ENVIRONMENTAL RESEARCH
LETTERS

**ACCEPTED MANUSCRIPT • OPEN ACCESS**

# Mitigation of non-$CO_2$ greenhouse gases from Indian agriculture sector

To cite this article before publication: Omkar Patange *et al* 2024 *Environ. Res. Lett.* in press https://doi.org/10.1088/1748-9326/ad4e4e

Manuscript version: Accepted Manuscript

Accepted Manuscript is “the version of the article accepted for publication including all changes made as a result of the peer review process, and which may also include the addition to the article by IOP Publishing of a header, an article ID, a cover sheet and/or an ‘Accepted Manuscript’ watermark, but excluding any other editing, typesetting or other changes made by IOP Publishing and/or its licensors”

This Accepted Manuscript is **© 2024 The Author(s). Published by IOP Publishing Ltd**.

As the Version of Record of this article is going to be / has been published on a gold open access basis under a CC BY 4.0 licence, this Accepted Manuscript is available for reuse under a CC BY 4.0 licence immediately.

Everyone is permitted to use all or part of the original content in this article, provided that they adhere to all the terms of the licence https://creativecommons.org/licences/by/4.0

Although reasonable endeavours have been taken to obtain all necessary permissions from third parties to include their copyrighted content within this article, their full citation and copyright line may not be present in this Accepted Manuscript version. Before using any content from this article, please refer to the Version of Record on IOPscience once published for full citation and copyright details, as permissions may be required. All third party content is fully copyright protected and is not published on a gold open access basis under a CC BY licence, unless that is specifically stated in the figure caption in the Version of Record.

View the article online for updates and enhancements.

This content was downloaded from IP address 84.113.107.231 on 22/05/2024 at 15:38

# Mitigation of non-$CO_2$ greenhouse gases from Indian agriculture sector

Omkar Patange[1*], Pallav Purohit[2], Vidhee Avashia[3], Zbigniew Klimont[2], Amit Garg[3]

[1]Economic Frontiers (EF) Program, International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361, Laxenburg, Austria.

[2]Pollution Management Research Group, Energy, Climate, and Environment Program, International Institute for Applied Systems Analysis (IIASA), Schlossplatz 1, A-2361, Laxenburg, Austria.

[3]Public Systems Group, Indian Institute of Management Ahmedabad (IIMA), Vastrapur, Ahmedabad 380015, Gujarat, India

[*]Author to whom any correspondence should be addressed.
E-mail: patange@iiasa.ac.at

## Abstract

The Indian agriculture sector is driven by small and marginal farmers and employs two-thirds of the Indian work force. Agriculture also accounts for around a quarter of the total greenhouse gas emissions, mainly in the form of methane ($CH_4$) and nitrous oxide ($N_2O$). Hence, agriculture is an important sector for India's transition to net-zero emissions and for the achievement of the sustainable development goals. So far, very few studies have assessed the future trajectories for $CH_4$ and $N_2O$ emissions from the agriculture sector. Moreover, assessment of $CH_4$ and $N_2O$ mitigation potential at a subnational (state) level is missing but is important owing to the regional diversity in India. To fill this gap, we focus on methane and nitrous oxide emissions from the agricultural activities using 23 sub-regions in India. We use the GAINS modelling framework which has been widely applied for assessing the mitigation strategies for non-$CO_2$ emissions and multiple air pollutants at regional and global scales. We analyze a current policy and a sustainable agriculture scenario using different combinations of structural interventions and technological control measures to inform the Indian and global climate policy debates. Our results suggest that a combination of sustainable agricultural practices and maximum feasible control measures could reduce the $CH_4$ and $N_2O$ emissions by about 6% and 18% by 2030 and 27% and 40% by 2050 when compared to the current policies scenario with limited technological interventions. At a sub-national level, highest mitigation potential is observed in Uttar Pradesh, followed by, Madhya Pradesh, Rajasthan, Gujarat, Maharashtra, Andhra Pradesh, and Telangana. The mitigation of agricultural $CH_4$ and $N_2O$ also has co-benefits in terms of reduced local pollution, improved health, and livelihood opportunities for the local communities.

**Keywords:** India, agriculture, Methane ($CH_4$), nitrous oxide ($N_2O$), climate strategies, co-benefits.

## 1. Introduction

India is the fourth largest emitter of greenhouse gases (GHG) in the world. As a fast-growing major economy, India's future emissions trajectory is important for the global climate goals. Since the Paris Climate Change agreement, many national (Durga et al., 2022; Vishwanathan & Garg, 2020) and international (Grubler et al., 2018; IEA, 2022; Kikstra et al., 2021) modelling assessments have focused on scenarios to mitigate $CO_2$ emissions from the energy sector which contributes around 70% of the total GHG emissions globally and in India (MoEFCC, 2021; Olivier & Peters, 2020). However, the policy emission targets are generally formulated with reference to total GHG emissions (as $CO_{2eq}$) that include agriculture, waste, industrial processes, and product use, and include non-$CO_2$ greenhouse gases (NCGG) like methane ($CH_4$), nitrous oxide ($N_2O$) and fluorinated gases. Although $CH_4$ and $N_2O$ have a smaller share in the overall GHG emissions, they have a significantly higher global warming potential (GWP) compared to $CO_2$ and are currently estimated to cause a cumulative warming of 0.65 °C (Ravishankara et al., 2021; U. Singh et al., 2022). The climate impact of NCGG is often expressed in terms of their relative mass of $CO_2$. $GWP_{100}$ is one such common metric to measure the long-term GWP of NCGG with respect to $CO_2$ over a period of 100 years. For $CH_4$, the latest assessment of the Intergovernmental Panel on Climate Change (IPCC) have used a source-specific $GWP_{100}$ of 27 (non-fossil) and 29.8 (fossil), whereas, for $N_2O$, the overall $GWP_{100}$ value is 273 (Forster et al., 2021). With these $GWP_{100}$ values, the NCGG emissions in national and international inventories are often reported in terms of $CO_{2eq}$ to compare them with $CO_2$ emissions. In 2016, $CH_4$ and $N_2O$ accounted for 16% and 6% of the total GHG emissions in India (MoEFCC, 2021) and were primarily associated with activities from the agriculture sector (enteric fermentation, rice cultivation, application of nitrogen fertilizers) with enteric fermentation being second largest GHG source in India after electricity generation. Agriculture also employs two-thirds of Indian work force and contributes to 16% of gross value added (GVA) (MoEFCC, 2021).

Typically, the Indian modelers assess the NCGG emissions exogenously; they are not part of the larger optimization framework of most models. Limited research is devoted to discussing policies to reduce NCGG. The extant literature on NCGG could be divided into three categories. First, the assessment of emissions using historical data which includes the official reporting of national inventory to the United Nations Framework Convention on Climate Change (UNFCCC) (ex. MoEFCC, 2021, 2023). In addition, there are sectoral or activity specific emission factors and inventory assessments of $CH_4$ and $N_2O$ from agriculture and other sectors (Bhatia et al., 2013; Datta et al., 2009; Fagodiya et al., 2020; Gupta et al., 2009; Hemingway et al., 2023; Pathak, 2015; Patra, 2017; Sharma et al., 2011). According to the recent reports, the agriculture sector has contributed to 74% of $CH_4$ and 72% of $N_2O$ emissions in 2016 (Figure 1). Although the share of $CH_4$ and $N_2O$ in total GHG emissions has reduced from 24% in 2016 to around 18% in 2019, the overall agricultural emissions have steadily risen at an annual rate of 0.3% in the past decade (MoEFCC, 2021, 2023).

