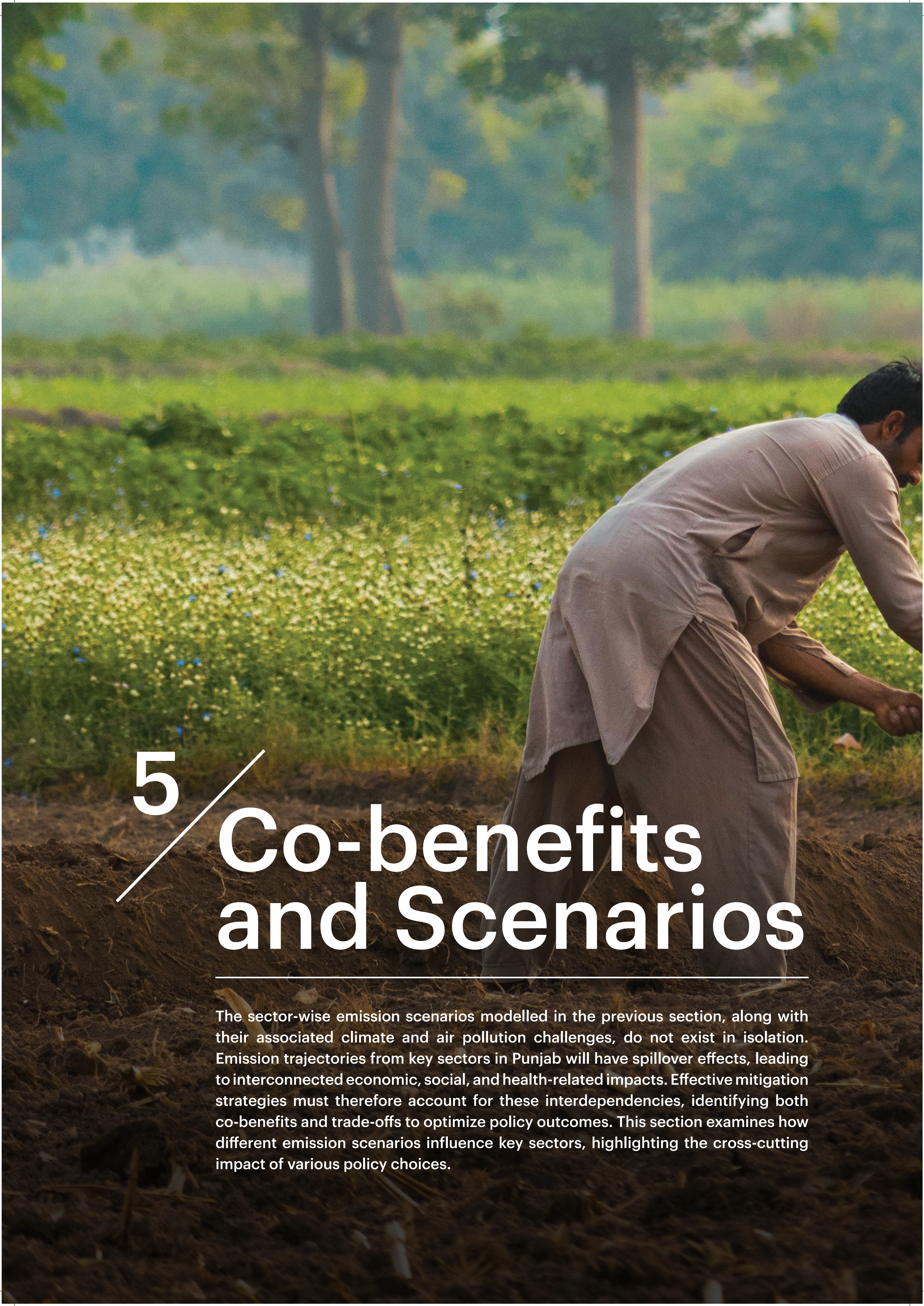


Figure 21: Estimated annual changes in (a) CH_4 emissions from the Livestock sector in Punjab under different scenarios (b) estimated annual CH_4 emission per kg of milk produced under different scenarios



5 Co-benefits and Scenarios

The sector-wise emission scenarios modelled in the previous section, along with their associated climate and air pollution challenges, do not exist in isolation. Emission trajectories from key sectors in Punjab will have spillover effects, leading to interconnected economic, social, and health-related impacts. Effective mitigation strategies must therefore account for these interdependencies, identifying both co-benefits and trade-offs to optimize policy outcomes. This section examines how different emission scenarios influence key sectors, highlighting the cross-cutting impact of various policy choices.

5.1 Impact of Heat Stress on Human Health and the Economy

Punjab is projected to face a sharp rise in temperatures—up to 4.5°C by the end of the century—with pre-monsoon highs reaching 5.8°C.[102] Winter maximums and annual minimum temperatures are also set to rise significantly, intensifying heat-related risks for vulnerable populations.[103]

Additionally, urban centres like Chandigarh[104] and Ludhiana[105] are particularly susceptible to the Urban Heat Island effect[106][107], which can increase cooling energy consumption[108] by up to 19% and water demand by nearly 4%, while also compromising groundwater quality and aquatic ecosystems.[109] This will also increase the demand for electricity. For every degree Celsius that temperatures rise in urban areas, electricity consumption increases by 0.45% to 4.6%.[110]

Short-lived climate forcers, such as methane, black carbon, and ozone precursors, exacerbate heat stress by directly warming the atmosphere and increasing ground-level ozone, a powerful greenhouse gas and air pollutant. Reducing SLCFs, therefore, offers a near-term strategy to mitigate temperature rise and the intensity of extreme heat events.

Sectoral interventions across industry, transport, waste, and residential sectors offer tangible pathways. In the industry sector, transitioning from coal to natural gas and deploying air pollution control devices can cut methane emissions by up to 54% and significantly reduce PM and SO_2. In transport, electrifying the vehicle fleet under a comprehensive EV policy could reduce CH_4 by 58% and NOx by 32%, curbing secondary pollutants like ozone that intensify heat and crop loss. Residential cooking, when complemented with biogas and/or solar adoption, reduces both CH_4 and BC significantly. In waste management, adopting composting and anaerobic digestion while limiting open burning is key to controlling methane and BC emissions. Together, these cross-sector measures can not only reduce the intensity and frequency of heatwaves but also yield co-benefits for food security, public health, and energy sustainability—making SLCF mitigation a critical pillar of Punjab's heat-resilience strategy.

5.2. Impact on livelihood through Food Security

Air pollution and climate change are increasingly threatening Punjab's agricultural productivity, food security, and rural livelihoods. In 2022, abnormal spikes in maximum and minimum temperatures led to an estimated 15–25% decline in crop yields and a 15% drop in milk yield in the livestock sector.[111] With agriculture contributing roughly 26% to Punjab's Gross State Domestic Product (GSDP), these shocks have substantial economic implications.[112]

A major driver of this disruption is rising ground-level ozone, a potent greenhouse gas and air pollutant formed through atmospheric reactions between nitrogen oxides (NO_x) and non-methane volatile organic compounds (NMVOCs).[113] Ozone is highly toxic to crops—damaging leaves, impairing photosynthesis, and reducing both yield and quality. Recent estimates show that wheat production losses due to ozone across the Indo-Gangetic Plain totalled 3.4 million tonnes between 2019–2021[114], translating into $923 million in economic losses, with Punjab among the most affected regions. These yield losses are further converted into production losses and economic losses in relation to crop commodity prices.[115]

In 2019, Punjab's transport and industry sectors accounted for 87% and 10% of the state's total NO_x emissions, respectively, making them key contributors to ozone formation. This reinforces the urgent need to reduce these precursors to protect Punjab's agricultural economy. Scenario modelling in this report indicates that under ALT4, a comprehensive electric vehicle (EV) transition, Punjab could reduce NO_x by 32% and NMVOCs by 28% by 2047. A phased, well-incentivized rollout, particularly through infrastructure support and strong enforcement, would play a pivotal role in limiting ozone formation, thereby safeguarding crop productivity and securing farmer incomes.

