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Greenhouse gas emission from agriculture and their mitigation strategies

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Abstract

The ever-increasing global demand for food and related products, agrochemicals etc. has resulted in the emission of greenhouse gases (GHG) such as CO_2, CH_4 and N_2O. This is because agriculture contributes to around 80% of anthropogenic N_2O emissions, 40% of CH_4 emissions and 1% of CO_2 emissions. There is a continuous increase in GHG emissions from agriculture, which leads to a number of catastrophic consequences such as climate change, global warming, biodiversity loss etc. The increase in atmospheric concentration of GHGs also affects the plant growth and its productivity. This paper discusses the potential mitigation strategies of GHG emissions by applying various management options. Mitigation strategies include implementing better management options, selecting appropriate crop varieties, conservation agriculture, reducing food waste, preventing crop residue burning etc.

Keywords: Greenhouse gases, mitigation, conservation agriculture, adaptation

1. Introduction

There are currently 7 billion people living on this planet, and this number is expected to increase to 9.1 billion by 2050 (Chataut *et al*., 2023) [18], which will lead to higher food demand. According to IPCC data (2014) [42], CO_2 contributes 77% to global warming. Of this, 65% is produced by fossil fuels and industrial processes, while 11% comes from forestry and other land uses. On the other hand, methane contributes 16% and nitrous oxide 6% to global warming. The main sources of CH_4 and N_2O are agriculture.

In parallel with the growth of food production, the consumption of chemical fertilizer increased by 200-300% between 1970 and 2010 (IPCC, 2014) [42]. The FAO (2020) reported that the annual demand for nitrogen, phosphorus pentoxide (P_2O_5), and potassium oxide (K_2O) is expected to increase by 1.5%, 2.2% and 2.4% respectively between 2015 and 2020. The production and manufacturing of fertilizers consumes about 1.2% of the world's energy and is responsible for about 1.2% of total greenhouse gas emissions (Kongshaug, 1998). Livestock manure contributes to 6% of total anthropogenic CH_4 emissions (Yusuf *et al*., 2012) [123]. Smith *et al*. (2007) [112] reported that agricultural CH_4 and N_2O emissions increased by 17% from 1990 to 2005. From 1980 to 2007, a 176% increase in N_2O emissions was observed (Bhatia *et al*. 2013) [13].

Increasing concentrations of GHGs in the atmosphere, such as CO_2, CH_4 and N_2O are expected to contribute to global warming. On the other hand, the agricultural sector is highly vulnerable to climatic influences that can threaten global food security. As this sector is highly vulnerable to temperature rises and fluctuations in rainfall patterns (Shiferaw *et al*., 2014) [106].

Climate change could push more than 100 million additional people into poverty worldwide by 2030 (Rozenberg and Hallegatte, 2015) [97], as climate change is likely to affect crops photosynthesis and productivity (Mahato, 2024) [70]. Due to the negative impact on agriculture (Mahato, 2014) [68] alone, more than 73 million poor people are expected to be affected (Hossain *et al*., 2020) [36]. Scientists (Banga & Kang, 2014, Saab, 2016, Garland & Curry, 2022, Kole *et al*., 2015) [11, 99, 27, 55] are working on making climate-resilient plants and seeds and also on developing crop varieties (Liu *et al*., 2022, Balafoutis *et al*., 2017, Osipitan & Radicetti, 2019, Nalley *et al*., 2013) [64, 8, 84], which emit fewer GHGs compared to traditional crop varieties.

The significance of the study is to reduce GHG emissions by selecting the appropriate crop variety and its management options. The study will also contribute to sustainable agriculture and achieving the Sustainable Development Goals (SDG), namely food security and zero hunger. This review can help farmers, researchers, policy makers and academician in decision- making in the agricultural sector, to limit global warming below 2 °C.