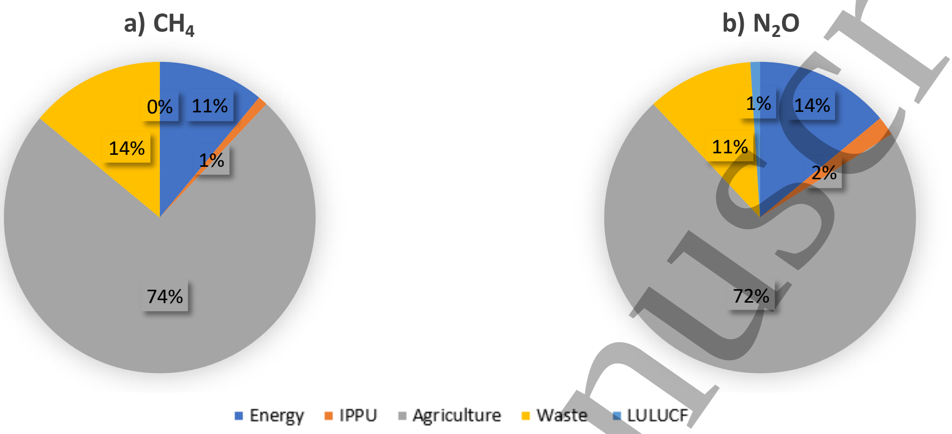


Figure 1: Sectoral contributions to $CH_4$ and $N_2O$ emissions in 2016 (Source: MoEFCC, 2021)

The second type of studies have focused on emissions from specific activities like rice cultivation or livestock rearing and their mitigation strategies (Chhabra et al., 2013; Garg et al., 2011; Mishra et al., 2012; Powlson et al., 2014; Reddy et al., 2019; B. Singh & Singh, 2008; Sirohi & Michaelowa, 2007). The third type of studies focus on scenario modelling and are conducted at national and international levels. In case of India, few studies have developed scenarios to assess the NCGG from the agriculture sector (Ashok et al., 2021; Garg, 2004; Jha et al., 2022). In the past, Garg et al (2004) have explored a reference and two mitigation scenarios for $CH_4$ and $N_2O$ emissions from India using a spatially explicit AIM/Enduse model (Kainuma et al., 1999). Their findings suggest that including $CH_4$ and $N_2O$ could provide additional mitigation potential and flexibility when formulating decarbonization policies. In recent studies, Ashok et al (2021) have used national and regional simulation models to study supply interventions like micro-irrigation, limiting water intensive crops like sugarcane along with demand interventions like behavioral shift from rice to millets to achieve food security in a changing climate scenario. The focus is on overall agricultural sustainability with the aim to achieve zero-hunger (SDG 2). Jha et al (2022) have used a partial-equilibrium integrated assessment model, MAgPIE (Dietrich et al., 2019; Lotze-Campen et al., 2008), to explore sustainable pathways for the agriculture, forestry, and land use (AFOLU) sectors. Their findings suggest that productivity improvements in crop and animal-based products and dietary shift could reduce the total AFOLU sector GHG emissions by up to 80% by 2050.

There are limited studies exploring the non-$CO_2$ emissions mitigation pathways. Further, recent research, particularly after the Paris agreement, has focused on national level analysis. However, assessment of NCGG mitigation potential considering subnational level is important owing to the regional diversity in India. We attempt to fill this gap by focusing on methane and nitrous oxide from key agricultural activities in India. We analyze two scenarios using different combinations of activities and control measures. In the next section we describe the methods, data sources and scenarios used for this study. Section 3 presents the results and section 4 discusses their implications for policy and future research. Section 5 concludes the discussion with key policy recommendations.

## 2. Methods, Data, Scenario description

### *The GAINS Model*

We model the future emission trajectories from the Indian agriculture sector using the GAINS modelling framework (Amann et al., 2011) which has been widely applied for the analysis of NCGG (Harmsen et al., 2023; Höglund-Isaksson et al., 2020; Purohit et al., 2020; Winiwarter et al., 2018) emissions and air pollution (Klimont et al., 2017; Purohit et al., 2019; Purohit & Höglund-Isaksson, 2017; World Bank, 2022). Past and future emissions are estimated in GAINS for all key anthropogenic activities, explicitly considering the emission reduction technologies, where applied (equation 1):

$$EMM_{i,p} = \sum_k \sum_m A_{i,k} EF_{i,k,m,p} \, X_{i,k,m,p} \qquad (1)$$

Where i, k, m, p represents region, activity type, abatement measure, and pollutant, respectively; $EMM_{i,p}$ represent the emissions of pollutant p (i.e., $CH_4$, $N_2O$) in region i; $A_{i,k}$ is the activity level of type k (e.g., fertilizer consumption) in region i; $EF_{i,k,m,p}$ the emission factor of pollutant p for activity k in region i after application of control measure m; and $X_{i,k,m,p}$ is the share of total activity of type k in region i to which a control measure m for pollutant p is applied.

The EF could vary based on the control measure (m) whose implementation depends on alternate policies scenarios and technology penetration rates (Amann et al., 2020; Höglund-Isaksson et al., 2020; Winiwarter et al., 2018). For our analysis, the key activities for agricultural $CH_4$ and $N_2O$ emissions included rice cultivation, livestock rearing and fertilizer application in agricultural soils. We use India-specific EF, along with their uncertainty ranges, for these activities, obtained from India's national communication to the UNFCCC and related literature (Bhatia et al., 2013; Chhabra et al., 2013; MoEFCC, 2023). For control strategies, we have considered irrigation management in rice fields, feed management and anerobic digestors for livestock and nitrogen inhibitors for judicial use of fertilizers, among other measures. For this work, we have considered 23 sub-national regions within India (see SI for details).

### *Activity data*

Historical data between 1990 and 2020 was obtained from various government and international reports. The state wise area, production, and yield statistics for rice and other crops were obtained from the Agricultural Statistics of India (MoAFW GoI, 2023a). Data on milk and non-milk animals, state wise milk yields, per capita milk availability, meat and eggs consumption from non-dairy cattle, pigs and poultry were obtained from the latest Livestock Census and the Basic Animal Husbandry Statistics (DAHD GoI, 2022a, 2022b). The state wise synthetic nitrogen fertilizer production and consumption was obtained from the Ministry of Fertilizers and Fertilizer Association of India (FAI, 2022).

The future demand for agricultural products was projected using macroeconomic drivers like population and income. Primary drivers for selected agricultural activities included population, national gross domestic product (GDP) and gross value added (GVA) from the agriculture sector. The UN median population projections for India till 2050 (United Nations, 2019) were proportionately distributed at state level in the GAINS model. For the Current Policies Scenario (CPS), the population projections, combined with income growth and state-wise consumption trends, were used to estimate the future demand for different plant and animal-based products. However, in the case of commodities like rice, which is already in surplus supply, the production was driven by supply side policies like minimum support prices (MSP) and the Food Security Act (GoI, 2013). The current policies were used to adjust future projections for commodities like rice. In case of the Sustainable Agriculture Scenario (SAS), the per capita demand for agricultural crops and animal produce were projected based on the recommended dietary requirements by the EAT-Lancet report (Willett et al., 2019) and other socio-political, cultural, and geographic factors in the states. In terms of production, the yields of various crops, milk, and other animal produce for the past two decades, along with current policies, were used to project the yields of these commodities till 2050. Methods used for projecting future agricultural activity data from key sub-sectors are described in the supplementary information (SI).