Table 31: Sectors with highest potential for controlling Tropospheric Ozone formation in Punjab

Sector	Contribution to NO_x Emissions (2019)	Key Issues	Suggested Control Measures
Transport	87%	Major source of NO_x and increasing influence on ozone due to NMVOCs sensitivity	Promote EVs, encourage non-motorized transport
Industry	10%	High NO_x contributor	Controlling fugitive emissions from solvent use

Beyond heat stress and agricultural disruption, targeted SLCP mitigation offers Punjab a suite of critical co-benefits. Reducing black carbon, methane, and ozone precursors can substantially improve public health by lowering rates of respiratory and cardiovascular diseases, particularly in vulnerable groups. Additionally, lower surface temperatures ease demand on power infrastructure, enhance energy efficiency, and help conserve water—especially vital in Punjab's urban centres facing heat island effects and growing water stress. In rural areas, improved livestock health, better waste management, and the promotion of clean energy solutions such as biogas and solar cooking can boost productivity and livelihoods. These measures, alongside their environmental benefits, also open new avenues for green jobs, circular economy opportunities, and access to emerging carbon markets—positioning Punjab as a frontrunner in subnational climate leadership.

6 / Sector-Specific Challenges

Each sector's ALT scenarios encounter unique challenges during planning and implementation. This section provides an in-depth analysis of the sector-specific obstacles. We have outlined the various challenges that the state may encounter in successfully implementing the most viable alternative scenarios, as illustrated in the chart below. This chart below is designed to clearly identify the most effective strategies across various sectors, as well as the challenges that authorities may encounter during implementation. By highlighting these challenges, we can pinpoint the areas that require focused attention to achieve the desired outcomes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6.1 Sector-specific Implementation Challenges

Transport Sector

The transport sector in Punjab faces significant challenges in transitioning to cleaner alternatives. Despite policy incentives, EV penetration remains low, with only around 21,000 EVs registered, most of which are two-wheelers. According to Vahan 4 data, EVs account for just 0.26% of Punjab's total vehicle stock, well below the national average of 5.59%, highlighting a substantial gap in uptake. This is compounded by inadequate charging infrastructure, with only 301 public charging stations across the state, leading to range anxiety and low consumer confidence. High costs of electric buses and limited local manufacturing capacity further impede progress.

Additionally, insufficient renewable energy availability for charging EVs, resistance to the scrappage policy due to lack of incentives, and limited scrappage and recycling canters add to other barriers. Hydrogen infrastructure faces high implementation costs and administrative hurdles, while the absence of established supply chains and enabling policies for H-CNG blending points to a larger need for coordinated policy support.

While the Punjab EV Policy 2023 includes a feebate model—penalizing polluting vehicles and rewarding cleaner ones—it lacks broader financial mechanisms such as low-interest loans or leasing schemes that could ease the upfront burden for consumers. The policy also does not outline a comprehensive strategy for battery recycling and disposal, raising long-term environmental concerns. Furthermore, there is no clear roadmap to integrate renewable energy into the EV ecosystem, which limits the full climate benefits of electrification.

Industry and Power sector

The industry sector in Punjab faces multiple challenges that hinder sustainable growth. Clusters of highly polluting industries, especially in Ludhiana and Jalandhar, along with illegal mining activities, contribute to environmental degradation, while weak monitoring systems limit enforcement. MSMEs also face knowledge gaps regarding energy-efficient technologies, while high costs of retrofitting infrastructure, such as for absorption chillers for waste heat utilization, , deter cleaner technology adoption. Punjab is home to over 1.6 lakh MSMEs, many of which are in sectors with significant energy-saving potential but lack the resources to upgrade. Challenges in accessing financial resources further increases the cost of technology upgradation. This is compounded by a lack of trust in new technological solutions within both the industry and financial sectors. Furthermore, new technologies often require reskilling of the workforce, which adds another layer of difficulty to upgrading industrial practices.

Residential sector

Punjab has not yet achieved a full transition to clean cooking options, particularly in rural and peri-urban areas. While LPG access has improved through schemes like PMUY, supply chain disruptions and the relatively high cost of refills continue to limit consistent usage. The adoption of cleaner alternatives such as improved biomass cookstoves, biogas systems, and solar cooking technologies remains slow due to entrenched preferences for traditional chulhas and open-fire methods, often perceived as more effective for local cooking styles. Uptake is further constrained by high upfront costs, limited awareness of long-term benefits, and a lack of trained personnel for maintenance—particularly in rural regions. Solar cookers face additional limitations in Punjab's foggy winters and monsoon months. To enable a meaningful shift, clean cooking solutions will need to be supported by coordinated behaviour change campaigns, improved last-mile delivery of LPG and PNG, and targeted financial incentives for household-level adoption.

Waste sector

The waste sector in Punjab faces mounting pressure from growing urbanization and rising waste volumes. While collection is nearly universal at 99.8%, only 41% of the waste is processed, with 59% landfilled, resulting in high emissions and environmental degradation. Inefficient diversion of waste to MRFs, high operational costs of waste-to-energy plants, and limited composting and anaerobic digestion facilities compound the problem. Additional challenges include the high carbon intensity of waste combustion, limited market demand for compost and biogas products, and insufficient waste collection and transportation infrastructure. Scaling up composting, anaerobic digestion, and recycling requires significant investments in infrastructure and technology, as well as robust systems for consistent waste collection and source segregation. Limited awareness and public participation in proper waste disposal and segregation practices also pose a challenge, as community engagement and behaviour change are crucial for minimizing open burning and optimizing waste diversion. Addressing these barriers will require a holistic approach that prioritizes low-emission processing methods, upgrades waste handling infrastructure, and fosters public awareness to effectively reduce the environmental impact of waste management in the state.

Agriculture sector

Punjab's agriculture remains heavily skewed towards rice, with the crop accounting for nearly 40% of the gross cropped area in 2020–21.[116] While the state ranks high in yield, the productivity of rice and wheat has plateaued, and the current cropping pattern is increasingly becoming economically and ecologically unsustainable.[117] Continued paddy cultivation places pressure on depleting groundwater resources, especially for marginal and small farmers who rely on submersible pumps. The MSP regime reinforces this dependence, discouraging diversification into less water-intensive crops. Adoption of sustainable practices such as Direct Seeding of Rice (DSR) limited due to high upfront costs, low awareness, lack of training, and weak market linkages. Farmers face challenges accessing credit and are highly sensitive to costs due to low profit margins. The absence of enabling infrastructure, and visible economic returns has further constrained the shift to alternative cropping systems. As a result, yields have stagnated, and resource degradation continues.

Livestock sector

The livestock sector in Punjab faces declining populations having reduced by 13% between 2012 and 2019. The primary reason is that dairy farmers now often choose to go for high-yielding animals like the Holstein Friesian breed, which have more lactations, and produce 10,000 to 12,000 litres of milk in each lactation period. Adding to this, the reduced availability of grazing lands caused majorly by urbanization, degradation of Panchayati lands, migration by dairy farmers to look for better pastures, encroachment on designated grazing areas, and disputes complicates open grazing practices. Risks of overgrazing, land-use conflict, reduced agricultural productivity and land degradation persist due to insufficient land availability. Additionally, challenges like infrastructure needs, disease management, and farmer adaptation to open grazing practices require strong policy support, financial incentives, and effective implementation strategies to achieve the targeted emission reductions. It is also to be noted that there are challenges related to nutritive forage availability for all cattle breeds in Punjab, which might be a constraint to fully implementing ALT-2 and ALT-3 in the state. Punjab faces a 20–30% fodder deficit, which limits the adoption of high-quality forage; overcoming this requires investments in silage and fodder bank infrastructure. Moreover, smallholder farmers often require training and capacity-building support to optimize fodder management, as improper feeding practices can lead to reduced yields or cattle health issues. Another major constraint is land competition, as fodder crops compete with food crops for limited land resources. This necessitates the promotion of efficient cultivation practices such as intercropping to ensure balanced land use while meeting fodder demands.