The potential to mitigate climate change by reducing emissions of non-CO_2 GHGs is receiving increasing attention (Reay *et al*. 2012) [94]. Coordinated efforts should be made at both national and global levels to invest in research and development, pest and disease control and agricultural expansion.

Greenhouse gases emission and climate change

The average global surface temperature could increase by 1.4 °C to 5.8 °C by 2100 AD with significant regional variations (IPCC, 2007) [43]. The increase in GHG emissions from agriculture is increasing worldwide (Shakoor *et al*., 2021, Bennetzen *et al*., 2016, Balogh, 2020, Carlson *et al*., 2017) [103, 12, 10, 16], which are mainly responsible for changing the Earth's climate. Anthropogenic enrichment of atmospheric greenhouse gases has led to an increase in Earth's average temperature of >1 °C since the late 19th century, with the current warming rate being 0.20 °C per decade (IPCC).

From 1750 to 2023, there is considerable increase in atmospheric concentrations of CO_2, CH_4 and N_2O (Table 1).

Table 1: Atmospheric concentration and characteristics of GHGs emitted from agriculture

GHGs	Atmospheric concentration of GHGs				Contribution in global warming (%) (IPCC, 2014)	Atmospheric lifetime (years)	Radiative forcing (IPCC 2001)	Global Warming Potential (GWP)	
	1750	2005	2019	2023				100 year GWP*	20 year GWP**
CO_2	280 ppm	379 ppm	410 ppm	418 ppm	77	50-200	1.46 Wm^{-2}	1	1
CH_4	715 ppb	1774 ppb	1867 ppb	1923 ppb	16	10-11	0.48 Wm^{-2}	23	56
N_2O	270 ppb	319 ppb	333 ppb	336 ppb	6	120	0.15 Wm^{-2}	296	280

(Source: IPCC)

*Calculated over the period of 100 years, ** calculated over the period of 20 years

Although CH_4 and N_2O are released in smaller quantities than CO_2, they have a greater Global Warming Potential (GWP) than CO_2 (Chataut *et al*., 2023) [18].

1.2 Greenhouse gases emission from agriculture

Agriculture is responsible for about 80% of anthropogenic N_2O emissions while it is responsible for about 40% of CH_4 emissions (Chataut *et al*., 2023) [18] and 1% of CO_2 emissions. Rice cultivation contributes to the emission of major greenhouse gases of concern (CH_4 and N_2O) into the atmosphere, which have a negative impact on atmospheric chemistry and the environment. Crops such as legumes, oilseeds, vegetables and fruits are responsible for a significant portion of GHG emissions (Chataut *et al*., 2023) [18]. The observed rate of increase in global average temperature is above the critical rate of 0.1 °C per decade (Leggett, 2011) [60], may affect soil organic carbon (SOC) pools, dynamics and structural stability and may disrupt carbon (C), nitrogen (N) and water cycles, leading to negative impacts on biomass productivity, biodiversity and the environment.

According to a 2018, IPCC report CO_2 emissions must be reduced by 45% by 2030 compared to 2010 to meet the goals of the Paris Agreement. Therefore, in addition to meeting global food needs, there must also be a significant reduction in GHG emissions.

Methane emission

Rice crops and livestock are the largest emitters of methane in agriculture (Zhang *et al*., 2016) [125]. Methane emissions from global rice fields varied between 18.3Tg CH_4/yr under intermittent irrigation and 38.8 Tg CH_4/yr under continuous flooding (Zhang *et al*., 2016) [125]. Rice fields are flooded with irrigation water up to 4-6 cm. The main route of CH_4 emission from anaerobic paddy soils to the atmosphere is through the arenchyma of the rice plant (Aulakh *et al*., 2001, Nouchi *et al*., 1990, Smartt *et al*., 2016) [4, 79, 111]. Rice roots could absorb CH_4 gas in the gas phase without water absorption (Nouchi *et al*., 1990) [79]. The CH_4 dissolved in the soil water surrounding the root diffuses into the cell wall water of the root cells, gasifies into the root cortex, and is then largely released through the micropores in the leaf sheaths (Hristov, 2018, Wassmann & Aulakh, 2000) [37, 121].

