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Drivers of GHG Emissions in Major Agricultural Emitter Countries Across the World

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ABSTRACT

Background: Agriculture impacts the economy and society globally. However, it also contributes to global greenhouse gas (GHG) emission significantly. It poses challenges to sustainability amidst growing population and rising food demands. Thus, to understand the factors affecting agriculture GHG emission plays an important role in designing effective mitigation strategies.

Methods: This study analyzes the drivers of agriculture GHG emission for top emitters across the World from 1992 to 2022 by disintegrating the emission into agriculture emission intensity effect, agriculture structure effect, productivity effect, mechanization effect and the labor effect. Also, to assess and track the pattern of sustainability across countries over the period of time, a sustainability index (SI) was constructed.

Result: The results showed that the sustainability index for India increased till 2013-15 and decreased thereafter. For rest of the top emitters, it increased throughout indicating unsustainability. The absolute changes in emission were driven by agricultural emission intensity effect, structure effect, productivity effect, mechanization effect and labor effect.

Key words: Agriculture, Climate change, Emissions, Mechanization, Sustainability.

INTRODUCTION

Agriculture plays a vital role in survival and economic well-being of societies across globe. The sector provides food security and supports livelihood for almost 0.87 billion people and contributes 4.31 per cent in 2021 to World's GDP (FAO, 2021). However, alongside its developmental role, agriculture is a significant source of greenhouse gas (GHG) emissions, placing it at the core of global climate mitigation debates. IPCC (2022) stated that the agriculture, forestry and other land use (AFLOU) alone contribute around 23 per cent of total anthropogenic GHG emission. Amongst AFLOU, agriculture is solely responsible for approximately 10-12 per cent of the global emission. The emission primarily stems from methane (CH_4) and nitrous oxide (N_2O), the two potent GHG with global warming potential higher than CO_2 (Singh *et al.,* 2014; Basheer *et al.,* 2024).

Net forest conversion contributes the highest to agriculture emission (18.54%) worldwide (Fig 1). The second category is enteric fermentation from livestock with 18.29 per cent share and is highly responsible for CH_4 emission globally. Though, rice cultivation contributes only 4.30 per cent to global emission, but has significant contribution in methane gas emission from agriculture in Asian countries such as India, China, Indonesia (FAOSTAT, 2024). Categories such as drained organic soil, on-farm energy use contributes more than five per cent of the emission but are highly responsible for N_2O gas emission. Steady increase in emission of the potent gases have been observed over the past three decades, in tandem with global population growth and rising food demands (Tubiello *et al*., 2022; Crippa *et al*., 2021). Thus, agriculture not only feeds the World but also fuels climate change. The effect of climate change and GHG emission on agriculture is also significantly increasing and the economic losses are substantially affecting the population either directly or indirectly. The World Bank (2016) estimated that climate change could result in five per cent yield losses globally by 2030 and 30 per cent losses by 2080. The loss of production for crops and livestock due to climate change was estimated to be $3.8 trillion over the past 30 years which was five per cent of the agricultural GDP globally (FAO, 2023).

Though, agricultural sector accounts for approximately 24 per cent of global GHG emission, it is highly concentrated (Saha *et al.,* 2025). China tops with 22 per cent contribution to GHG emission followed by Brazil and Indonesia contributing 21 and 13 per cent respectively. India stands the fourth with 12 per cent of contribution and USA, the fifth with 12 per cent contribution to GHG emission (FAOSTAT, 2024).

The study on agricultural greenhouse gas emission, in the past few decades, have gained a significant attention

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due to its impact on climate change and implications on sustainability. This has prompted the scientists and researchers to understand the determinants of agricultural greenhouse gas emission. Patra (2014) conducted a study on trends and projected estimates of GHG emission from livestock in India in comparison to the World and other developing countries from 1961 to 2010. The results showed that enteric fermentation was significantly responsible for increase in GHG emission and the percentage increase in methane emission due to enteric fermentation in India was greater than the World. The study concluded that the contribution of India to global GHG emission was less than the developing countries. Dietz *et al.* (2015) conducted a study on greenhouse gas emissions in the US states. The study found that population and economic forces were major factors of environmental stress. The findings revealed that 1 per cent increase in employment leads to 1.21 per cent increase in emissions and 1 per cent increase in population leads to 0.94 per cent increase in greenhouse gas emissions. The study concluded that policies that support environmental protection can help mitigate the negative impact of population growth and economic growth on the environment.

Song *et al.* (2023) conducted a study to observe the impact of agricultural inputs on Carbon emission in China over the past three decades. The results showed that inputs like fertilizers, agricultural industries and energy-use intensity were positively related with Carbon emission. The degree of migration from rural areas, investment in agriculture and large-scale plantation showed a negative relationship with Carbon emission. The study concluded that the government of China should focus on technology driven farming and should promote sustainable development in its agriculture. Similarly, Karstensen *et al.* (2020) conducted a study to identify the key drivers of greenhouse gas emission in India. The results showed that compared to the World, emission in India has increased from 1.3 per cent in 1970 to 6.3 per cent in 2015. The study also projected that share of India in global GHG emission will increase from 7.5 per cent in 2020 to 14 per cent in 2040. The major factor that contributed to this increase is the economic growth in India leading to increase in use of energy. The study concluded that the country needs to focus more on use of green energy and invest in renewable energy, thus, promoting sustainable development. Das *et al.* (2026) conducted a study to analyse the trend of methane and nitrous oxide emission from livestock from 1980 to 2024. The results showed a persistent upward trend for both methane and nitrous oxide gas emission. The study concluded that without the implementation of any targeted mitigation measures, the emission from livestock is likely to increase with significantly higher uncertainty in methane projections.