Table 32: Summary of challenges for sector-specific strategies

Sector	Strategies	State Specific Challenges
Agriculture	Ban on burning of straw/ agriculture residue	Monitoring the ban of crop residue burning Development of market for agricultural residue
	Reduction in land under paddy cultivation & crop diversification	Lack of incentives to crop diversification
Transport	Promotion of EVs	High upfront costs of EVs Insufficient charging infrastructure for EVs, and Availability of quality power supply
	Promotion of electric buses	
	Increased biofuel	Lack of Proper infrastructure – Collection, storage and transportation of feedstock Supply constraints of biofuels
	Hydrogen fuel	Lack of Policy Support Lack of Proper infrastructure – Collection, storage and transportation of feedstock.
Industry	Setting up co-generation power projects and common boilers for MSME clusters to use biomass,	Lack of Proper infrastructure – Collection, storage and transportation of feedstock. Resistance from small industries due to cost concerns
	Switch to Natural gas	High capital investment needed for switching to natural gas. Inconsistent supply of natural gas in some regions. Challenges in integrating renewable energy with existing industrial setups.
	Replacement of coal with paddy straw pellets in brick kilns	Lack of Proper infrastructure – Collection, storage and transportation of feedstock
	Promotion and utilisation of renewable energy	Increase in the population growth and energy demand Technical challenges to use RE in certain industries
	Use of hydrogen as fuel	High costs and technical challenges of using green hydrogen in existing processes. Need for infrastructure development for green hydrogen production and supply. Lack of clear policy directives for hydrogen usage.
	Adoption of clean production practices and enhanced use of resource-efficient bricks	High costs in retrofitting existing infrastructure and technical feasibility for some brick kilns

Sector	Strategies	State Specific Challenges
Power	Increase the share of renewable energy in the energy mix	High upfront investments
Residential Cooking	Provision of LPG to households	Continuation of existing efforts by the state to ensure 100% LPG penetration in rural and urban areas
	Provision of electric cooking stoves/ induction stoves	Increase in the power demand Expensive cookware
Waste	Door-to-door collection, segregation at the source	Lack of awareness of segregation at household level and collection centres. Lack of Collection Infrastructure.
	Processing of municipal solid waste	Lack of segregation Inconsistent collection systems High processing costs.
	Bioremediation of legacy waste	Economic viability Possibility of incomplete remediation.
	Waste-to-Energy (WTE) Plants	Inefficiency in energy generation – due to low calorific value in majority of waste materials Possible Emissions from burning of waste

7 Conclusion & Way Forward

Based on the study analyses, Punjab has substantial potential to reduce non-CO_2 pollutants, particularly SLCPs, emissions across multiple sectors. Such mitigation will contribute towards achieving India's climate goals and overall sustainability of the state economy, besides reducing the risk of increasing heat stress. However, any mitigation strategy for any pollutants will need clear policy targets for fruition which, in turn, will hinge on granular understanding of the sector-specific emissions landscape. The report highlights the emission reduction potential of ongoing and proposed policies. Table 33 presents a sectoral overview of SLCFs and recommended strategies to control emissions.

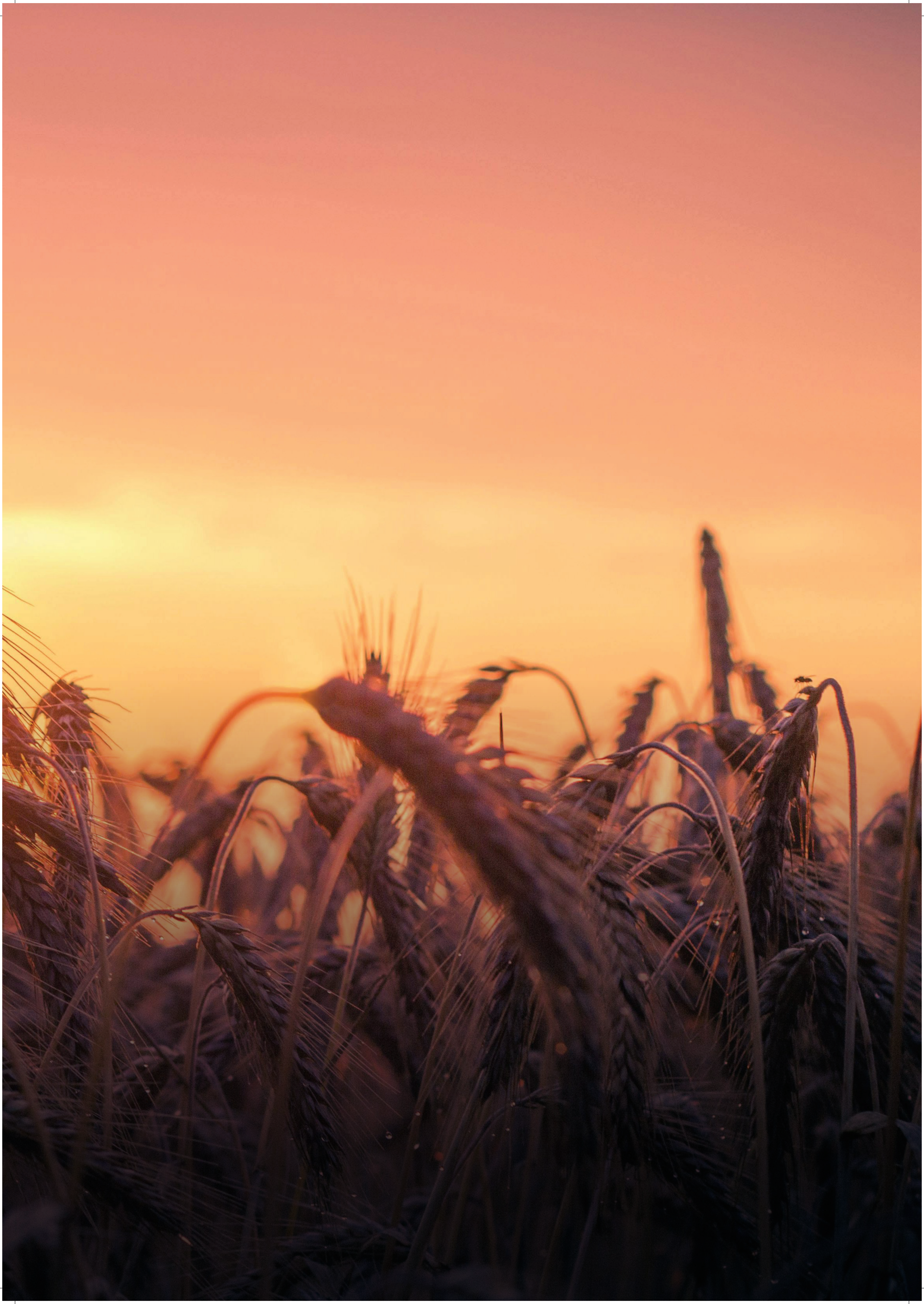

Table 33: Summary of emission reduction under different alternative scenarios compared to BAU in 2047