### *Scenarios and control strategies*

Table 1: Scenarios used for assessing the $CH_4$ and $N_2O$ emissions from the agriculture sector.

| | | Technological intervention |
|---|---|---|
| | (1) CPS_CLE (current policies scenario using current legislations) | (2) CPS_MFR (current policies scenario using maximum feasible reduction) |
| Structural intervention | (3) SAS_CLE (sustainable agriculture scenario using current legislations) | (4) SAS_MFR (sustainable agriculture scenario using maximum feasible reduction) |

In Table 1, CPS_CLE represents the baseline scenario, wherein it assumes the continuation of existing agricultural policies relevant to $CH_4$ and $N_2O$ emissions, without any extra efforts to implement technology interventions. SAS_CLE, on the other hand, assumes an integrated transition of agriculture sector to meet the social and environmental goals. For example, reducing land under rice cultivation to meet the dual goals for sustainable diets and mitigation of methane emissions from rice fields. With the maximum feasible reduction (MFR) in both CPS and SAS, we project the mitigation of NCGG from agriculture if activity-specific technological interventions were implemented to their full technical potential. In the Indian context, the guiding policy framework for agricultural mitigation policies is the National Mission for Sustainable Agriculture (NMSA), one of the missions within the National Action Plan on Climate Change (NAPCC) from 2008 (GoI, 2008; MoEFCC, 2021). The NMSA has led to policies like National Livestock Mission and the National Innovations in Climate Resilient Agriculture (NICRA) which are driving the mitigation efforts in the agriculture sector (See Table S2a and S2b for details of scenario-specific policies, technologies and application rates).

## 3. Results

Our results discuss the methane and nitrous oxide emissions estimates for the reference year 2015, followed by the projections for the CPS and SAS, showcasing the mitigation potential with maximum feasible technological interventions in the major agricultural activities. We also report the uncertainty in total $CH_4$ and $N_2O$ emissions due to uncertainty in activity-specific emission factors. Further, we present the sub-national heterogeneities in $CH_4$ and $N_2O$ emissions due to variation in agricultural activities and their corresponding mitigation potential for the period 2020-2050.

### *3.1 Current and future $CH_4$ and $N_2O$ emissions in baseline and alternative scenarios*

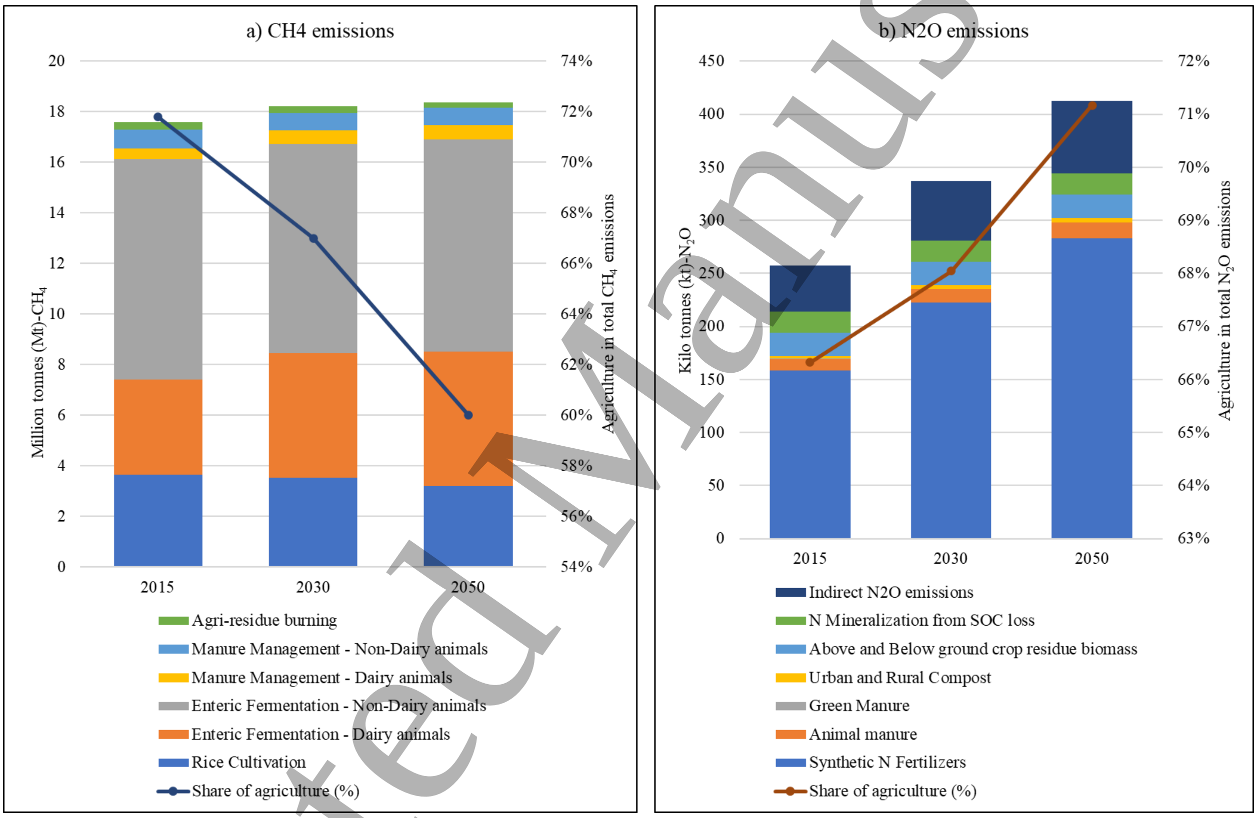


Figure 2: Activity wise $CH_4$ and $N_2O$ emissions under the current policies scenario (2015-2050). Note: In figure (b), N Mineralization from soil organic carbon (SOC) loss is due to change in land use agricultural management practices as reported in the Indian National Inventory (Bhatia et al., 2013).

In 2015, the agricultural activities contributed to an estimated 17.60 (±4.00) million tonnes of $CH_4$ (Mt-$CH_4$) as shown in Figure 2(a). Our results suggest a 72% contribution of agricultural activities to methane emissions followed by the waste sector (13%). Fuel production and combustion, industrial processes and non-energy fuel usage made up the remaining 15% of the emissions. The major activities contributing to methane emissions from agriculture sector were enteric fermentation from dairy and non-dairy animals (71%) and rice cultivation (21%). The remaining emissions came from activities like manure management and agricultural residue burning.

Under the current policies scenario (CPS_CLE), the projected $CH_4$ emissions increase to 18.21 (±4.15) Mt-$CH_4$ by 2030 and to 18.37 (±4.25) Mt-$CH_4$ by 2050. In the CPS_CLE, the share of agricultural activities in methane emissions is estimated to reduce to 67% (2030) and 60% (2050) due to rise in emissions from the waste sector (21% in 2050). The future $CH_4$ emissions from agriculture sector are again driven by enteric fermentation (75%) and rice cultivation (17%) followed by manure management (7%) and biomass residue burning in agricultural fields (1%). The area under rice has remained around 44 million hectares in the past two decades. Although the rice production has increased due to yield improvements (by over 40%) during this period, the methane emissions are primarily associated with area under cultivation and the type of rice ecosystems. As a result, $CH_4$ emissions have remained around 3.5 Mt-$CH_4$/year in recent years and are expected to reduce moderately to 3.21 Mt-$CH_4$/year by 2050 due to ongoing technological interventions. In the CPS, we assume further increase in rice yields between 2020 and 2050 and the continuation of minimum support price (MSP) for rice which lead to surplus production of rice.