The flooding of the soil during rice cultivation creates an anaerobic condition in the root surface of the plant and thus also for the microorganisms living therein in the rhizosphere. Under such conditions, anaerobic methanogenic bacteria produce CH_4 as a product of their energy metabolism. The process is called methanogenesis (Singh *et al*., 2018, Kogel-Knabner *et al*., 2010) [108, 54].

About 60-90% of CH_4 emissions from flooded rice fields arise from plant-mediated transport (Aulakh *et al*., 2001, Wassmann & Aulakh, 2000, Cheng *et al*., 2006) [4, 121, 20], the remaining 10% occurs through ebuliation and diffusion. Ebulition contributes to total emissions because large amounts of fresh organic matter were added to the soil (Neue, 1993) [78]. More than 50% of the CH_4 produced in rice fields is oxidized in the early phase of the growing season (Wassmann *et al*., 1993) [122], while up to 90% is consumed in the late season of rice maturation. Consequently, the emitted proportion of CH_4 produced decreases with the growth and development of rice.

On the other hand, aerobic methanotropic bacteria in well-aerated soils oxidize CH_4 as an energy source with methanol as a by-product. Therefore, CH_4 production in well aerated areas and intermittent flooding conditions is much lower than in flooded areas (Qian *et al*., 2022) [90]. Smith *et al*. (2007) [112] reported that the anaerobic condition in wetland rice fields is one of the major sources of methane due to soil flooding. Cheng *et al*. (2006) [20] reported in his research that increased concentration of atmospheric carbon dioxide is likely to result in a 58% increase in CH_4 emissions compared to normal atmospheric CO_2 concentration.

Nitrous oxide emission

Most of the N_2O gas formed in soil is emitted from natural and cultivated soil by microbial processes through nitrification and denitrification processes (Bremner, 1997) [15]. The main source of N_2O emissions from agricultural soils is the use of nitrogenous fertilizers (IPCC, 2013) [44]. Due to the heavy use of nitrogenous fertilizers, a certain amount of N_2O is also released from the rice fields (Ghosh *et al*., 2003) [28]. Most N_2O is emitted in the first three weeks after flooding and rice transplanting (Wang *et al*., 2011, Pittelkow *et al*., 2013) [119, 88].

With three irrigation regimes, namely flooding, intermittent irrigation and natural drying. Natural drying had the largest contribution to N_2O emissions (Huang *et al*., 2007) [39]. Soil cracks stimulated the greater N_2O emissions, while flooded irrigation systems contributed the least (Huang *et al*., 2007) [39]. Flooded rice fields are not an effective source of atmospheric N_2O because N_2O is further reduced to nitrogen under the strong anaerobic conditions. However, for irrigated rice, rapid natural drainage during the rice growing season, may cause the top-soil to remain aerobic for an extended period of time and dissolved oxygen in the irrigation water may add oxygen to the surface soil. Thus, both nitrification and de-nitrification can produce a significant amount of N_2O and subsequently release it from the soil. Maximum denitrification rates are observed when the pore space filled with soil water is >90%. By minimizing the time a soil is saturated, denitrification should be limited. Less N_2O was emitted from less frequently irrigated soils (Mekala *et al*., 2017) [74].