The existing empirical studies have primarily examined agricultural emissions within single country context and there is insufficient comparative decomposition analysis across major emitting countries. Also, the Laspeyres additive method has been widely used for decomposition analysis in energy or industrial sector but had a limited use in agricultural sector. Addressing these gaps is essential for developing evidence-based mitigation strategies across major GHG emitters. This research, thus, aims to fill the gap by using Laspeyres additive decomposition method to analyze the economic drivers of agriculture greenhouse gas emission for top emitters including the World.

The study hypothesized that mechanization of agriculture is the key driver of agricultural emission and different components of change in emissions. The study is novel in its approach to investigate this hypothesis by utilizing the combination of decomposition analysis with Simultaneous equation model using panel data approach. The rest of the paper was organized as follows. Section 2 presented the data and methodology which details data and analytical tool followed by Section 3 presenting Results and discussion of the same with reference to past studies and at last section 4 draws conclusion and policy implications.

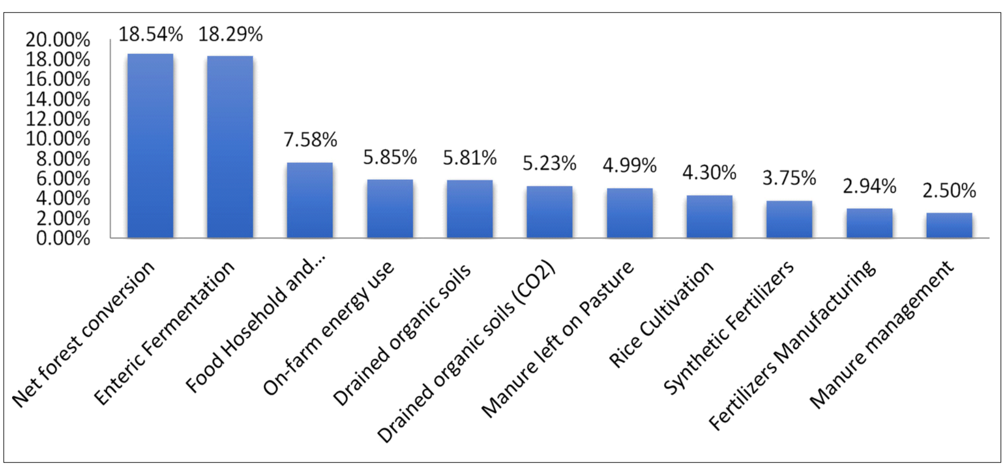

Fig 1: Category-wise CO_2 eq. agricultural emissions share in the world 2022 (FAO, 2022).

MATERIALS AND METHODS

The study was purely based on secondary data which were obtained from the official website of Food and Agriculture Organization Statistics (FAOSTAT). Top 10 emitters including a special region EU 27 and the World was included for the study. The data was collected from 1991 to 2022. An index number is a construct used to compare data on several variables over a period of time. The year in reference to which all comparisons are made is referred to as base year. The year 1991 was selected as the base year for the decomposition analysis because a methodologically consistent data on agriculture and GHG emission are available from the early 1990s onward. This year also mark the change in global agriculture landscape after fall of Berlin's Wall and collapse of Soviet Union. For India this year marks the beginning of liberalization, privatization and globalization.

The details on the variables and its description are provided in Table 1.

For decomposition analysis of data under study, Laspeyres additive decomposition model was used. A technique that employs a well-known concept of percentage changes to make it easier to understand and utilize results when making comparative evaluations (Sun *et al.,* 2018).

In this study, the method was applied to break down and analyze the factors contributing to emissions in agriculture. An alternative form of Kaya identity was adopted which is provided in Equation 1.

Equation 1

$$\text{GHG emission in agriculture} = \text{Agriculture emission intensity} \times \text{Agriculture structure indicator} \times \text{Agriculture productivity} \times \text{Agriculture mechanization indicator} \times \text{Agriculture labour}$$

Agriculture Emission intensity is defined as the total amount of emission (CO_2 eq. AR5 kt) emitted by the agriculture sector for every million USD of gross value added in agricultural sector.

Equation 2

$$\text{Agriculture emission intensity} = \frac{\text{Agriculture emission}}{\text{Gross value added in agriculture sector}}$$

Agriculture structure indicates gross value added in agriculture sector (USD) per one USD of gross value of agriculture production.

Equation 3

$$\text{Agriculture structure indicator} = \frac{\text{Gross value added in agriculture sector}}{\text{Gross value added in agriculture production}}$$

Agriculture productivity is defined as gross value of agriculture production (000' USD) per 1000 hectare of agricultural land.

Equation 4

$$\text{Agricultural productivity} = \frac{\text{Gross value of agriculture production}}{\text{Agriculture land}}$$

Agriculture mechanization indicator denotes agricultural land (000' hectare) per workers engaged in agriculture.

Equation 5

$$\text{Agriculture mechanization indicator} = \frac{\text{Agriculture land}}{\text{Agriculture labor}}$$

Agricultural labour means number of labourers engaged in agriculture.