According to the latest livestock census (2019), the population of cattle and buffaloes has remained almost the same, compared to the 2012 figures. However, there has been a decrease of 6% in indigenous cattle over 2012. On the other hand, there is a rising trend in the case of exotic and crossbred cattle as their population increased by 35% between 2007 and 2012 and by 27% between 2012 and 2019 (DAHD GoI, 2022a). The milk production, mainly from cows and buffaloes, also doubled in the past two decades. Since the crossbred dairy cattle emit more $CH_4$ per head as compared to the indigenous breed (Garg, 2004), we observe a rising trend in livestock emissions despite a marginal rise in overall cattle population.

The $N_2O$ emissions in 2015 were estimated at 257.16 (±82.29) kilo tonnes of $N_2O$ (kt-$N_2O$) as shown in Figure 2(b). Agricultural activities contributed to around 66% of the total $N_2O$ emissions followed by energy (17%) and the waste sector (13%). In agriculture, direct $N_2O$ accounted for around 80% while the indirect emissions from nitrogen volatilization, runoff and leaching contributed the remaining share. For direct $N_2O$, use of synthetic nitrogen fertilizers resulted in about 75% of the emissions followed by above and below ground biomass crop residues (10%), N mineralization from soil organic carbon (SOC) loss (9%), organic manure from livestock (5%), compost and green manure (~1%).

In the CPS_CLE, the projected $N_2O$ emissions increase to 337.40 (±107.97) kt-$N_2O$ by 2030 and to 412.82 (±132.10) kt-$N_2O$ by 2050. The share of direct and indirect $N_2O$ from agriculture was projected to increase to 68% (2030) and 71% (2050). By 2050, energy and industrial processes contributed to around 19% of the total $N_2O$ emissions with waste sector accounting for the remaining 10% share. In the past few years, consumption of nitrogen fertilizers has gone up due to policy changes that have driven an increased share of Nitrogen in NPK fertilizers applied by farmers (Some et al., 2019). However, excluding a few states like Punjab and Haryana, the per hectare consumption of synthetic N fertilizers is still low in many parts of India. Assuming the policies of agri-intensification, driven using subsidized urea and non-urea N fertilizers, the CPS_CLE projects the fertilizer emissions to increase by 41% in 2030 and 79% in 2050, when compared to 2015. In addition, the rising share of dairy animals contribute to an increase of $N_2O$ from animal manure by 14% (2030) and 32% (2050).

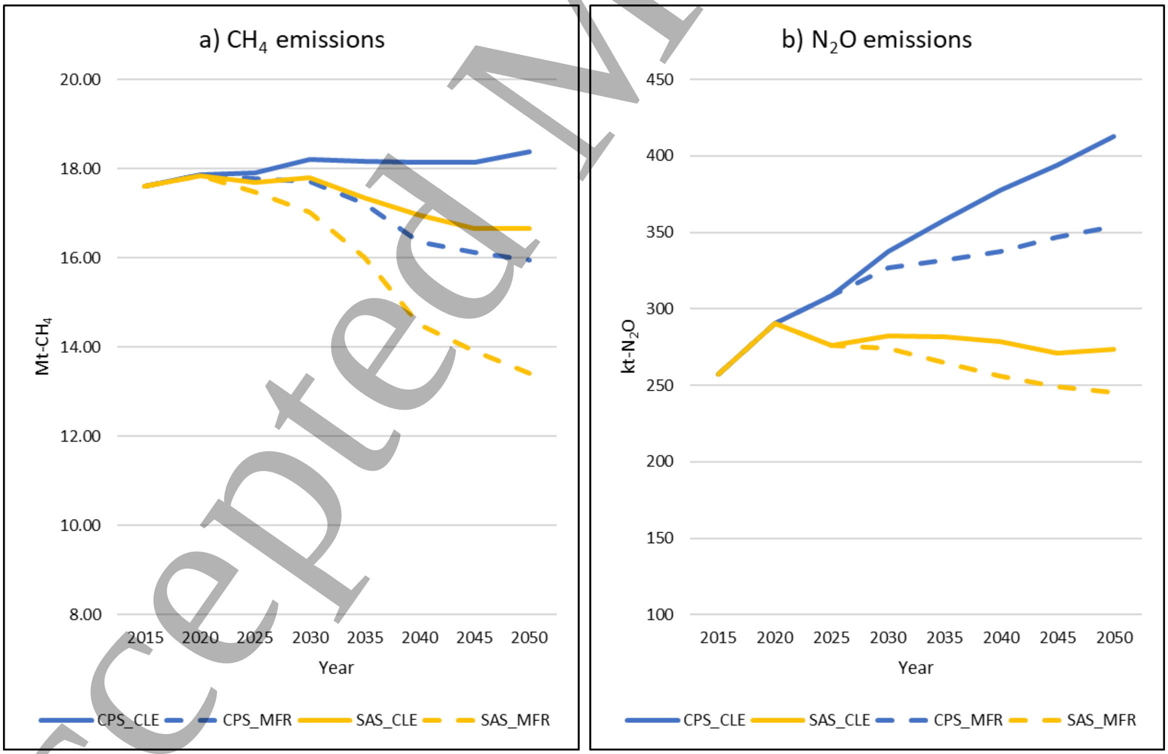


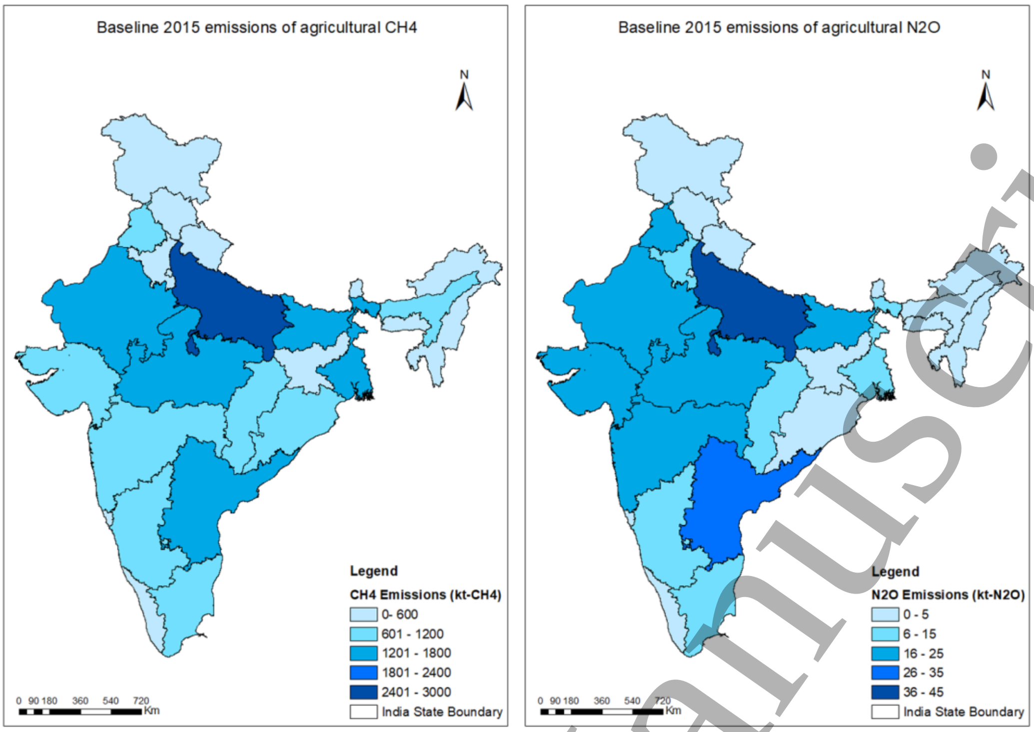
Figure 3: $CH_4$ (left) and $N_2O$ (right) emission projections from agriculture sector under the CPS and SAS scenarios.