Agricultural CO_2 emissions

The conversion of forest areas into agricultural areas emits large amounts of CO_2 (Ramdani & Hino, 2013, Arneth *et al*., 2017, Omar *et al*., 2016) [92, 3, 83]. Soil stores a large amount of organic carbon (Tamocai *et al*., 2009) [114] and about 10% of the CO_2 in the atmosphere passes through the soil each year (Raich and Potter, 1995) [91]. The mechanization of the agricultural industry is responsible for the enormous CO_2 emissions (Lin & Xu, 2018) [61]. Energy (petrol, diesel, electricity etc.) is used in the agricultural sector for operation such as irrigation, transportation, harvesting, value addition, etc. leading to an increase in CO_2 emissions (Golasa *et al*., 2021, Pradhan *et al*., 2017, Alves and Motinho, 2014) [31, 89, 2]. Several researchers (Sharma & Rajput, 2022, Wang *et al*., 2018, Jain *et al*. 2006) [104, 120, 46] also reported that biomass burning is responsible for GHGs emission.

Other factor of GHG emission

In addition to direct GHGs emission from agriculture, other indirect factors such as biomass burning, food waste, dietary practices (Green *et al*., 2017, Hallstrom *et al*., 2015) [33, 35] etc. also lead to GHG emissions. Reay *et al*. (2012) [94] reported that about 3% of the world's agricultural N_2O (200 Gg N/year) is emitted through food waste. Therefore, avoiding food waste can also reduce emissions. On the other hand, changing diet (reducing consumption of non-vegetarian foods) can also reduce N_2O emissions (Scarborough *et al*., 2023, Keshari, 2022) [102, 52].

Smith *et al*. (2007) [112] reported that, biomass combustion is an important source of global CH_4 and N_2O emissions from agriculture, along with soil emissions and rice production. Biomass burning contributes about 12% of global methane and nitrous oxide emissions from agriculture. Bhatia *et al*. (2013) [13] reported that residues of nine crops such as rice, wheat, millet, sugarcane, jute, maize, cotton, rapeseed mustard and groundnut are commonly burned in the field resulting in GHG emissions.

Materials and Methods

Literature searches were conducted on climate change, agriculture, global agriculture, greenhouse gas emissions from agriculture, methane and nitrous oxide emissions etc. Research papers from online databases such as Google Scholar and Research gate, Science Direct, IOP Publishing, MDPI, books, articles and technical reports are used for this work. Reviews, empirical and theoretical works on the respective topic were selected from publications between 1982 and 2023. In total approximately 200 articles were examined and only 140 articles were ultimately used in this review.

Results and Discussion

Global agriculture scenario

One of the most pressing societal problems is global food security (Idso, 2011) [40], which is also mentioned in the sustainable development goals (SDGs). To feed the world's population of 9 billion people by 2050, global food production is expected to increase by 70 to 100% (Idso, 2011, Odegard and Van der Voet, 2014) [40, 80]. The agricultural sector's contribution to global GDP increased from 3.2% in 2006 to 4.3% in 2021 (economic times).

About 38% of the Earth's surface is dominated by arable land (Zabel *et al*., 2019) [124]. The three most important food crops in the world are wheat (*Triticum aestivum* L.), maize (*Zea mays* L.) and rice (*Oryza sativa*) Rong *et al*. (2021) [96]. Rong *et al*. (2021) [96] reported in their research that the current global potential yield of three major crops such as wheat, maize and rice is 7.7, 10.4 and 8.5 t/ha which is much higher than the actual yields of 4.1, 5.5 and 4.0 t/ha and this can be achieved through proper crop management.