Sector	Strategies	$PM_{2.5}$	SO_2	NO_x	CO	NMVOCs	BC	CH_4
Transport	ALT 1	-12%	-17%	-13%	-24%	-16%	-14%	-26%
	ALT 2	-31%	-19%	-26%	-41%	-22%	-25%	-52%
	ALT 3	-6%	-8%	-9%	-10%	-6%	-13%	-14%
	ALT 4	-37%	-25%	-32%	-47%	-28%	-31%	-58%
Industry (Power, DG, Brick)	ALT 1	-76%	-54%	-43%	-70%	-25%	-37%	-23%
	ALT 2	-17%	-8%	-34%	-10%	-18%	-34%	-22%
	ALT 3	-15%	-9%	-34%	-9%	-21%	-35%	-26%
Residential Cooking	ALT 1	-	-	-	-	-	-	-
	ALT 2	-	-	-	-	-	-	-
	ALT 3	-2.94%	-5.13%	-3.91%	-4.12%	-3.80%	-	-3.70%
Agriculture	ALT 1	-	-	-	-	-	-	-36%
	ALT 2	-	-	-	-	-	-	-78%
	ALT 3	-	-	-	-	-	-	-91%
Livestock	ALT 1	-	-	-	-	-	-	-38%
	ALT 2	-	-	-	-	-	-	-31%
	ALT 3	-	-	-	-	-	-	-52%
Waste	ALT 1	-0.8%	-0.5%	-	-	-	-8.3%	-0.5%
	ALT 2	55.8%	54.9%	-	-	-	-16.7%	-1.5%
	ALT 3	116.0%	114.6%	-	-	-	25.0%	-2.8%

Note: Increase in emissions of $PM_{2.5}$, BC and SO_2 for waste sector are marginal in absolute terms.

Table 34 below provides a summary of the major sectors – industry, transport, agriculture and livestock – contributing towards SLCF emissions in Punjab. It also presents an overview of which policies should be prioritised for SLCF mitigation in these sectors.

Table 34: Sector-wise Overview of Key SLCFs, Mitigation Strategies, and Expected Outcomes and the Description of Implementation Efforts.

Sector	Key Pollutants	Mitigation Strategies	Expected Outcomes	Description of Implementation Efforts
Agriculture	PM_{10}, $PM_{2.5}$, BC, CH_4	Assured 100% coverage in implementation of ban on crop residue burning Promoting improved farming practices and crop diversification (ALT 1,2, and 3)	Elimination of air pollutant emissions Drastic reductions in CH_4 emissions, 75-92%	▪ Improved technical and financial assistance for transitioning away from crop residue burning ▪ Continuation of state efforts to monitor crop residue burning. Eventual involvement of smart technologies to improve MRV. ▪ Financial incentives and training sessions on alternate farming practices such as DSR ▪ Improved MSP and government procurement for alternate crops over paddy
Livestock	CH_4	Adoption of advanced fodder while increasing indigenous and cross bred cattle, and keeping buffalo growth constant (ALT 3)	Substantial reduction in methane emission intensity, up to 52%	Invest in fodder management programs and promote growth of indigenous and cross bred cattle.
Industry	PM_{10}, $PM_{2.5}$, BC, SO_2, NO_x, NMVOC	▪ Transition to Natural Gas (ALT 1) ▪ Expanding the adoption of REBs ▪ Using renewable energy in the power sector	Significant reductions in key pollutants (up to 82% reduction potential), improved energy efficiency; centralized monitoring	▪ Financial incentives and support for large-scale transformations, particularly to SMEs ▪ Monitoring technologies for emission reductions ▪ Promotion of renewable energy and fuels through regulation and subsidies ▪ Financial penalisation for inefficiency in plant emissions
Transport	NO_x, NMVOC, BC, $PM_{2.5}$	Implementation of Vehicle Scrappage Policy (ALT 2) Expansion of EVs and public transport (ALT 1 and ALT 4)	▪ Reduction in NOx and VOC emissions; decreased secondary pollutants like ozone and aerosols (over 25%) ▪ Reduction in air pollution through reduced PM emissions (over 30%) ▪ Additional more than 50% reduction in CH_4, leading to reduced climate impact	▪ Improved criteria and assessment for vehicle fitness, along with ensuring consistent evaluation and certification ▪ Improved EV charging infrastructure and grid connections ▪ Ensuring quality power supply

Sector	Key Pollutants	Mitigation Strategies	Expected Outcomes	Description of Implementation Efforts
Residential (Cooking and Waste)	NMVOC, PM10, PM2.5, BC, CH4	▪ Continued expansion of LPG (BAU) ▪ Promotion of cleaner fuels in cooking (ALT 1 and 2) ▪ Closure of landfills through remediation efforts (BAU) ▪ Promotion of sustainable waste processing methods for MSW (ALT 1,2, and 3) ▪ Ensuring source segregation	▪ Starc reductions in particulate matter (PM), BC, and VOC emissions from the cooking sector ▪ Significant reduction in BC and CH4 emissions from waste	▪ Continued expansion of LPG through policy efforts ▪ Financial incentives and awareness programs to adopt cleaner fuels for cooking in rural areas ▪ Implementation of existing policy plans and targets to close landfills ▪ Improve segregation through awareness, technical tracking of waste, and financial penalties ▪ Financial and regulatory support to set up sustainable waste management infrastructures ▪ Ensure offtake of products from waste management e.g., recycled plastic, energy generated etc.

It is evident that to meet its climate and air quality targets, Punjab must adopt an integrated approach that prioritizes renewable energy expansion, green industrial transformation, widespread electric vehicle deployment, and sustainable agricultural practices. Significant emissions reductions can be achieved by strengthening the policy landscape and fast-tracking targeted interventions across key sectors—transport, industry, agriculture, residential, and waste—while ensuring that economic development remains inclusive and resilient.

To drive this transformation, Punjab will need to invest in coordinated strategies involving regulatory reforms, financial incentives, technology deployment, and capacity building, tailored to address state-specific challenges. In parallel, substantial infrastructure development will be critical for success. This includes scaling up public EV charging networks, expanding clean energy access for households, modernizing irrigation and crop diversification systems, and developing efficient waste segregation and processing facilities.

These infrastructure enhancements will play a foundational role in enabling the implementation of climate-resilient solutions and unlocking Punjab's mitigation potential. Engaging with private sector stakeholders, leveraging national mechanisms such as carbon markets, and encouraging cross-sectoral collaboration will further amplify the impact of state interventions. Together, these efforts can chart a clear path toward a cleaner, more sustainable, and healthier future for the people of Punjab.

8

Annexure: Sector-specific Methodologies for Estimating Emissions

Industry

The approach for estimating emissions from the industrial sector used in this study is based on the activity data of fuel consumption in the manufacturing processes and the type of fuel consumed. Emissions of particulate matter (PM_{10} & $PM_{2.5}$), SO_2, BC, CH_4, and NOx into the ambient atmosphere mainly occur during the combustion process. The data concerning coal consumption is obtained from the annual survey of industries, providing a comprehensive insight into fuel usage patterns in the industrial sector.

The emissions from the industrial sector are estimated using the fuel consumption data and emission factor; the following is the equation to estimate industrial emissions:

$$Ep = Cf \times EF$$

Where Ep is the emission of pollutant p, Ef is the emission factor of the fuel consumed (Table 35), and Cf is the fuel consumed by the industry.