Equation 6

$$\text{Agriculture labour} = \text{Number of labourers engaged in agriculture}$$

The absolute changes in agricultural emission were decomposed into emission intensity, agriculture structure, agriculture productivity, agriculture mechanization and agriculture labor effect with the help of Laspeyres additive decomposition scheme. The scheme started with a multiplicative Kaya identity and final scheme is given is equation 7 which is additive in nature.

Equation 7

$$\text{Absolute change in GHG emission} = \text{Agriculture emission intensity effect} + \text{Agriculture structure effect} + \text{Agricultural productivity effect} + \text{Agriculture mechanisation effect} + \text{Agriculture labour effect}$$

Each effect denotes the changes in GHG emission from agriculture due to changes in respective indicator.

Equation 8

$$EI_{eff} = \Delta EI_t \times Str_{t-1} \times Prod_{t-1} \times Mech_{t-1} \times Ag\_Lab_{t-1}$$

$$+ \frac{1}{2} \times (\Delta EI_t \times \Delta Str_t \times Prod_{t-1} \times Mech_{t-1} \times AgLab_{t-1} + \Delta EI_t \times Str_{t-1} \times \Delta Prod_t \times Mech_{t-1} \times AgLab_{t-1} + \Delta EI_t \times Str_{t-1} \times Prod_{t-1} \times \Delta Mech_t \times AgLab_{t-1} + \Delta EI_t \times Str_{t-1} \times Prod_{t-1} \times Mech_{t-1} \times \Delta AgLab_t)$$

$$+ \frac{1}{3} \times (\Delta EI_t \times \Delta Str_t \times \Delta Prod_t \times Mech_{t-1} \times AgLab_{t-1} + \Delta EI_t \times \Delta Str_t \times Prod_{t-1} \times \Delta Mech_t \times AgLab_{t-1} + \Delta EI_t \times \Delta Str_t \times Prod_{t-1} \times Mech_{t-1} \times \Delta AgLab_t + \Delta EI_t \times Str_{t-1} \times \Delta Prod_t \times \Delta Mech_t \times AgLab_{t-1} + \Delta EI_t \times Str_{t-1} \times \Delta Prod_t \times Mech_{t-1} \times \Delta AgLab_t + \Delta EI_t \times Str_{t-1} \times Prod_{t-1} \times \Delta Mech_{t-1} \times \Delta AgLab_t)$$

$$+ \frac{1}{4} (\Delta EI_t \times \Delta Str_t \times \Delta Prod_t \times \Delta Mech_t \times AgLab_{t-1} + \Delta EI_t \times Str_{t-1} \times \Delta Prod_t \times \Delta Mech_t \times \Delta AgLab_t + \Delta EI_t \times \Delta Str_t \times \Delta Prod_t \times Mech_{t-1} \times \Delta AgLab_t + \Delta EI_t \times \Delta Str_t \times Prod_{t-1} \times \Delta Mech_t \times \Delta AgLab_t)$$

$$+\frac{1}{5}(\Delta EI_t \times \Delta Str_t \times \Delta Prod_t \times \Delta Mech_t \times \Delta Ag\_Lab_t)$$

Where,

EI_{eff}= Effect on agricultural emissions due to changes in agricultural emission intensity (emission intensity effect).

ΔEI_t= Changes in agriculture emission intensity.

ΔStr_t= Changes in agriculture structure indicator.

$\Delta Prod_t$= Changes in agriculture productivity.

$\Delta Mech_t$= Changes in Mechanization.

$\Delta AgLab_t$= Changes in agricultural labourer.

EI_{t-1}= Value of agriculture emission intensity at in the t-1.

Str_{t-1}= Value of agriculture structure indicator at in the t-1.

$Prod_{t-1}$= Value of agriculture productivity at in the t-1.

$Mech_{t-1}$= Value of mechanization at in the t-1.

Ag_Lab_{t-1}= Value of agricultural labour at in the t-1.

The similar equation was prepared for Str_{eff}, $Prod_{eff}$, $Mech_{eff}$ and Lab_{eff} to calculate agriculture structure effect, agriculture productivity effect, mechanization effect and agriculture labor effect.

Where,

Str_{eff}= Effect on agricultural emissions due to changes in agriculture structure indicator (agricultural structure effect).

$Prod_{eff}$= Effect on agriculture emissions due to changes in agriculture productivity (agriculture productivity effect).

$Mech_{eff}$= Effect on agricultural emissions due to changes in mechanization (Mechanization effect).

Lab_{eff} = Effect on agricultural emissions due to changes in agricultural labour (agriculture labour effect).

The outcome of decomposition analysis was presented with the help of mean and coefficient of variation in Table 3. The share of each effect in change in emission was worked out and was presented for two time periods. The two time periods included base period of 1992 to 1994 and the current period of 2019 to 2021. The average share was worked out for both base and current period.

The effects calculated for each country over the years were then used to tabulate the sustainability index for each country.

Equation 9

$$Y'_{it} = \frac{Y_{it} - Y_{min}}{Y_{max} - Y_{min}}$$

Where,

Y'_{it}= The normalized value of effect.

Y_{it}= The actual value of effect for country i in time t.

Y_{min}, Y_{max}= Minimum and maximum value of the indicator across all countries and years.

Thereafter, average of the normalized value of indicator is computed for each country to calculate a composite index.