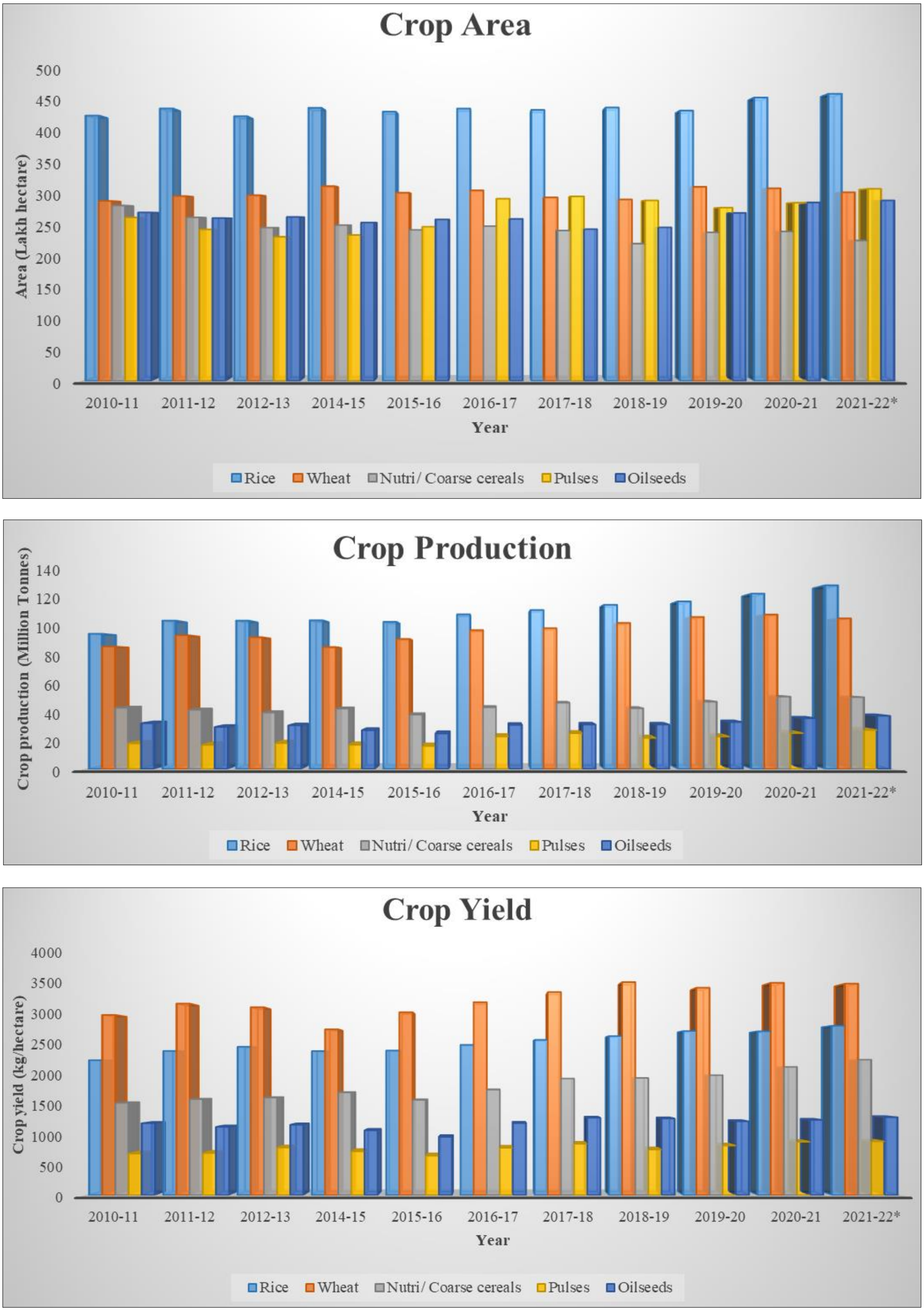
Asian countries such as China and India are the largest producers of staple foods such as wheat and rice. The rice grown in Asia account for about 87% of the world's total rice cultivation area and about 80% of it is grown under flood conditions (Zou *et al*., 2005) [127]. Therefore, there is enormous potential for reducing GHG emissions in this region.

Agriculture in India

Agriculture plays an important role in the Indian economy and about 54.6% of the total labour force is employed in agriculture and allied sectors. The total geographical area of the country is 328.7 million hectares. According to the land use statistics of 2018-19, the net sown area of the country is 42.4% (Department of Agriculture & Farmers welfare, Government of India, 2021) [22]. Rice is the most important agricultural crop in India, followed by wheat, coarse cereals, pulses and oilseeds.