Table 35: Emission Factors (Kg/t) of Different Pollutants from Different Fuels Used in Industries in Punjab

Emission Factor (Kg/t)	Pet Coke	Charcoal	Wood	Diesel	Furnace Oil	Natural gas	LPG	Coal	LDO	Rice Husk	Bagasse
PM_{10}	3.73	200	17.3	0.24	2.592	0.0001216	2.1	187.6	0.24	5.3	8.1
$PM_{2.5}$	2.13	70	15.743	0.216	1.73664	0.0001216	2.1	65.66	0.216	3.445	5.265
SO_2	13.46	9.75	0.2	9.405	37.68	0.0000096	0.4	9.75	33.858	0.11	0.18
NO_x	3.82	12	1.3	1.2	6.6	0.0016	1.8#	4.5	1.2	0.19	0.36
CO	2.73	160	126.3	0.6	0.6	0.001344	0.252#	0.3	0.6	14.05	12.39
NMVOCs* (kT/PJ)	0.01	0.01	0.015	0.004	0.005	0.003	-	0.01	0.004	0.015	0.048
BC	0.0165	0.2783	0.191	0.004	0.02928	3.96623E-07	4.96124E-07#	0.2046	0.004	0.1747	0.2437
CH_4* (kT/PJ)	0.01	0.01	0.01	0.003	0.003	0.0471	0.001	0.001	0.003	0.003	0.011

*Sources: SA Six cities, CPCB, Coal: based on ash content and sulphur content for PM and SO_2, Rice Husk:[118] *Gains Asia, #Kg/10^6 m^3*

Table 36: Estimated Emissions from Industries in Punjab

Industry	PM_{10}	$PM_{2.5}$	SO_2	NO_x	CO	NMVOC	BC	CH_4
Total Emissions (kT/year)	181.5	76.3	51.7	20.6	409.9	11.97	2.8	104.6

Note: The estimated emissions are solely from the combustion of fuels PCB provides.

Brick Kilns

This study has employed an approach based on brick production and production technology to estimate emissions from brick kilns. The production-based approach utilises the weight of each brick as the activity data. The cumulative weight of bricks produced annually across all kilns was used to estimate emissions from the brick kiln industry.

Emissions were calculated using the following equation:

$$Ep = B_T \times Ef$$

Where, **Ep** is the emission of pollutant *p*, **BT** is the cumulative weight of bricks produced annually, and Ef is the production-based emission factor.

According to the discussion with the PSCST, the primary technology utilised for brick production in Punjab is the Zig-Zag brick firing technology. The total weight of bricks produced using this technology was estimated based on the total number of bricks produced annually in a region and the weight of the fired brick. After consultation with experts and drawing from TERI's experience in this sector, we assumed the weight of the fired brick to be 3 kg.

Emission factors for different pollutants associated with various production technologies were selected after reviewing published literature including studies by GAINS*[119],[120],[121] (Table 37)

Table 37: Technology-wise Emission Factors for Different Pollutants from Brick Kilns

Technology	Emission factor (g/Kg of fired bricks)							
	PM_{10}	$PM_{2.5}$	BC	SO_2	NOx*	CO	NMVOCs*	CH_4*
Zig-Zag	0.26	0.13	0.04	0.32	0.00004	1.47	0.1	0.06

The total emissions estimated from brick kilns in Punjab are summarised in Table 38.

Table 38: Estimated Emission from Brick Kilns in Punjab

District	PM_{10}	$PM_{2.5}$	BC	SO_2	NO_x	CO	NMVOCs	CH_4
Amritsar	0.65	0.32	0.10	0.79	0.00	3.65	0.25	0.15
Barnala	0.17	0.08	0.03	0.21	0.00	0.95	0.06	0.04
Bathinda	0.51	0.25	0.08	0.62	0.00	2.86	0.19	0.12
Faridkot	0.18	0.09	0.03	0.22	0.00	0.99	0.07	0.04
Fatehgarh Sahib	0.12	0.06	0.02	0.14	0.00	0.65	0.04	0.03
Fazika	0.42	0.21	0.06	0.52	0.00	2.38	0.16	0.10
Ferozepur	0.20	0.10	0.03	0.25	0.00	1.13	0.08	0.05
Gurdaspur	0.54	0.27	0.08	0.66	0.00	3.04	0.21	0.12
Hoshiarpur	0.24	0.12	0.04	0.29	0.00	1.35	0.09	0.06
Jalandar	0.44	0.22	0.07	0.54	0.00	2.46	0.17	0.10

District	PM_{10}	$PM_{2.5}$	BC	SO_2	NO_x	CO	NMVOCs	CH_4
Kapurthala	0.11	0.06	0.02	0.14	0.00	0.64	0.04	0.03
Ludhiana	0.81	0.41	0.13	1.00	0.00	4.60	0.31	0.19
Mansa	0.36	0.18	0.06	0.44	0.00	2.04	0.14	0.08
Moga	0.44	0.22	0.07	0.54	0.00	2.50	0.17	0.10
Pathankot	0.22	0.11	0.03	0.27	0.00	1.23	0.08	0.05
Patiala	0.16	0.08	0.03	0.20	0.00	0.93	0.06	0.04
Ropar	0.15	0.08	0.02	0.19	0.00	0.87	0.06	0.04
Sangrur	0.36	0.18	0.06	0.44	0.00	2.04	0.14	0.08
Sri Muktsar Sahib	0.21	0.11	0.03	0.26	0.00	1.21	0.08	0.05
SAS Nagar	0.60	0.30	0.09	0.74	0.00	3.41	0.23	0.14
SBS Nagar	0.27	0.13	0.04	0.33	0.00	1.51	0.10	0.06
Tarantran	0.51	0.25	0.08	0.63	0.00	2.88	0.20	0.12
TOTAL	**7.67**	**3.83**	**1.18**	**9.43**	**0.00**	**43.34**	**2.95**	**1.77**

Power Plants

The equation used for estimation of emissions from coal-based power plant is,

$$[E_{PM}]_c = \sum_{(a=1)}^{n} [P_c]_a \times [A_c]a \times (1 - fb_r) \times M \times (1 - RE_a)$$

$$[E_{Pg}]_c = \sum_{(a=1)}^{n} [P_c]_a \times EF_{pg} \times (1 - RE_a)$$

Where, EPM is the emission of particulates, Epg is the emission of gaseous pollutants, [Pc] a is annual coal consumption in plant a, [Ac]a is ash content of coal in TPP a, fbr is the ratio of bottom ash to fly ash, M is the particulate mass fraction (0.4 for $PM_{2.5}$ to PM_{10} and 0.75 for PM_{10} to total particulates following the guidelines of USEPA[122]), REa is the efficiency (%) of installed air pollution emission control equipment at TPP a and EFpg is the emission factor of the particular gaseous pollutant (p) from TPP. The emission factors used for calculation of emissions from coal and biomass-based power plants are provided in (Table 39).

Table 39: Emission Factors Used for Emission Estimation of Coal- and Biomass-based Thermal Power Plants

Pollutant	Emission factor	Pollutant	Emissions Factors (kT/PJ) #
		PM_{10}	0.2136
SO_2 (Kg/t) *	19.5* S	**$PM_{2.5}$**	0.1848
NO_x (Kg/t) **	4.50	**SO_2**	0.0169
CO (Kg/t) **	0.30	**NO_x**	0.13
NMVOCs (Kg/t) ***	0.2713	**BC**	0.0072
NMVOCs (kt/PJ)	0.01	**NMVOCs**	0.015
BC (kt/PJ)	0.00263	**CO**	0.1
CH_4 (kt/PJ)	0.001	**CH_4**	0.003

The annual coal and biomass consumption (Pc) in each Thermal Power Plant (TPP) during 2019 was sourced from the CEA, 2020 database and data shared by the PSCST. The total annual coal (domestic and imported) consumed in TPPs in Punjab during 2019 amounted to 12.1 Mt. All coal-based TPPs in Punjab are equipped with Electrostatic Precipitators (ESPs) to control particulate matter emissions. The ash content (Ac) of domestic coal consumed at each TPP and the annual ESP efficiency data of each TPP were also collected from the CEA database[123]. The sulphur content of domestic coal was considered as 0.5%. Studies suggest that the sulphur content of Indian coal ranges between 0.28% and 0.63%. Indonesia, Australia, and South Africa account for over 80 percent of India's coal imports[124]. The average ash and sulphur content of imported coal were taken as 15% and 0.63%, respectively. A 20% ratio of bottom to fly ash was applied following AP-42. The estimated emissions from power plants are provided in Table 40 and 41.