Equation 10

$$SI_{it} = 1-\frac{1}{n}\sum_{j=1}^{n} Y'_{ijt}$$

Where,

SI_{it}= Sustainability index for country i in year t.

n= Number of indicators.

Higher the value of SI, greater was the sustainability of agricultural emissions. The sustainability index was tabulated for each country by taking the triennium ending for the period under study and the results were tabulated in the table. The holistic index prepared was used to provide a measure of how agricultural system balances the growth of productivity while simultaneously reducing the agriculture GHG emission. The index also offers a quantifiable benchmark to assess the sustainability of each region (Goyal and Dhawan, 2021). However, the index and decomposition method are subject to the drivers identified and its relevance to the countries in study.

To investigate the dynamic relationship among agriculture GHG emission drivers, the study employed a simultaneous equation model (SEM) based on panel data framework. The analysis accounted for data spanning 1992 to 2022 across top emitters with India serving as the benchmark for country-specific dummy variables. The SEM consisted of four inter-relation equations, each capturing distinct effect derived from the decomposition analysis of GHG emissions. The approach allowed for the examination of endogenous relationships among the variables while accounting for country-specific heterogeneity. The equations were structured as follows:

Equation 11

$$\Delta EMI = \beta_o + \beta_1 IE_{it} + \beta_2 SE_{it} + \beta_3 PE_{it} + \beta_4 ME_{it} + \sum_{j=2}^{n}\gamma_j D_{jit} + \epsilon_{it}$$

Equation 12

$$IE_{it} = \alpha_o + \alpha_1 SE_{it} + \alpha_2 PE_{it} + \alpha_3 ME_{it} + \sum_{j=2}^{n}\lambda_j D_{jit} + v_{it}$$

Equation 13

$$SE_{it} = \theta_o + \theta_1 PE_{it} + \theta_2 ME_{it} + \sum_{j=2}^{n}\delta_j D_{jit} + \mu_{it}$$

Equation 14

$$PE_{it} = \phi_o + \phi_1 ME_{it} + \sum_{j=2}^{n}\sigma_j D_{jit} + \omega_{it}$$

Where,

ΔEMI: Absolute change in emission intensity.

IE_{it}: The agriculture emission intensity effect.

SE_{it}: The agriculture structure effect.

PE_{it}: The productivity effect.

ME_{it}: The mechanization effect.

D_{jit}: Country-specific dummy variables.

ϵ_{it}, v_{it}, μ_{it}, ω_{it}: Stochastic error term.

β_o, β_1, β_2, β_3, β_4, α_o, α_1, α_2, α_3, θ_o, θ_1, θ_2, ϕ_o, ϕ_1: The non-zero partial regression coefficients.

$\gamma_j, \lambda_j, \delta_j, \sigma_j$: The coefficient associated with the country dummy variable (D_{jit}) for country j.

The triangular or causal model represented here is recursive in nature indicating a unidirectional causal structure from mechanization effect to productivity effect, structure effect and ultimately to change in Emission intensity (Gujarati and Porter, 2009).

RESULTS AND DISCUSSION

The global agricultural emissions were marked by significant disparities among top emitters' (Fig 2). Countries such as China, Brazil, EU 27 region, Indonesia, India and the USA are responsible for more than 50 per cent of global agriculture emission. China's and Brazil's contribution of 12.24 and 12.04 per cent to global emission are mainly due to its excessive use of fertilizers and livestock farming. Livestock farming contributed significant proportion of CH_4 and N_2O emissions in both nations, in Brazil it accounted for 63 percent of total agricultural emissions. Paddy cultivation also accounted for 22 to 38 per cent of CH_4 emission in China. Extensive use of fertilizers also contributed to N_2O emissions (Brentrup *et al.*, 2018; FAO, 2022; Tian *et al.*, 2024; Gao *et al.*, 2025).

Indonesia contributes seven per cent of total global GHG emission from agriculture mainly due to rise in paddy and oil palm cultivation; paddy and oil palm contributed nine per cent to Indonesia's agricultural GHG emission in 2020 (Purba *et al.*, 2023). India stands fifth with 6.97 per cent contribution to global GHG emission from agriculture. Enteric fermentation, Paddy cultivation, excessive use of fertilizers and manures, crop residue burning especially in Northern part of India are the major sources of GHG emission (Kumar and Aravindakshan, 2022).

Amongst the top emitters, China had the highest agriculture emissions, agriculture GDP, Gross production value in agriculture, agricultural land and labor employed. China recorded the highest CV in agricultural GDP (37.2%) and substantially lower CV for agricultural land (0.7%) due to strict regulation regarding land use policy (Table 2). For agriculture emissions, Indonesia (32.36%) exhibited the highest CV though ranked fourth in agriculture emission. While China and Brazil respectively ranked the first and the second in emission, had substantially lower CV of 19.11 and 18.65 per cent for agricultural emissions. On account of matured economies with stable production structure, USA, Canada and Japan exhibited lowest CV of agricultural emissions. The EU 27 region had the second highest agricultural GDP with lowest CV (5.6%). India, EU 27 region and USA had the large agricultural sector after China. For agricultural GDP, EU 27 region had the lowest CV (4.3%),

Table 1: Description of the variable under study.