As illustrated in Figure 3, $CH_4$ and $N_2O$ emissions from agriculture sector are projected to increase in the CPS_CLE due to the anticipated economic and population growth in future years. However, the effect of the structural interventions (SAS) and the maximum feasible technology interventions (MFR) is seen in later years. The 9% decline in $CH_4$ emissions in 2050 from structural interventions alone (SAS_CLE), compared to CPS_CLE, are observed from two sub-sectors – dairy animals (54%) and rice cultivation (45%). The structural interventions in dairy sector are primarily targeted at improving the milk yields which lead to reducing the number of dairy animals when compared to the CPS scenario. In case of rice cultivation, the area under crop is gradually decreased with increase in yields to meet the recommended per capita rice consumption of a nutritional diet. Further, area under rice cultivation is shifted to eastern states of India from northern states of Punjab and Haryana where groundwater levels are going down (Bhattarai et al., 2021). For $N_2O$ emissions, the driving factor is the consumption of N-fertilizers. The use of synthetic fertilizers per hectare of agricultural land is already very low in many states of India. Hence the structural interventions, in terms of reducing the per hectare N-use and timing of application are limited to a few regions with high per hectare fertilizer use. The effective reduction of $N_2O$ in 2050 between SAS_CLE and CPS_CLE is around 40% with limited technological interventions. Further, emissions from manure nitrogen reduce by 5% in 2050 between SAS_CLE and CPS_CLE.

The additional mitigation potential is explored through the MFR scenarios. Interventions like the system of rice intensification, shorter duration variety of rice, and intermittent drying of rice fields are implemented to reduce the $CH_4$ emissions. These result in additional 0.36 Mt-$CH_4$ of reduction from rice between the SAS_CLE and SAS_MFR scenarios by 2050. For livestock, dietary management with concentrated fodder, breed improvement, pasture management along with anaerobic fermentation of animal waste was implemented as a control measure. These interventions contribute to around 2.7 Mt-$CH_4$ reduction in 2050 between the SAS_CLE and SAS_MFR. Total reduction in $CH_4$ emissions between SAS_CLE and SAS_MFR by 2050 is around 20%. In case of $N_2O$, stringent technology control measures with nitrogen inhibitors and nano-urea (Upadhyay et al., 2023) further reduce the N-fertilizer emissions by 25% in 2050 between SAS_CLE and SAS_MFR. The total mitigation potential between CPS_CLE and SAS_MFR for the period 2020-2050 was around 70 Mt-$CH_4$ and 2.7 Mt-$N_2O$.

## *3.2 Sub-national heterogeneities in $CH_4$ and $N_2O$ emissions from agriculture sector of India*

**Panel A**



**Panel B**

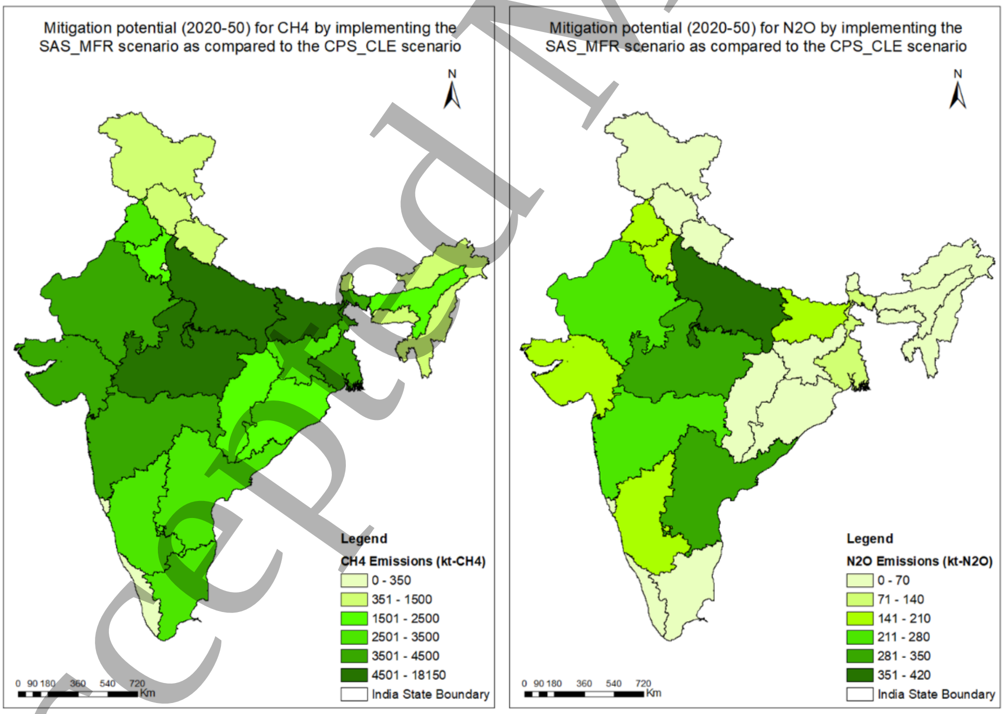


Figure 4: $CH_4$ and $N_2O$ emissions in the reference year 2015 (Panel A) and mitigation potential between 2020-50 in SAS_MFE as compared to the CPS_CLE scenario (Panel B)

At the sub-national level, methane and nitrous oxide emissions show a large variation as illustrated in Figure 4 (Panel A). In 2015, Uttar Pradesh, owing to its large size and agrarian economy, was a major contributor with about 17% of the $CH_4$ and 18% of the $N_2O$ emissions. Andhra Pradesh, Rajasthan, West Bengal, and Madhya Pradesh were the other leading states in terms of methane emissions. For $N_2O$, Andhra Pradesh and Telangana, Maharashtra, and Punjab were the next big emitters. At sectoral level, Uttar Pradesh, West Bengal, Punjab, Odisha, and Andhra Pradesh were the leading states in rice cultivation and contributed to over 50% of the methane emissions from area under rice. In case of livestock rearing, Uttar Pradesh, Rajasthan, Madhya Pradesh, Jharkhand, Andhra Pradesh, and West Bengal accounted for the major share of $CH_4$ and $N_2O$ emissions resulting from enteric fermentation, manure management and animal manure applied to agricultural fields. The use of synthetic N fertilizers also varied in terms of per hectare consumption. For instance, even though Punjab and Haryana do not have a large share of $N_2O$ emissions, their per hectare consumption is one of the highest (175-200 kg/hectare) (MoAFW GoI, 2023a). We also studied the subnational mitigation potential for $CH_4$ and $N_2O$ emissions. The maximum potential, when comparing CPS_CLE and SAS_MFR is observed in Uttar Pradesh (26% for $CH_4$, 15% for $N_2O$), followed by, Madhya Pradesh, Rajasthan, Gujarat, Maharashtra, Andhra Pradesh, and Telangana (Figure 4, Panel B).