Table 40: Total Emissions (kt/Yr) from Coal-based Power Plants during 2019 in Punjab

	PM_{10}	$PM_{2.5}$	NO_x	SO_2	CO	CH_4	NMVOCs	BC
Gh TPP (Leh.Moh.)	0.61	0.24	2.91	6.31	0.19	3.09	0.18	0.41
Goindwal Sahib TPP	0.84	0.34	4.02	8.71	0.27	4.26	0.24	0.56
Rajpura TPP	4.56	1.83	23.85	54.03	1.59	25.28	1.44	2.62
Ropar TPP	0.70	0.28	3.32	7.19	0.22	3.52	0.20	0.46
Talwandi Sabo	5.57	2.23	28.54	64.11	1.90	30.26	1.72	3.98

Table 41: Emissions from Biomass-based Power Plants during 2019 in Punjab

Pollutant	Emissions (kt/yr)
PM_{10}	6.28
$PM_{2.5}$	5.43
NO_x	3.82
SO_2	0.50
CO	2.94
CH_4	0.09
NMVOCs	0.35
BC	0.21

Transport

The equation to estimate vehicular tailpipe emission in the transport sector is,

$$E_p = \sum_{c=1}^{n}\sum_{s=1}^{4} VKT_{c,s} \times EF_{c,s,p} \times \varepsilon_{c,s} \times n_c$$

Where, Ep is the total emission of a pollutant (p); c is the type of vehicle; s is the emission control norm (BSI to BSIV); VKT is the daily Vehicle Kilometre travelled by vehicle type c; EF is the emission factor of pollutant p and ε is the percentage of vehicle under an emission control norm (s) and n is the total number of vehicles in vehicle type c. The methodology of calculating emissions from the sector is explained in **(Figure 20)**

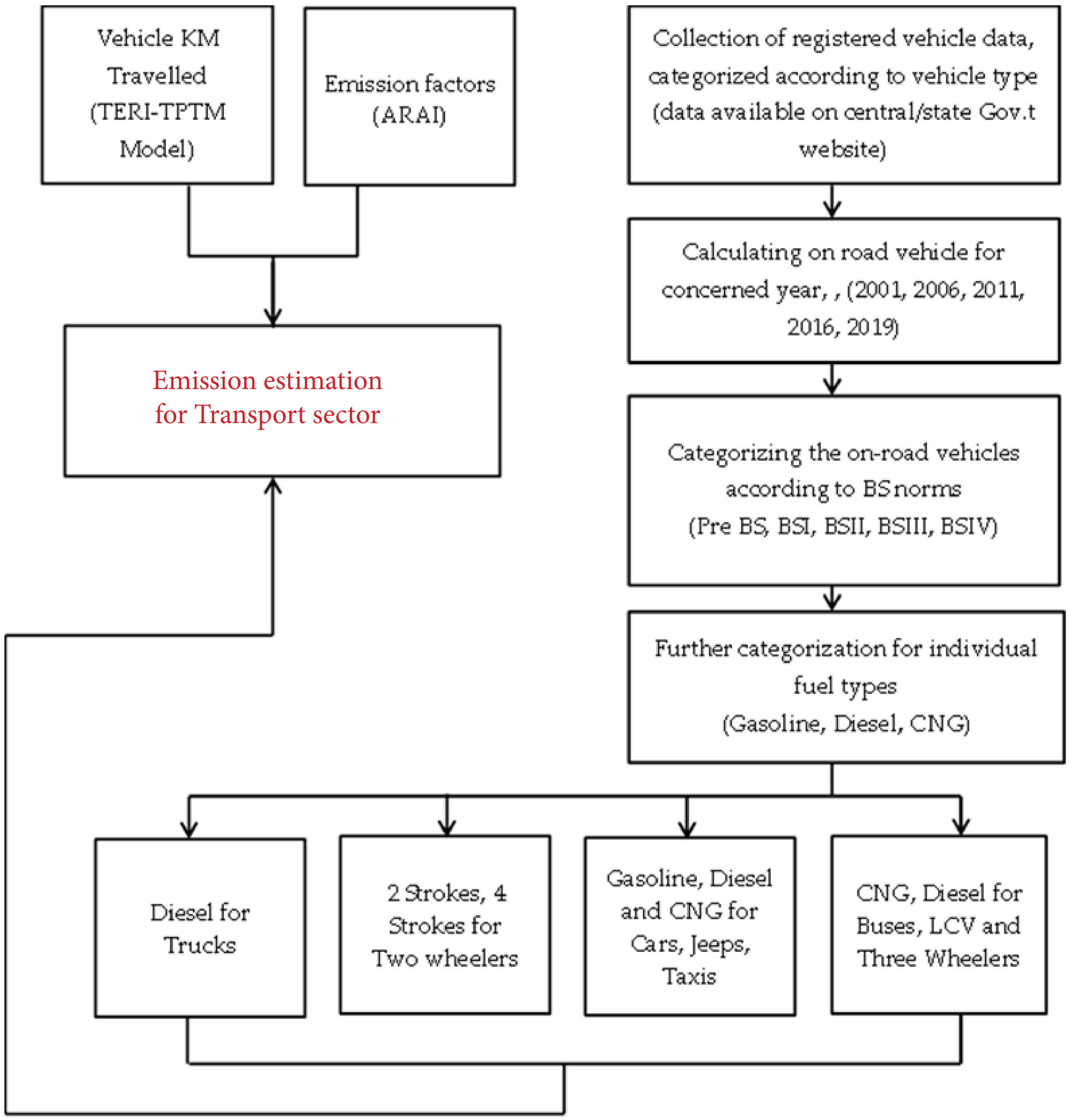

Figure 22: Methodology for estimating emissions from the transport sector

The estimated state level annual Vehicle Kilometre Travelled (VKT) of different categories of vehicle during 2019 was adopted from the TERI-Transport Model (TERI-TPTM) (Table 39). The model first estimates the total transport demand in Punjab, which is an aggregation of the projected passenger and freight demand, defined as the annual Billion Passenger Kilometres (BPKM) and Billion Tonne Kilometres (BTKM) respectively.

Passenger Demand (BPKM): For arriving at the total passenger demand a multi- step approach is followed. Firstly, the vehicle ownership is projected based on socio-economic variables such as GDP and population. The vehicle ownership is then disaggregated for urban and rural areas. Further, based on the assumptions of fuel type, fleet utilisation and vehicle occupancy for different vehicle segments (two wheelers, three wheelers, four wheelers, buses and rail) the annual BPKM is calculated for both urban and rural areas separately. Lastly, the total annual BPKM at pan India level is arrived at by the summation of urban and rural BPKM.

Freight Demand (BTKM): For arriving at the total freight demand, a similar approach is followed with the differentiating factor being the consideration of sectorial GDP in the estimation of commercial vehicle ownership. The total annual BTKM is computed as an aggregation of BTKMs of LCVs and HCVs.

Table 42: TERI-TPTM Model Simulated Daily VKT of Different Types of Vehicles

VKT (Km/day)	2W	3W	Car	LDV	HDT	HDB
2019	23	135	61	81	237	191

2W: 2-wheeler; 3W: 3-wheeler; LDV: Light Duty Vehicle; HDB: Heavy Duty Bus; HDT: Heavy Duty Truck.

It was assumed that, after introduction of one BS emission norm, the vehicles under lower BS emission norm were not sold in the market. The lifespan for private (2W, 3W, Cars) and commercial (Trucks, Buses, LMV, Tractors) vehicles was assumed as 15 and 20 years, respectively. This was used to estimate the total number (n) of different types of vehicles under different emission norms during a particular year from the cumulative annual registered vehicle data published by the MoRTH (2020) for Punjab.[125] The emission factors (EF) of PM_{10}, $PM_{2.5}$, NO_x, SO_2, hydrocarbon, CO, BC, and CH_4 for this exercise were adopted from ARAI (2008) and IPCC (2006).