Variables	Unit	Description
Agriculture emission	Co2 eq.AR5 Kt	Agri food system emissions including pre and post production emissions, farm gate emissions, agricultural land emissions and emissions from land use changes.
Agriculture GDP	Million USD at constant 2014-16 prices	Value added in agriculture, forestry and fisheries.
Employment in agriculture	1000 per worker	Total population engaged in agriculture and allied sectors.
Gross production value in agriculture	1000 USD at constant 2014-16 prices	Gross value of total agricultural production.
Agricultural land	1000 hectare	Land use for agriculture purpose.

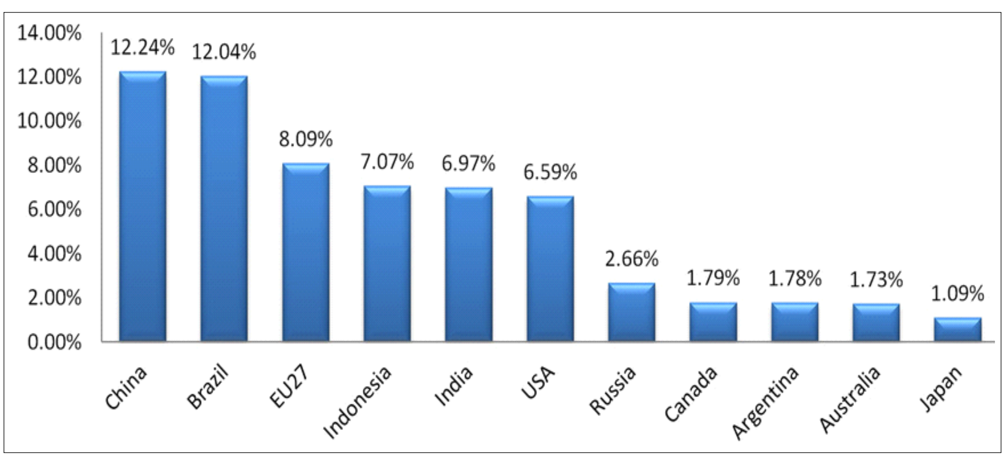

Fig 2: Share of top emitter countries in agricultural emissions to the world.

Brazil had the second highest (30.5%) followed by Indonesia (30.42%).

The gross production value in agriculture sector was second highest in EU 27 followed by USA and India. The Brazil had the highest CV of 31.92 per cent followed by India with CV of 30.23 per cent in gross production value reflecting higher volatility in production and prices. The lowest CV in gross production value is in EU 27 region reflecting mature production structure and stable prices. The Australia had the third highest agricultural land with highest CV (10.7%) while India had the lowest (0.5%).

After China, India had the highest number of labors employed in agriculture globally with lowest CV (5.7%) on account of growing population with higher dependency of rural population on agriculture. Though EU 27 region had substantially lower number of labors employed in agricultural, had the highest CV (27.9%) on account of inter-industry migration and declining interest of youth towards agriculture.

The changes in emission were driven by agricultural emission intensity, structure effect, productivity effect, mechanization effect and labor effect (Table 3). China recorded the largest increase in its emissions in past three decades while Japan had recorded the lowest increase in emission. Japan had the highest CV of change in emissions while China had substantially lower CV (152%). The lowest CV for change in emission was exhibited by India (109%). Indonesia recorded the largest decrease in emissions among all top agricultural emission emitters followed by Brazil and Russia. For the World, agricultural emissions increased over the last three decades. China and India contributed 80 per cent of this increase in emission from agriculture.

In the World, emission intensity effect was the largest component of change in emissions. It was negative for the World and for top emitters with exception of Japan which recorded positive value for this effect. The negative value of this effect indicate that agricultural GDP had grown at faster pace than the agricultural emissions. Thus, Japanese agriculture is becoming unsustainable with fast paced emissions coupled with slow value additions (World Bank, 2025). Brazil, Indonesia and China together contributed 50 per cent of emission intensity effect in the World. Argentina had the highest CV of 985 per cent indicating significant fluctuation in agriculture emission per unit of agriculture output (Table 3).

The agriculture structure effect was the third largest component of change in emissions in the World. China, Indonesia and USA accounted for one third of this effect in the World. The structure effect and agricultural economic growth were the drivers of agriculture emission for China with 5.14 MT and 0.35 MT from 2000 to 2018, respectively (Sui and Lv, 2021) Argentina, EU 27, Japan, Russia and Brazil had the negative values for this effect. These countries had slow pace of value addition in agriculture sector compared to increase in gross production value in

Table 2: Descriptive statistics of indicators under study.

Countries	Agriculture emission (CO_2 eq 000' kt)		Agricultural GDP (Billion USD)		Gross production value in agriculture (Billion USD)		Agricultural land (100 000' hectare)		Labors employed in agriculture (100 000' workers)	
	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
China	1898	19.1	725	37.2	985	27.8	5239	0.7	2903	24.7
Brazil	1842	18.7	60	30.5	132	31.9	2305	1.4	103	13.3
EU27	1242	4.3	207	5.6	344	4.3	1739	5.0	130	27.9
Indonesia	1084	32.4	91	30.4	98	26.2	484	10.1	402	6.1
India	1078	14.0	291	29.6	295	30.2	1801	0.5	2052	5.7
USA	1014	3.9	146	22.0	320	11.3	4159	0.9	28	14.3
Russia	409	13.6	49	14.0	70	17.5	2163	0.6	64	26.9
Australia	264	17.9	27	20.8	34	14.9	4101	10.7	4	11.4
Argentina	274	11.0	27	18.1	49	19.6	1251	3.7	16	9.6
Canada	275	3.3	25	19.0	38	16.9	597	3.1	4	17.4
Japan	167	3.7	54	16.8	98	7.0	51	6.6	28	23.5
World	15408	4.8	2555	26.9	3490	18.7	48122	0.7	9541	5.5

Note: The mean values were rounded off to provide ease of interpretation and readability.

agriculture. China had the lowest CV of 174 per cent while Canada had the highest CV (7497%) with lowest positive structure effect. Intensive production practices can undermine the sustainability while intensive value addition would lead to greater sustainability by making better use of resources thus enhancing the sustainability of agri-food system (Sial *et al.,* 2021) (Table 3).