The area under rice cultivation in India increased from 428.62 lakh hectares to 463.79 lakh hectares from 2010-2011 to 2021-2022. Rice productivity increased from 95.98 million ton to 130.29 million ton during the same period (fig.1). The rice yield per hectare also increased from 2239 to 2809 kg/hectare during the same period (fig1c). The above statistics show that cultivation in India is continuously increasing and agricultural land has been under pressure due to increasing yields in the past. As a result, the quality of the soil deteriorated, leading to an increasing use of agrochemicals.

The area under wheat cultivation increased by 14 lakh hectares. Similar patterns were observed in both legumes and oilseeds (fig.1a). While the arable area under coarse cereals declined by 56.87 lakh hectares between 2010-11 and 2021-22 (www.agricoop.nic.in).



(**Source:** www.agricoop.nic.in)

Fig 1: Histogram showing crop area (a), crop production (b) and crop yield (c) of India between 2010-2022

All research was compiled to examine the possible sources of greenhouse gas emissions from agriculture. The study also illustrate the agricultural sector's contribution to climate change and global warming. Field management such as the type and amount of fertilizer used, water consumption, and the application of other agrochemicals can influence the production of CH_4 and N_2O in soils and their emission from soils (Olliver *et al*., 2011) [82].

Mitigation of CH_4 fluxes

The application of fresh organic matter results in a large amount of CH_4 emissions (Neue, 1993) [78] from the paddy fields. In order to reduce CH_4 emissions, the use of undecomposed organic materials should be avoided. Wassmann *et al*. (1993) [122] reported that CH_4 emissions were comparatively higher during the early growing season from rice fields, therefore much of the research should focus on developing crop varieties that emit less GHGs. CH_4 production in well aerated land and intermittent flooding is much lower than in flooded areas (Qian *et al*., 2022) [90]. Therefore, the focus should be on water management in the field and selection of the least water-intensive crop varieties.

Mitigation of N_2O fluxes

Efficient use of fertilizer N occurs when fertilizer application coincides with the phase of rapid plant uptake. Therefore, multiple applications of small amounts of nitrogen fertilizer throughout the growing season would be a more effective means of supplying nitrogen to plant growth than a single large application early in the season. Controlled release fertilizer formulations should limit N_2O emissions by controlling nitrate input to limit denitrification. The use of nitrification inhibitors such as nitrapyrin, sulfathiazole, dicyandiamide, terrazole, thiourea etc. limit N_2O emissions from ammonium-based fertilizers. The most commonly used nitrification inhibitor is nitrapyrin (Zhou *et al*., 2020) [126]. It is rarely effective due to sorption to soil colloids, hydrolysis and loss through volatilization. The use of calcium carbide coated with layers of wax and shellac as a slow release source of acetylene has resulted in reduced nitrification and higher yield. Wax-coated $CaCO_3$ also inhibited N_2O emission (Mahmood *et al*., 2014) [71]. Umar *et al*. (2023) [116] mentioned in their research that in silty and sandy loam soils, the use of stearic acid combined zinc coated urea reduces N_2O emissions.

Mitigation of CO_2 fluxes through carbon sequestration

Agricultural land can also act as a carbon sink by implementing a better management option, agroforestry (Lal, 2003, Paustian *et al*., 1997) [59, 87]. Through the process of photosynthesis, CO_2 is continuously exchanged between the atmosphere and the soil. The incorporation of plant organic matter into the soil is called CO_2 influx. On the other hand, CO_2 outflow causes this organic substance to be broken down by soil organisms. This balance between the amounts of carbon depends on the carbon input from plant and animal residues and the carbon emissions from decomposition. Both carbon input and carbon output are influenced by natural factors such as soil physical factors (texture, clay mineralogy, and soil profile), climate (temperature, rainfall) and agricultural management practices. Therefore, soil carbon emission and absorption rates vary by management system, and geographically.