Table 43: Emission Estimates in kt/year from the Transport Sector in Punjab

Vehicle Type	PM_{10}	$PM_{2.5}$	BC	NO_x	SO_2	CO	NMVOC
Truck	9.4	9.1	1.9	105.7	0.3	65.5	58.2
Tractor/Trailer	1.2	1.2	0.2	13.1	0.0	8.0	4.8
Bus	1.0	0.9	0.2	11.7	0.0	9.4	0.4
Cars	1.1	1.1	0.2	17.3	0.3	38.1	5.4
MUVs	0.5	0.5	0.1	4.0	0.0	3.7	0.7
2 wheelers	10.5	10.2	0.6	58.0	0.1	279.7	95.2
3 wheelers	0.6	0.6	0.1	2.3	0.2	5.2	1.1
LCVs	5.5	5.3	1.1	49.7	0.4	50.4	13.2
Totals	**29.7**	**28.9**	**4.4**	**261.7**	**1.3**	**460.0**	**179.0**
	CH_4						
Transport	**1.44**						

Diesel Generator Operation

The emission inventory for DG sets for 2019 is calculated based on diesel consumption in DG sets (activity data) and emission factor (adopted from AP-42, USEPA). Sector-specific fuel consumption is derived using total annual diesel consumption in India and the percentage share of each sector in total fuel usage. Annual diesel consumption in India is taken from MoPNG's annual reports, and sector-specific fuel consumption percentage share is used from the PPAC report 2021. Further, emissions are estimated using equations below:

$$E_d = F_d \times Cal_d$$

$$E_{DG} = E_d \times EF$$

Where Ed is the total energy equivalent of the diesel fuel consumed by DG sets annually, Fd is the total fuel consumed by DG sets annually, and Cald is the calorific value of diesel, which is 45.5 MJ/Kg.

Tailpipe emission control devices and technologies are not included in current emission estimates. According to expert interviews and literature reviews, there is limited data on the number of diesel generator sets equipped with these devices. But better devices to control emissions from exhaust pipes have been made and are expected to be used more in the future. Pollutant-wise emission factors are taken from AP-42, USEPA, provided in (Table 44)

Table 44: Emission Factor for DG sets as per AP-42, USEPA

Pollutants	Emission Factor (g/kwh)
PM_{10}	0.5
$PM_{2.5}$	0.4
SO_2	0.4
NO_x	6.8
CO	1.5

*Conversion of ng/J -> g/Kg = 0.0036

Emissions for various pollutants in the state of Punjab are shown in below table (Table 45).

Table 45: Emissions (kt/year) from the Operation of Diesel Generators in Different Sectors in Punjab in 2019

	PM_{10}	$PM_{2.5}$	BC	NO_x	SO_2	CO
Agri Pump sets	0.12	0.10	0.04	1.66	0.11	0.36
Mobile towers DG sets	0.06	0.05	0.02	0.83	0.05	0.18
Power generation						
Industrial DG sets	0.18	0.15	0.06	2.50	0.16	0.54
Commercial DG sets	0.10	0.08	0.03	1.39	0.09	0.30
Residential DG sets	0.04	0.03	0.01	0.56	0.04	0.12
Total	**0.49**	**0.41**	**0.16**	**6.93**	**0.46**	**1.49**

Residential

$$[E_P]_R = \sum_{s=1}^{n} \sum_{f=1}^{6} Pop_{(s,f)} \times C_{(s,f)} \times EF_{(f,p)}$$

The basic equation employed for emission estimation from the residential sector is,

Where, $[E_p]_R$ is the emission of a particular pollutant (p) from the residential sector, $Pop_{(s,f)}$ is the population of a state using a particular fuel (f), $C_{(s,f)}$ = State specific per capita consumption of a particular fuel, $EF_{(f,p)}$ = Emission factor of the particular pollutant (p) of the particular fuel type (f). Six major fuels those are used in the residential households for cooking purposes is included in this emission inventory estimation – a) Fuel wood, b) dung cake, c) crop residue, d) coal, e) kerosene and f) LPG. State specific population of Punjab during 2019 was taken population projection report for India and states[126].

State specific monthly per capita consumption of different fuels ($C_{s,f}$) in the rural and urban areas for Punjab is taken from NSSO (2014) report[127]. Electricity used in the residential sector has no reported emission of air pollutants, so it is not considered during the preparation of present emission inventory. On the other side, emissions from the PNG and gobar gas uses in residential sector are not considered owing to their very low usages.

NSSO (2014) reports household consumption of various goods during 2011-2012. However, there is significant growth in household LPG usages after 2011, this affects the biomass and kerosene usage pattern in the residential sector. The biomass and kerosene consumption and use in the residential sector 2019 were re-estimated by incorporating the growth rate of LPG.

Indian Petroleum and Natural Gas Statistics report has been referred to estimate the growth trend of LPG consumption in residential households. MoPNG reports LPG consumption information at state level and therefore for present estimation we have considered LPG consumption data of Punjab for the years 2016 to 2019 to estimate the LPG growth at district level. Accordingly, an annual LPG consumption growth of 5.98% has been considered for Punjab. The increase of numbers of household using LPG is then uniformly distributed to adjust the number of fuelwood-, crop residue-, and dung cake-using households during 2019.

The activity data of different fuels was fed into above equation along with the fuel specific emission factors of different pollutants ($EF_{(f,p)}$) (Table 46) to calculate the emission of different pollutants from the use of different fuel types in residential sector.

Table 46: Emission factors (g/Kg) of Different Pollutants from Different Fuel Types used in the Residential Sector

Pollutant	FW	CR	CDC	COAL	KEROSENE_C	LPG
$PM_{2.5}$	4.6	5.7	4.4	4.04	3	0.35
PM_{10}	6.77	8.6	10.5	8.26	3.6	0.35
SO_2	0.8	0.7	0.6	15.33	0.4	0.4
NO_x	1.7	1.8	1	2.16	1.3	2.9
CO	66.5	64	78.6	59.46	43	2
NMVOC	15.89	8.5	24.1	10.5	17	19

BC	0.4	0.3	0.4	0.00826	0.6	

FW: Fuel wood; CR: Crop residue; DC: Dung cake; K: Kerosene; LPG: Liquid Petroleum Gas

Table 47: Total emissions (kt) of Different Pollutants from The Residential Sector in Punjab in 2019

	FW	CR	DC	Coal	K	LPG	Total
$PM_{2.5}$	1.30	0.34	1.72	0.00	0.00	0.17	3.52
PM_{10}	1.91	0.52	4.09	0.00	0.00	0.17	6.69
SO_2	0.23	0.04	0.23	0.00	0.00	0.19	0.69
NO_x	0.48	0.11	0.39	0.00	0.00	1.40	2.37
CO	18.74	3.83	30.64	0.00	0.01	0.96	54.19
NMVOC	4.48	0.51	9.39	0.00	0.00	9.15	23.53
BC	0.11	0.02	0.16	0.00	0.00	0.00	0.29

FW: Fuel wood; CR: Crop residue; DC: Dung cake; K: Kerosene; LPG: Liquid Petroleum Gas

Agricultural Residue Burning

Emission inventory of different pollutants from the burning of different crop residues in the cropland has been developed by following the IPCC, 2006 inventory preparation guideline. The primary crops considered for inventory preparation are rice, wheat, maize, sugarcane and cotton. These crops have been selected as they are prone to burning across the country, as mentioned in different published literature along with National Policy for Management for Crop Residues (NPMCR). Emission from the in-situ burning of crop residue is calculated using the equation below,

$$\text{Epol} = \sum_{S=1}^{35}\sum_{D=1}^{n}\sum_{C=a}^{n} Pa \times Ra \times fDa \times fBa \times EFpol$$

Where, Epol = Emission of a particular pollutant (pol) (g); Pa is the total production of a particular crop (C) in a particular district (D) of the state (S) in kilogram (here only Punjab has been taken); Ra is the fraction of residue generated for the production (Pa) of the particular crop (a); fDa is the fraction of dry matter in the residue of the particular crop (a); fBa is the combustion efficiency of crop residue that is burnt, Bf is the burning fraction of the crop estimated based on MODIS FRP data, and EFpol is the emission factor of the particular pollutant (g/Kg). Emission estimation equation does not show controls as there are no direct emission control measures for control of agricultural burning emissions at the fields. However, burning fractions are to be reduced by implementing in-situ and ex-situ measures.