The agricultural productivity effect was the second largest component of change in emissions in the World. Brazil, China and India accounts for 50 per cent of this effect in the World. Japan, Russia, Canada, Australia and Argentina had the lowest value for this effect. These countries had slower pace of increase in gross production value in agriculture as compared to increase in agricultural land. Japan had the highest CV of 2874 per cent while China had the lowest CV (51%) (Table 3).

The mechanization and labor effect are the smallest component of change in emission in the World. China is the only country to surpass the global mean for mechanization effect. Large tractors and advanced equipment uplifted the technological advancement in China's agriculture sector which led to promotion of modernized agriculture in China from 2002 to 2012 (Meng *et al.,* 2024). While India was the only country with a negative value for this effect; for India, gross value production in agriculture had slower pace than the increase in agricultural labors. Australia had the highest CV (2020%) with lowest positive value for this effect while China had the lowest CV (87%). India and Indonesia were the only countries with positive value of labor effect which indicated increase in labors employed in agriculture. Indonesia had the highest CV (719%) while EU 27 region had the lowest CV (76%) (Table 3).

For India, compared to the base period (1992-94), the current period (2019-21) showed a decline of 2.2 per cent point in contribution of agriculture emission intensity effect (Table 4). This indicated a faster growth in agriculture GDP as compared to agriculture emission. The National Mission on Sustainable Agriculture, a part of National Action Plan on Climate Change, had directly focused on making India sustainable. The development of climate resilient technologies, diversifying cropping pattern and many other practices has led to slight reduction in the agriculture emission intensity effect (Padhee and Whitbread, 2022). Similarly, all other effects except mechanization and labor effect showed a decline in their respective contribution. As opposed to India, China showed an increase in contribution of agriculture emission intensity effect by 5.38 percent point. The total CO_2 emission from agricultural land of China increased with an average growth rate of 1.82 per cent annually due to agricultural diesel, plastic films and fertilizers from 1995 to 2020 (Liu *et al.,* 2023). While, the mechanization effect had no significant change, the productivity effect showed a decline of 20.56 percent point in its contribution.

While comparing Indonesia and Japan, agriculture emission intensity and labor effect had contrasting absolute

Table 3: Country-wise components of change in emission from agriculture [Unit: CO_2 eq 000' kt].

Countries	Agriculture emission intensity effect		Agriculture structure effect		Agriculture productivity effect		Mechanization effect		Labour effect		Change in emission	
	Mean	CV (%)	Mean	CV(%)	Mean	CV(%)	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
China	-45.4	106	19.4	174	57.4	51	55.0	87	-54.5	90	31.8	152
India	-20.1	195	0.8	2913	35.2	105	-8.8	300	8.2	317	15.3	109
USA	-16.6	399	8.6	667	12.9	292	6.3	663	-7.4	560	3.8	660
Argentina	-3.4	985	-0.8	2465	6.0	251	1.4	679	-2.1	452	1.1	1190
Canada	-4.0	377	0.1	7497	5.5	287	4.6	401	-5.3	350	1.0	465
Japan	3.0	309	-1.8	482	0.2	2874	2.8	133	-4.0	96	0.2	2014
EU27	-5.8	857	-1.4	1798	8.0	427	32.5	97	-35.1	76	-1.8	-1061
Australia	-8.9	537	2.7	1775	5.8	518	0.7	2020	-3.0	386	-2.8	-1091
Russia	-4.1	756	-0.5	3483	1.7	1575	9.6	328	-10.0	312	-3.4	-479
Brazil	-76.1	230	-2.6	1354	66.6	93	12.6	665	-14.5	556	-14.0	-1159
Indonesia	-49.7	775	3.8	874	17.5	211	5.8	559	4.2	719	-18.5	-2103
World	-361.9	107	93.4	321	331.4	85	42.2	372	-42.7	386	62.5	586

Note: Mean values were rounded off to provide ease of interpretation and readability. CV in percentage terms.

contributions. For Indonesia, agriculture emission intensity effect showed an increase in its contribution by 40 per cent point. In 2022, Indonesia had the highest emission intensity mainly due to land-use changes (Tubiello *et al.,* 2024). While Japan showed a significant decline of 22.77 per cent point. Due to loss of area and interest of youth in agricultural sector, the capability of the sector had declined in 2020-21. This led to decrease in agricultural emission (Kazuya, 2023). For labor effect, Indonesia exhibited a notable decline in its contribution marking a 12.2 per cent point decline relative to base period while Japan showed significant increase of 21.02 per cent point. For the agriculture structure and productivity effects, both the countries exhibited a notable decline in their contributions. For Indonesia and Japan, mechanization effect showed a significant increase in the contribution respectively (Table 4).