## 4. Discussion

Our scenario results suggest that mitigation of non-$CO_2$ emissions from the agriculture sector require a systemic approach to integrate social, environmental and climate goals. In India, around 42% of the total geographic area is under agriculture (net sown area) and around 55% of the population is dependent on agriculture-based livelihood (MoAFW GoI, 2023b). The major activities contributing to $CH_4$ and $N_2O$ emissions are also driven by small and marginal farmers. On the other hand, emissions from agriculture sector are rising and are expected to grow in the future due to rising consumption driven by economic growth. Considering the limitations due to subsistence farming, the mitigation technologies implemented at the farm-end (such as agri-mechanization) would be particularly challenging due to their high cost for small and marginal farmers. Alternatively, technologies implemented centrally or at the industry end (such as neem-coating of urea for nitrogen inhibition) could have wide application rates. However, the industrial-scale mitigation technologies will require wider policy support and government interventions at the beginning to increase their application rates as envisaged in our MFR scenarios. It is also important to highlight here that the technical mitigation potential considered in the MFR scenarios may further reduce due to economic and socio-cultural constraints in the given states. The MFR scenarios thus present a technically feasible reduction based on the application rates and mitigation potential without diving into the costs and political economy of these interventions.

We do not study the NCGG mitigation potential for other sectors like waste and fossil fuels. However, based on earlier assessments, waste and fossil fuel activities show a higher cumulative mitigation potential of around 50% (2020-2050) for $CH_4$ emissions when comparing the baseline (CLE) and the MFR scenario (Höglund-Isaksson et al., 2020). Similarly, for $N_2O$, industrial production sectors have a mitigation potential between 80-99% whereas wastewater treatment could further mitigation 40% emissions between 2020-2050 when comparing the baseline and the MFR scenarios (Winiwarter et al., 2018). However, in 2050, both these sectors have limited share in the total $N_2O$ emissions when compared to the agriculture sector.

The mitigation of NCGG from agriculture sectors also have co-benefits in terms of reduced local pollution, improved health, and livelihood opportunities for the local communities. Recent studies from Europe (Klimont et al., 2017; Klimont & Winiwarter, 2015) and China (Bai et al., 2019) indicate that agricultural $NH_3$ emissions have emerged as a major contributor to the formation of fine particulate matter ($PM_{2.5}$) resulting in air pollution and health hazards for the local population. A modelling assessment of ambient air quality in India also suggests that one-third of the $PM_{2.5}$ emissions are contributed by secondary sources that involve $NH_3$ from agriculture (Purohit et al., 2019). The mitigation measures for reducing the use of synthetic N-fertilizers could benefit in reducing the agricultural $NH_3$ emissions. Similarly, burning of crop residue in the fields has emerged as a major source of air pollution in north India (Shyamsundar et al., 2019). Apart from raising awareness among farmers to stop burning the residue, waste-to-energy production by converting surplus residue to bio-pellets or second-generation biofuels could also help in generating local employment (Purohit & Chaturvedi, 2018; Purohit & Dhar, 2018). Further, co-benefits for waste-to-energy production also exist in the livestock sector. The number of unproductive female cattle has gone up over the past few decades due to a lack of policies for such animals (DAHD GoI, 2022a). One way to deal with this is by setting up dry-cattle farms where adult unproductive cattle are housed and the manure, along with other biomass waste in the area, is used for biogas production. These community scale biogas plants, while reducing the methane emissions, could be used for electricity production or supply of compressed biogas to other industries.

Finally, there are three types of uncertainties associated with the $CH_4$ and $N_2O$ emissions reported in this study. First, the uncertainty due to emission factors that is reported in the results section. The activity specific EF uncertainty is reported in Tables S1a and S1b (SI). The second type of uncertainty arises from the application rates and mitigation potential of different technological interventions. Using the upper and lower bounds of activity-specific mitigation potential and application rates (Tables S2a and S2b), we found that the overall mitigation potential for $CH_4$ varies between 59 to 91 Mt-$CH_4$ between 2020-50 whereas the corresponding variation on mitigation potential of $N_2O$ was between 2.66 to 2.69 Mt-$N_2O$ (See Section S2 for details). The third type of uncertainty is associated with the activity data which was not analyzed here. Based on previous studies (Bhatia et al., 2013), the activity data uncertainty for $CH_4$ may vary between 3-22% and for $N_2O$ between 11-17%.

## 5. Conclusions

In a post-Paris agreement scenario, this study is one of the first to explicitly model India's agricultural non-$CO_2$ emissions at a subnational level. It underscores the need for effective strategies and addresses the gap in India's modeling landscape, which typically treats these emissions separately, with limited policy exploration. Our results suggest that the methane and nitrous oxide emissions could be brought down by 27% and 40% by 2050 in the sustainable agriculture scenario using best available technologies when compared to the same year in the current policies scenario. This, of course, is the technical mitigation potential which may further reduce based on socio-cultural and political economy constraints. Nevertheless, the results highlight the importance of combining structural transformations with technological interventions to achieve the climate targets while also meeting the relevant sustainable development goals. Further, the measures to reduce $CH_4$ and $N_2O$ emissions have co-benefits in terms reduced $PM_{2.5}$ emissions, improved air quality and health benefits for the people. Going forward, the NCGG scenarios could be implemented in conjunction with mitigation scenarios for $CO_2$ to understand the additional mitigation potential for total GHG emissions. Modelling of NCGG with $CO_2$ would also improve our understanding of marginal abatement costs of GHG mitigation to meet the policy commitments.

## Acknowledgement

This research was partially funded by the European Union's Horizon 2020 Research and Innovation programme under grant agreement no. 821471 (ENGAGE).

## References

Amann, M., Bertok, I., Borken-Kleefeld, J., Cofala, J., Heyes, C., Höglund-Isaksson, L., Klimont, Z., Nguyen, B., Posch, M., Rafaj, P., Sandler, R., Schöpp, W., Wagner, F., & Winiwarter, W. (2011). Cost-effective control of air quality and greenhouse gases in Europe: Modeling and policy applications. *Environmental Modelling & Software*, *26*(12), 1489–1501. https://doi.org/10.1016/j.envsoft.2011.07.012

Amann, M., Kiesewetter, G., Schöpp, W., Klimont, Z., Winiwarter, W., Cofala, J., Rafaj, P., Höglund-Isaksson, L., Gomez-Sabriana, A., Heyes, C., Purohit, P., Borken-Kleefeld, J., Wagner, F., Sander, R., Fagerli, H., Nyiri, A., Cozzi, L., & Pavarini, C. (2020). Reducing global air pollution: The scope for further policy interventions. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *378*(2183), 20190331. https://doi.org/10.1098/rsta.2019.0331

Ashok, K., Natarajan, R., Kumar, P., Sharma, K., & Mathur, M. (2021). Sustainable alternative futures for agriculture in India—The energy, emissions, and resource implications. *Environmental Research Letters*, *16*(6), 064001. https://doi.org/10.1088/1748-9326/abf0cd

Bai, Z., Winiwarter, W., Klimont, Z., Velthof, G., Misselbrook, T., Zhao, Z., Jin, X., Oenema, O., Hu, C., & Ma, L. (2019). Further Improvement of Air Quality in China Needs Clear Ammonia Mitigation Target. *Environmental Science & Technology*, *53*(18), 10542–10544. https://doi.org/10.1021/acs.est.9b04725

Bhatia, A., Jain, N., & Pathak, H. (2013). Methane and nitrous oxide emissions from Indian rice paddies, agricultural soils and crop residue burning. *Greenhouse Gases: Science and Technology*, *3*(3), 196–211. https://doi.org/10.1002/ghg.1339

Bhattarai, N., Pollack, A., Lobell, D. B., Fishman, R., Singh, B., Dar, A., & Jain, M. (2021). The impact of groundwater depletion on agricultural production in India. *Environmental Research Letters*, *16*(8), 085003. https://doi.org/10.1088/1748-9326/ac10de