Carbon sequestration is favoured by management systems that minimize soil disturbance and erosion, maximize recycling of crop residues, and maximize water and nutrient use efficiency of crop production. Reducing tillage intensity, particularly by eliminating tillage, has been found to promote carbon sequestration (Haddaway *et al*., 2017, Ogle *et al*., 2012, Feng *et al*., 2020) [34, 81, 26]. In addition to carbon sequestration, increasing soil organic matter generally brings significant benefits to soil biological, chemical and physical properties, translating into improvements in soil fertility and sustainability. These improvements include improved water holding capacity, increased water infiltration, reduced runoff, increased soil buffering capacity and increased storage of essential soil nutrients.

Impact of nutrient management/ fertilizer application on GHG emission

The main fertilizers used are urea, ammonium sulphate, potassium nitrate, etc. In rice cultivation, the highest N_2O emissions were observed after fertilization and also after transplanting (Kim *et al*., 2021, Liu *et al*., 2014) [53, 65]. Depending on nitrogen treatment and variety, total seasonal emission changes (Kavdir *et al*., 2008, Chen *et al*., 2019) [48, 19].

Bhatia *et al*. (2013) [13], conducted an inventory of GHG from Indian agricultural soils. Their study found that the global warming potential of Indian agricultural land was 148Tg in 2007. Their study also reported that the annual direct and indirect N_2O-N emission was 118.67 Gg and 19.49 Gg, respectively. Annual emissions of 250 Gg CH_4 and 6.5 Gg of N_2O were recorded from burning agricultural residues in the field.

Strategies for GHG emission reductions

Monitoring GHG emission: Monitoring the GHG emissions of various crops and developing agronomic to reduce GHG emissions. The agronomic assessment of greenhouse gas emissions has been carried out by several scientists (Linquist *et al*., 2012, Liu *et al*., 2022) [62, 64], which needs to be further improved for agricultural, horticultural and forestry plant and tree species.

Selecting the appropriate cultivator: For large-scale production, crop varieties with low GHG emissions should be selected. These include low carbon exudation from the roots, a higher harvest index to reduce organic matter input, and the selection of varieties with low CH_4 transport and high CH_4 oxidation efficiency in the rhizosphere. Millet is a nutritionally superior and climate-resilient crop and has great potential in India. Finger millet (Ragi / Mandua) performs best when grown organically. Local varieties of finger millet have better nutritional quality (content of protein, omega-6 and polyunsaturated fatty acids) compared to HYVs. Several researchers (Ervin *et al*. 2011, Raymond *et al*., 2011) [23, 93] have reported that genetic engineering is an effective strategy for controlling GHGs from crops, but it requires long term field testing and could have potential side effects on human safety and the environment.

Tillage management- Several scientists (Rochette *et al*., 2008, Carvalho *et al*. 2009, Aulakh *et al*. 1984, Ball *et al*.

1999) [95, 17, 5, 9] have reported that no tillage (NT) compared to conventional tillage (CT) methods emit more N_2O. Tillage leads to changes in soil structure, soil aeration, microbial activity, soil moisture, soil temperature, rate of residue decomposition and nitrogen mineralization, thus affecting N_2O emission (Signor & Cerri, 2013) [107]. Escobar *et al*. (2010) [24] reported that N_2O emission in NT practices increased three-fold compared to CT in subtropical oxisol in Brazil due to the larger population of denitrifying microorganisms in NT practices.

Baggs *et al*. (2006) [7] reported that soil moisture in the field increases due to the presence of crop residues during no-tillage (NT), resulting in greater microbial activity near the soil surface, consuming more oxygen and creating anaerobic microsites. Other studies by (Liu *et al*., 2011) [63] reported that in China, on implementing crop rotation of wheat and maize, straw significantly increased soil temperature, due to their heat retaining properties. Higher temperature may have stimulated the enzymatic activity of denitrifiers and nitrifiers and increased microbial production of N_2O. In the conventional tillage (CT) system, this mechanism would be dissipated by tillage in the upper soil layer, increasing soil oxygen concentration in soil and consequently reducing N_2O emission (Signor & Cerri, 2013) [107].