For Russia and EU 27 region, agriculture emission intensity effect, agriculture structure effect and the mechanization effect exhibited a significant decline in their respective contribution. The contribution of productivity effect for both the countries had remarkably increased from base to current period whereas the labor effect, for Russia, declined by 7.63 per cent point and increased by 17.31 per cent point for EU 27 region (Table 4).

The agriculture emission intensity effect showed significant increase in its contribution for Argentina by 12.3 per cent point relative to base period while significantly declined for Brazil by 33 per cent point. The agriculture structure effect declined in its contribution in absolute change in agriculture emission for both Argentina and Brazil. While, the productivity effect remained same for Brazil, its contribution significantly increased for Argentina. The contribution of mechanization effect notably declined by 22.59 per cent point relative to base period for Argentina whereas increased for Brazil by 22.29 per cent point while the labor effect increased significantly for both the countries (Table 4).

While the contribution of agriculture emission intensity effect significantly declined by 24 per cent point for the USA, it increased by 13.13 per cent point for Canada. The contribution of agriculture structure effect and the mechanization effect significantly increased for both countries while the productivity effect notably declined. The contribution of labor effect declined significantly for USA and increased for Canada (Table 4).

On comparing Australia with the World, the contribution of agriculture emission intensity effect declined notably by 83.13 per cent point for Australia and globally increased by 23.34 per cent point from base to current period. The contribution of agriculture structure effect and the labor effect notably increased for Australia and the World. While, the contribution of the productivity effect remained same for Australia, it significantly declined by 12.3 per cent point for the World. The contribution of the mechanization effect declined for both Australia and the World (Table 4).

The triennium ending sustainability index (SI) for India showed that the sustainability index has increased till 2013-15

Table 4: Composition of various effects in change in agricultural emission across the countries and the world [Unit: Percentage].

Countries	Agriculture emission intensity effect		Agriculture structure effect		Productivity effect		Mechanization effect		Labor effect	
	Base period (1992-94)	Current period (2019-21)	Base period (1992-94)	Current period (2019-21)	Base period (1992-94)	Current period (2019-21)	Base period (1992-94)	Current period (2019-21)	Base period (1992-94)	Current period (2019-21)
India	-23.89	-21.67	11.50	5.49	29.78	23.28	-17.64	-25.13	17.19	24.44
China	-21.37	-26.75	-6.94	16.32	33.45	12.89	21.83	21.82	-16.42	-22.21
Indonesia	-36.11	-75.93	-5.87	11.16	42.28	7.74	-5.15	3.56	10.59	-1.61
Japan	19.97	-2.80	-16.20	1.34	12.63	9.79	22.64	36.49	-28.56	-49.58
Russia	26.27	-3.21	1.30	-26.22	-38.13	47.06	14.91	11.76	-19.39	-11.76
EU27	12.48	-4.16	-20.02	-10.66	-6.82	10.82	39.38	35.77	-21.29	-38.60
Argentina	-28.47	-40.76	30.93	13.78	10.09	25.90	15.76	-6.83	-14.75	12.73
Brazil	-34.78	-1.92	1.92	-2.47	41.42	41.35	-13.55	-35.84	8.33	18.43
USA	-25.91	-2.21	-0.77	-16.20	38.30	20.97	-19.54	26.68	15.48	-33.94
Canada	-1.71	11.42	-25.77	17.41	38.21	-23.06	16.09	21.93	-18.21	-26.18
Australia	18.63	-64.50	-31.89	28.37	5.19	5.01	24.43	2.10	-19.85	0.01
World	-17.59	-40.93	-31.28	17.75	47.77	27.21	2.53	-6.93	0.83	7.19

Note: Sum of absolute value of all effect's contribution is 100 per cent.

Table 5: Sustainability index for major emitters including the world (Triennium ending average).

TE period	India	China	Indonesia	Japan	Russia	EU27	Argentina	Brazil	USA	Canada	Australia	World
1992-94	0.409	0.704	0.695	0.641	0.625	0.607	0.697	0.621	0.628	0.655	0.536	0.644
1995-97	0.487	0.690	0.679	0.672	0.674	0.510	0.683	0.569	0.653	0.585	0.585	0.647
1998-00	0.551	0.727	0.637	0.647	0.687	0.523	0.757	0.563	0.658	0.638	0.635	0.708
2001-03	0.500	0.745	0.522	0.563	0.636	0.564	0.814	0.508	0.453	0.509	0.552	0.732
2004-06	0.487	0.681	0.393	0.488	0.628	0.648	0.775	0.490	0.481	0.509	0.522	0.671
2007-09	0.653	0.620	0.386	0.416	0.594	0.640	0.747	0.440	0.527	0.500	0.507	0.630
2010-12	0.653	0.554	0.439	0.417	0.591	0.605	0.657	0.449	0.472	0.474	0.468	0.565
2013-15	0.613	0.470	0.397	0.365	0.576	0.536	0.491	0.363	0.421	0.464	0.498	0.439
2016-18	0.543	0.393	0.393	0.343	0.502	0.486	0.405	0.386	0.438	0.515	0.552	0.342
2019-21	0.548	0.306	0.386	0.342	0.461	0.454	0.326	0.358	0.371	0.503	0.611	0.288
Mean	0.544	0.589	0.493	0.489	0.597	0.557	0.635	0.475	0.510	0.535	0.547	0.567

TE: Triennium ending.

and decreased thereafter (Table 5). Suresh *et al.* (2022) found that the agricultural sustainability showed an overall improvement for all states of India from 1971 to 2011. While the exact opposite holds true for Canada and Australia. The sustainability index of rest of the countries and the World increased over the years indicated unsustainable development. Globally, the lowest index value was observed for 2019-21 due to high-emission agricultural practices worldwide particularly excessive use of fertilizers to support the rising population, deforestation and net forest conversions. China, Indonesia, Japan, Argentina and USA experienced steep reduction in sustainability. While Russia, EU 27 and Brazil experienced moderate decline in sustainability.