Chhabra, A., Manjunath, K. R., Panigrahy, S., & Parihar, J. S. (2013). Greenhouse gas emissions from Indian livestock. *Climatic Change*, *117*(1), 329–344. https://doi.org/10.1007/s10584-012-0556-8

DAHD GoI. (2022a). *20th Livestock Census*. Department of Animal Husbandry and Dairying (DAHD), Government of India (GoI). https://dahd.nic.in/related-links/livestock-census

DAHD GoI. (2022b). *Basic Animal Husbandry Statistics*. Department of Animal Husbandry and Dairying (DAHD), Government of India (GoI). https://dahd.nic.in/sites/default/filess/BAHS_2022-English.pdf

Datta, A., Nayak, D. R., Sinhababu, D. P., & Adhya, T. K. (2009). Methane and nitrous oxide emissions from an integrated rainfed rice–fish farming system of Eastern India. *Agriculture, Ecosystems & Environment*, *129*(1), 228–237. https://doi.org/10.1016/j.agee.2008.09.003

Dietrich, J. P., Bodirsky, B. L., Humpenöder, F., Weindl, I., Stevanović, M., Karstens, K., Kreidenweis, U., Wang, X., Mishra, A., Klein, D., & others. (2019). MAgPIE 4–a modular open-source framework for modeling global land systems. *Geoscientific Model Development*, *12*(4), 1299–1317.

Durga, S., Evans, M., Clarke, L., & Banerjee, R. (2022). Developing new pathways for energy and environmental decision-making in India: A review. *Environmental Research Letters*, *17*(6), 063004. https://doi.org/10.1088/1748-9326/ac6f13

Fagodiya, R. K., Pathak, H., Bhatia, A., Jain, N., Kumar, A., & Malyan, S. K. (2020). Global warming impacts of nitrogen use in agriculture: An assessment for India since 1960. *Carbon Management*, *11*(3), 291–301. https://doi.org/10.1080/17583004.2020.1752061

FAI. (2022). *All-India Consumption of Fertiliser Nutrients*. Fertilizer Association of India. https://www.faidelhi.org/statistics/statistical-database

Forster, P., Storelvmo, T., Armour, K., Collins, W., Dufresne, J.-L., Frame, D., Lunt, D., Mauritsen, T., Palmer, M., Watanabe, M., & others. (2021). *The Earth's energy budget, climate feedbacks, and climate sensitivity*.

Garg, A. (2004). Indian methane and nitrous oxide emissions and mitigation flexibility. *Atmospheric Environment*, *38*(13), 1965–1977. https://doi.org/10.1016/j.atmosenv.2003.12.032

Garg, A., Kankal, B., & Shukla, P. (2011). Methane emissions in India: Sub-regional and sectoral trends. *Atmospheric Environment*, *45*(28), 4922–4929.

GoI. (2008). *National Action Plan on Climate Change (NAPCC)*. Government of India, New Delhi.

GoI. (2013). *National Food Security Act (NFSA)*. Government of India, New Delhi. https://nfsa.gov.in/portal/nfsa-act

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., Rao, N. D., Riahi, K., Rogelj, J., De Stercke, S., Cullen, J., Frank, S., Fricko, O., Guo, F., Gidden, M., Havlík, P., Huppmann, D., Kiesewetter, G., Rafaj, P., … Valin, H. (2018). A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nature Energy*, *3*(6), 515–527. https://doi.org/10.1038/s41560-018-0172-6

Gupta, P. K., Gupta, V., Sharma, C., Das, S. N., Purkait, N., Adhya, T. K., Pathak, H., Ramesh, R., Baruah, K. K., Venkatratnam, L., Singh, G., & Iyer, C. S. P. (2009). Development of methane emission factors for Indian paddy fields and estimation of national methane budget. *Chemosphere*, *74*(4), 590–598. https://doi.org/10.1016/j.chemosphere.2008.09.042

Harmsen, M., Tabak, C., Höglund-Isaksson, L., Humpenöder, F., Purohit, P., & van Vuuren, D. (2023). Uncertainty in non-CO2 greenhouse gas mitigation contributes to ambiguity in global climate policy feasibility. *Nature Communications*, *14*(1), Art. 1. https://doi.org/10.1038/s41467-023-38577-4

Hemingway, C., Vigne, M., & Aubron, C. (2023). Agricultural greenhouse gas emissions of an Indian village - Who’s to blame: Crops or livestock? *Science of The Total Environment*, *856*, 159145. https://doi.org/10.1016/j.scitotenv.2022.159145

Höglund-Isaksson, L., Gómez-Sanabria, A., Klimont, Z., Rafaj, P., & Schöpp, W. (2020). Technical potentials and costs for reducing global anthropogenic methane emissions in the 2050 timeframe –results from the GAINS model. *Environmental Research Communications*, *2*(2), 025004. https://doi.org/10.1088/2515-7620/ab7457

IEA. (2022). *World Energy Outlook 2022*. International Energy Agency. https://www.iea.org/reports/world-energy-outlook-2022

Jha, C. K., Singh, V., Stevanović, M., Dietrich, J. P., Mosnier, A., Weindl, I., Popp, A., Traub, G. S., Ghosh, R. K., & Lotze-Campen, H. (2022). The role of food and land use systems in achieving India’s sustainability targets. *Environmental Research Letters*, *17*(7), 074022. https://doi.org/10.1088/1748-9326/ac788a

Kainuma, M., Matsuoka, Y., Morita, T., & Hibino, G. (1999). Development of an end-use model for analyzing policy options to reduce greenhouse gas emissions. *IEEE Transactions on Systems, Man, and Cybernetics, Part C (Applications and Reviews)*, *29*(3), 317–324.

Kikstra, J. S., Vinca, A., Lovat, F., Boza-Kiss, B., van Ruijven, B., Wilson, C., Rogelj, J., Zakeri, B., Fricko, O., & Riahi, K. (2021). Climate mitigation scenarios with persistent COVID-19-related energy demand changes. *Nature Energy*, *6*(12), Art. 12. https://doi.org/10.1038/s41560-021-00904-8

Klimont, Z., Kupiainen, K., Heyes, C., Purohit, P., Cofala, J., Rafaj, P., Borken-Kleefeld, J., & Schöpp, W. (2017). Global anthropogenic emissions of particulate matter including black carbon. *Atmospheric Chemistry and Physics*, *17*(14), 8681–8723. https://doi.org/10.5194/acp-17-8681-2017

Klimont, Z., & Winiwarter, W. (2015). Estimating costs and potential for reduction of ammonia emissions from agriculture in the GAINS model. *Costs of Ammonia Abatement and the Climate Co-Benefits*, 233–261.

Lotze-Campen, H., Müller, C., Bondeau, A., Rost, S., Popp, A., & Lucht, W. (2008). Global food demand, productivity growth, and the scarcity of land and water resources: A spatially explicit mathematical programming approach. *Agricultural Economics*, *39*(3), 325–338.