The seasonal district-wise production data (Pa) of different crops was collected from the Department of Agriculture Cooperation and Farmers' Welfare (DAC&FW), Ministry of Agriculture, and Government of India for the year 2019. Different crops' residue to crop fractions (Ra) has been replicated as in Datta and Sharma (2014).[128] The dry matter fraction in different crop residues (fDa) replicates as reported by Aerosol and Air Quality Research[129]. The combustion efficiency (fBa) of different crop residues is used as reported in Turn et al. (1997)[130] (Table 48).

Table 48: Coefficients of Different Crop Residues to Estimate the Emissions of Different Pollutants

Co-efficient	Rice	Wheat	Cotton	Maize	Sugarcane
Residue to Crop ratio (Ra)[a]	1.59	1.70	3.00	2.00	0.40
Dry fraction of residue (fDa)[b]	0.86	0.88	0.80	0.90	0.90
Combustion efficiency (fBa)[c]	0.89	0.86	0.90	0.92	0.68

a.[131]; b.[132]; c.[133]

The burning fraction (Bf) has been calculated from the MODIS Fire Radiative Power (FRP) data. The FRP dataset of the NASA's MODIS (aqua and tera) satellites is also used to identify the crop residue burning locations at grids over the state boundary during crop harvesting seasons of 2019. This is further employed to spatially allocate the emissions. The MODIS active fire products provide fire detections at the satellite overpass times. Terra and Aqua respectively cross the equator at approximately 10:30 a.m. and 1:30 p.m. local time during daytime and 10:30 p.m. and 1:30 a.m. during nighttime. The MODIS Level 2 active fire products (abbreviated MOD14 for Terra and MYD14 for Aqua) contain for each fire pixel the detection time, geographical coordinate, confidence (low, nominal, and high), fire radiative power (units: MW per pixel), brightness temperature at the MODIS band 21 (3.660–3.840 μm) and band 31 (10.780–11.280 μm), and average brightness temperature of the surrounding non-fire pixels at bands 21 and 31. The FRP estimates in MODIS Collection 6 (C6) active fire product are retrieved following the method developed by Wooster et al. (2003). The FRP products retrieved from MODIS C6 datasets were plotted on GIS along with LULC (land use and land cover) MODIS products for the study year. The FRP's detected over agricultural land use area were extracted for further analysis, as it is assumed that rest of the FRP's being detected may represent some other form of burning. This extracted data has been used to estimate yearly FRP detected in each district of the country. The maximum FRP value detected in any district of the country since the availability of the data i.e., 2001 has been assumed where almost 70% of the residue is being burnt.

Cultivation-related Emissions: Space Application Centre, Ahmedabad reported state specific methane emission factors from rice crop land.[134] Following the report, the Punjab state specific methane emission factors were used to estimate the methane emissions from rice crop lands. IPCC default emission factor for direct nitrous oxide emission estimation from crop land[135] was used during the estimation of nitrous oxide emission from different crop land. However, upper Indo-Gangetic Plain specific emission factors were used to estimate nitrous oxide emissions from wheat and maize crops.[136]

Estimated methane emissions from rice crop land of Punjab during 2019-20 were 193 kt (Table 49). During the estimation of methane emission, it was considered that there were no direct methane emissions from other crops like maize, wheat, sugarcane and Cotton as there was no continuous waterlogging condition during cultivation process of these crops.

Table 49: Total Agriculture-related Emissions in Punjab in 2019 (kt/yr)

District	PM_{10}	$PM_{2.5}$	BC	SO_2	NO_x	CO	NMVOC	CH_4
Amritsar	5.46	3.9	0.58	1.25	0.39	43.56	1.92	11.16
Barnala	0	0	0	0	0	0	0	7.03
Bathinda	17.68	11.64	1.4	3.13	1.67	116.91	14.07	11.03
Faridkot	5.8	4.1	0.6	1.36	0.37	47.28	2.22	7.15
Fatehgarh Sahib	3.45	2.49	0.37	0.84	0.25	27.63	1.43	5.30
Fazilka	11.89	7.85	0.93	2.13	1.17	76.72	10.37	11.77
Firozepur	8.01	5.57	0.82	1.72	0.5	65.77	1.91	7.03
Gurdaspur	5.18	3.75	0.58	1.12	0.46	38.93	1.78	10.73
Hoshiarpur	6.76	5.08	0.69	1.36	0.62	48.28	2.13	4.81
Jalandhar	8.94	6.46	0.96	2.06	0.68	70.13	3.35	10.79
Kapurthala	5.05	3.64	0.54	1.22	0.36	40.4	2.1	7.40
Ludhiana	13.37	9.59	1.42	3.32	0.87	109.22	5.66	15.96
Mansa	10.82	7.13	0.86	1.92	1.02	71.87	8.47	7.34
Moga	9.36	6.68	0.98	2.32	0.59	77	3.87	11.16
Muktsar	11.75	8.04	1.09	2.43	0.91	88.14	6.22	11.71
Pathankot	1.77	1.3	0.18	0.37	0.15	13.2	0.56	1.73
Patiala	6.4	4.57	0.67	1.56	0.41	52.31	2.55	14.49
Rupnagar	0	0	0	0	0	0	0	2.47
Sas Nagar	0	0	0	0	0	0	0	1.79
Sangrur	12.12	8.62	1.27	2.91	0.8	98.33	4.95	17.81
Shahid Bhagat Singh Nagar	4.26	3.09	0.45	0.94	0.33	32.91	1.44	3.70
Tarn Taran	0	0	0	0	0	0	0	11.34
Total	**148.08**	**103.52**	**14.4**	**31.96**	**11.55**	**1118.59**	**75.00**	**193.67**

Livestock and Manure Management

The formula applied to calculate methane (CH_4) emissions from livestock and manure management is as follows:

$$\text{Emissions} = N_{(T)} * EF_{(T)} * 10^3$$

Where, Emissions = methane emissions (kg/year),

$EF_{(T)}$ = emission factor for the defined livestock population, kg CH_4/head/year

$N_{(T)}$ = the number of head of livestock species

T = species/category of livestock

For estimating emissions from livestock and manure management, default IPCC emission factors were applied (Table 50).

Table 50: Emission Factors used for Estimating Emissions from Livestock and Manure Management

Category	Sub-Category	Age Group	Methane Emission Factor	
			Enteric Fermentation (kg CH_4/head/year)	Manure Management (kg CH_4/head/year)
Indigenous Cattle	Dairy Cattle	Indigenous	28.00	3.50
	Non-Dairy Cattle (indigenous)	0–1 year	9.00	1.20
		1–3 years	23.00	2.80
		Adult	32.00	2.90
Crossbred Cattle	Dairy Cattle	Cross-bred	43.00	3.80
	Non-Dairy Cattle (cross-bred)	0–1 year	11.00	1.10
		1–3 years	26.00	2.30
		Adult	33.00	2.50
Buffalo	Dairy Buffalo		50.00	4.40
	Non-Dairy Buffalo	0–1 year	8.00	1.80
		1–3 years	22.00	3.40
		Adult	44.00	4.00
Sheep	Non-Dairy		5.00	0.20
Goat	Non-Dairy		5.00	0.22
Horses and Ponies	Non-Dairy		18.00	2.19
Donkeys	Non-Dairy		10.00	0.90
Camels	Non-Dairy		46.00	2.56
Pigs	Non-Dairy		1.00	4.00
Poultry	Non-Dairy		0.00	0.00

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