Equation 11 of Simultaneous Equation Model (SEM) showed that changes in emission intensity effect and agriculture structure effect were causing nearly equal amount of effect on agricultural emissions (Table 6). India was the benchmark country in the regression model. While EU 27 had lower mean emission change compared to India by 4958.51 Co2 equivalent kilo tonnes, Indonesia had mean emission change higher by 9348.85 Co2 equivalent kilo tonnes than India. Rest of the countries didn't have any significant difference in mean changes in agricultural emissions with respect to India. The regressors in the model accounted for 99.7 per cent of the variation in change in emission.

Equation 12 showed that for every one unit increase in the structure effect and productivity effect, the intensity effect decreases by 0.778 and 0.845 units respectively, keeping other variables constant. The intensity effect for all the other countries were not significantly different from that of India, ceteris peribus. Equation 13 showed that, on an average, India experienced 10526.4 units increase in the structure effect, ceteris peribus. For every one unit increase in the productivity effect, the structure effect decreases by 0.239 unit, ceteris peribus. However, for every one unit increase in mechanization effect, the structure effect increases by 0.144 units, ceteris peribus. The structure effect of China is 14617.9 units higher than that of India whereas its lower by 14750.9 units for EU 27 region (Table 6).

Equation 14 showed that, on an average, India experienced 34378.6 units increase in the productivity effect, independent of any influence from mechanization effect. For every one unit increase in the mechanization effect, the productivity effect decreases by 0.091-unit, ceteris peribus. As for each country-specific dummy, the productivity effect of China and Brazil are 27997.7 units and 33397.4 units higher than that of India, respectively, ceteris peribus. However, the productivity effect of the USA, EU 27 region, Indonesia, Japan, Canada, Argentina and Australia are 20947.9, 23409.8, 16399.4, 33956.7, 28423.5, 28227.5 and 28535.5 units lower than that of India, respectively, ceteris peribus (Table 6).

Among all drivers of greenhouse gas emission from agriculture, Mechanization effect was common to all but for

Table 6: Result of simultaneous equation model.

Variables	Dependent variables			
	Equation 11	Equation 12	Equation 13	Equation 14
	Change in emission	Intensity effect	Structure effect	Productivity effect
Intercept (D_India)	595.97	10390	10526.4*	34378.6***
Intensity effect	0.995***			
Structure effect	0.95***	-0.778***		
Productivity effect	0.979***	-0.845***	-0.239***	
Mechanization effect	0.057***	0.011	0.144***	-0.091*
D_China	-1292.80	7200.95	14617.9*	27997.7***
D-_USA	-1462.74	-9456.06	242.829	-20947.9**
D_EU27	-4958.51***	-10871.9	-14750.9*	-23409.8***
D_Brazil	-2323.59	-32289.9	970.825	33397.4***
D_Indonesia	9348.85***	-42416.2	-3369.12	-16399.4*
D_Japan	-2017.24	-8671.11	-12714.0	-33956.7***
D_Canada	-1434.32	-9624.24	-9748.75	-28423.5***
D_Argentina	-1306.02	-9359.78	-10115.9	-28227.5***
D_Australia	-2700.36	-12377.3	-6580.03	-28535.5***
Observation	310	310	310	310
R^2	0.9972	0.086	0.129	0.319
Adjusted R^2	0.9971	0.048	0.097	0.296

Significance code *p<0.05; **p<0.01; ***p<0.001.

intensity effect. For intensity effect, the mechanization effect had indirect influence through productivity and structure effect.

CONCLUSION

The study identified the drivers of agriculture GHG emission for top emitters and the World and also tabulated the sustainability index based on the effects. To mitigate the rising agriculture emission due to the agriculture emission intensity effect, agriculture structure effect, productivity effect, mechanization effect and labor effect, policy-makers should focus on targeted policy interventions. To curb the increasing contribution of these effect, countries should adopt climate resilient farming targeting limited use of synthetic fertilizers, proper management for emission from enteric fermentation by improving livestock diet and manure management.

On-farm energy use also plays a significant role in increasing contribution of mechanization effect on agriculture emission, thus, government of countries such as Indonesia and Japan should encourage use of low emission machineries and promote energy efficient equipment. Lastly, countries such as India and Japan having relevant dynamics of labor effect should shift to precision farming that optimizes use of inputs and reduces emissions. Adequate training programs to encourage and adopt sustainable practices should also be a priority for the government. The countries adopting adequate measures to mitigate agriculture emission and integrating with organizations such as IPCC and UNFCCC will be a big leap towards sustainable development in the future.

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Disclaimers

The views and conclusions expressed in this article are solely those of the authors and do not necessarily represent the views of their affiliated institutions. The authors are responsible for the accuracy and completeness of the information provided, but do not accept any liability for any direct or indirect losses resulting from the use of this content.

Conflict of interest

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