Mishra, S. N., Mitra, S., Rangan, L., Dutta, S., & Singh, P. (2012). Exploration of 'hot-spots' of methane and nitrous oxide emission from the agriculture fields of Assam, India. *Agriculture & Food Security*, *1*(1), 16. https://doi.org/10.1186/2048-7010-1-16

MoAFW GoI. (2023a). *Agricultural Statistics at a Glance*. Ministry of Agriculture and Farmers Welfare (MoAFW), Government of India (GoI). https://agricoop.gov.in/en/Agricultural_Statistics_at_a_Glance

MoAFW GoI. (2023b). *Annual Report 2022-23*. Ministry of Agriculture and Farmers Welfare (MoAFW), Government of India (GoI). https://agricoop.gov.in/Documents/annual_report_english_2022_23.pdf

MoEFCC. (2021). *India Third Biennial Update Report to The United Nations Framework Convention on Climate Change*. Ministry of Environment, Forest and Climate Change, Government of India. https://unfccc.int/sites/default/files/resource/INDIA_%20BUR-3_20.02.2021_High.pdf

MoEFCC. (2023). *India: Third National Communication and Initial Adaptation Communication to the United Nations Framework Convention on Climate Change*. Ministry of Environment, Forest and Climate Change, Government of India.

Olivier, J. G. J., & Peters, J. A. H. W. (2020). *Trend in Global CO2 and GHG Emissions – 2020 Report*. PBL, Netherlands.

Pathak, H. (2015). Greenhouse Gas Emission fromIndian Agriculture: Trends, Drivers and Mitigation Strategies. *Proceedings of the Indian National Science Academy*, *81*(5). https://doi.org/10.16943/ptinsa/2015/v81i5/48333

Patra, A. K. (2017). Accounting methane and nitrous oxide emissions, and carbon footprints of livestock food products in different states of India. *Journal of Cleaner Production*, *162*, 678–686. https://doi.org/10.1016/j.jclepro.2017.06.096

PIB. (2020). *Decrease in Agricultural Holdings*. Press Information Bureau, Government of India. https://pib.gov.in/newsite/PrintRelease.aspx?relid=199780

Powlson, D. S., Stirling, C. M., Jat, M. L., Gerard, B. G., Palm, C. A., Sanchez, P. A., & Cassman, K. G. (2014). Limited potential of no-till agriculture for climate change mitigation. *Nature Climate Change*, *4*(8), Art. 8. https://doi.org/10.1038/nclimate2292

Purohit, P., Amann, M., Kiesewetter, G., Rafaj, P., Chaturvedi, V., Dholakia, H. H., Koti, P. N., Klimont, Z., Borken-Kleefeld, J., Gomez-Sanabria, A., Schöpp, W., & Sander, R. (2019). Mitigation pathways towards national ambient air quality standards in India. *Environment International*, *133*, 105147. https://doi.org/10.1016/j.envint.2019.105147

Purohit, P., & Chaturvedi, V. (2018). Biomass pellets for power generation in India: A techno-economic evaluation. *Environmental Science and Pollution Research*, *25*(29), 29614–29632.

Purohit, P., & Dhar, S. (2018). Lignocellulosic biofuels in India: Current perspectives, potential issues and future prospects. *Aims Energy*, *6*(3), 453–486.

Purohit, P., & Höglund-Isaksson, L. (2017). Global emissions of fluorinated greenhouse gases 2005–2050 with abatement potentials and costs. *Atmospheric Chemistry and Physics*, *17*(4), 2795–2816. https://doi.org/10.5194/acp-17-2795-2017

Purohit, P., Höglund-Isaksson, L., Dulac, J., Shah, N., Wei, M., Rafaj, P., & Schöpp, W. (2020). Electricity savings and greenhouse gas emission reductions from global phase-down of hydrofluorocarbons. *Atmospheric Chemistry and Physics*, *20*(19), 11305–11327. https://doi.org/10.5194/acp-20-11305-2020

Ravishankara, A., Kulenstierna, J., Michalopoulou, E., Höglund-Isaksson, L., Zhang, Y., Seltzer, K., Ru, M., Castelino, R., Faluvegi, G., & Naik, V. (2021). *Benefits and Costs of Mitigating Methane Emissions*.

Reddy, P. R. K., Kumar, D. S., Rao, E. R., Seshiah, C. V., Sateesh, K., Rao, K. A., Reddy, Y. P. K., & Hyder, I. (2019). Environmental sustainability assessment of tropical dairy buffalo farming vis-a-vis sustainable feed replacement strategy. *Scientific Reports*, *9*(1), 16745. https://doi.org/10.1038/s41598-019-53378-w

Sharma, S. K., Choudhury, A., Sarkar, P., Biswas, S., Singh, A., Dadhich, P. K., Singh, A. K., Majumdar, S., Bhatia, A., Mohini, M., Kumar, R., Jha, C. S., Murthy, M. S. R., Ravindranath, N. H., Bhattacharya, J. K., Karthik, M., Bhattacharya, S., & Chauhan, R. (2011). Greenhouse gas inventory estimates for India. *Current Science (Bangalore)*, *101*, 405–415.

Shyamsundar, P., Springer, N., Tallis, H., Polasky, S., Jat, M. L., Sidhu, H., Krishnapriya, P., Skiba, N., Ginn, W., Ahuja, V., & others. (2019). Fields on fire: Alternatives to crop residue burning in India. *Science*, *365*(6453), 536–538.

Singh, B., & Singh, Y. (2008). Reactive nitrogen in Indian agriculture: Inputs, use efficiency and leakages. *Current Science (00113891)*, *94*(11).

Singh, U., Algren, M., Schoeneberger, C., Lavallais, C., O'Connell, M. G., Oke, D., Liang, C., Das, S., Salas, S. D., & Dunn, J. B. (2022). Technological avenues and market mechanisms to accelerate methane and nitrous oxide emissions reductions. *IScience*, *25*(12), 105661. https://doi.org/10.1016/j.isci.2022.105661

Sirohi, S., & Michaelowa, A. (2007). Sufferer and cause: Indian livestock and climate change. *Climatic Change*, *85*(3), 285–298. https://doi.org/10.1007/s10584-007-9241-8

Some, S., Roy, J., & Ghose, A. (2019). Non-CO2 emission from cropland based agricultural activities in India: A decomposition analysis and policy link. *Journal of Cleaner Production*, *225*, 637–646. https://doi.org/10.1016/j.jclepro.2019.04.017

United Nations. (2019). *World Population Prospects 2019, Online Edition. Rev. 1.* United Nations, Department of Economic and Social Affairs, Population Division. https://population.un.org/wpp/Download/Standard/Population/

Upadhyay, P. K., Dey, A., Singh, V. K., Dwivedi, B. S., Singh, T., A, R. G., Babu, S., Rathore, S. S., Singh, R. K., Shekhawat, K., Rangot, M., Kumar, P., Yadav, D., Singh, D. P., Dasgupta, D., & Shukla, G. (2023). Conjoint application of nano-urea with conventional fertilizers: An energy efficient and environmentally robust approach for sustainable crop production. *PLOS ONE*, *18*(7), e0284009. https://doi.org/10.1371/journal.pone.0284009

Vishwanathan, S. S., & Garg, A. (2020). Energy system transformation to meet NDC, 2 °C, and well below 2 °C targets for India. *Climatic Change*, *162*(4), 1877–1891. https://doi.org/10.1007/s10584-019-02616-1

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., De Vries, W., Majele Sibanda, L., … Murray, C. J. L. (2019). Food in the Anthropocene: The EAT–Lancet Commission on healthy diets from sustainable food systems. *The Lancet*, *393*(10170), 447–492. https://doi.org/10.1016/S0140-6736(18)31788-4

Winiwarter, W., Höglund-Isaksson, L., Klimont, Z., Schöpp, W., & Amann, M. (2018). Technical opportunities to reduce global anthropogenic emissions of nitrous oxide. *Environmental Research Letters*, *13*(1), 014011. https://doi.org/10.1088/1748-9326/aa9ec9

World Bank. (2022). *Striving for Clean Air: Air Pollution and Public Health in South Asia*. World Bank.