Soil pH- soil pH also influences the emission of N_2O. Thomson *et al*. (2012) [115] reported that continuous acidification of agricultural soils through excessive use of nitrogen fertilizers could drastically reduce N_2O emissions.

Residual quality: Gomes *et al*. (2009) [32] showed in their research that the biochemical composition of plant residues added to the soil is responsible for higher or lower N_2O emissions. Liu *et al*. (2011) [63] reported that wheat straw incorporation increased N_2O emissions after the subsequent maize season, while maize straw incorporation did not affect the emission. Siqueira Neto *et al*. (2009b) [109] measured higher N_2O emissions in areas where corn-wheat is grown than in areas where soyabean-wheat is grown. Siqueira Neto *et al*. (2009a) [110] suggested that instead of nitrogenous fertilizers legumes could be used as a nitrogen source in agricultural systems.

Fertilizer usage- Soils can be modified and improved through the application of fertilizers designed to compensate for certain mineral deficiencies. Inadequate soil drainage can be improved with tile drainage and trenches. The focus of fertilizer application is on soil amendments and mineral fertilizers. The addition of iron compounds such as bauxite is expected to reduce CH_4 emissions. The aim should be to reduce electron acceptors in the sequential redox reaction. The application of higher doses of undecomposed organic matter should be avoided as it releases CH_4 as a by-product of anaerobic decomposition.

Signor & Cerri (2013) [107] found that the type of fertilizer also has an influence on the behaviour of N_2O emissions. Ammonia fertilizers increase N_2O emissions more slowly than nitrogen fertilizers because nitrogen sources can be denitrified immediately, while ammonia sources still need to be nitrified before denitrification. Abbasi & Adams (2000) [1] measured emissions three to eight times higher in soils treated with potassium nitrate (KNO_3), than in soils treated with ammonia fertilizer. The addition of sulphate increases the activity of sulphate-reducing bacteria, thereby reduces the activity of methanogens in the soil (Kristjansson *et al*. 1982) [57].

Aligning nitrogen supply with crop demand: A cropping system based on soil nutrient supply capacity and a crop with low soil nutrient requirements in marginal areas should be selected as a carbon sink.

Mohanty *et al*. (2012) [76] reported that application of nitrogen in fractional amounts synchronous with crop demand is an important strategy to improve nitrogen use efficiency, minimize nitrogen loss and regulate N_2O emission from the rice field. Farmers can use the leaf color chart, SPAD meter, etc. to determine the amount and quantity and timing of nitrogen application.

Use of nitrification inhibitors-Mohanty *et al*. (2012) [76] mentioned in their research that the use of nitrification inhibitors reduces N_2O emissions. Nitrification inhibitors such as nitrapyrin, 2-chloro-6 (trichloromethyl) pyridine (Pathak & Nedwell, 2001) [86], dicyandiamide (Malla, 2005) and encapsulated calcium carbide (Keerthisinghe *et al*., 1995, Keerthisinghe *et al*., 1993, Keerthisinghe *et al*., 1996) [51, 49, 50] application significantly reduced fertilizer induced loss of nitrous oxide. Addition of dicyandiamide (DCD) to urea reduced total N_2O-N emission at all moisture regimes (Kumar *et al*., 2000) [58]

Placement and source of fertilizer application- Keerthisinghe *et al*. (1995) [51], Liu *et al*. (2015) [66], Liu *et al*. (2006) [67] reported that the denitrification and N_2O losses of urea significantly decreased when the urea was placed deep compared to surface broadcast application. Breitenbeck and Bremner (1986) [15] mentioned in their research that application of N as anhydrous ammonia resulted in a much greater increase in N_2O emissions than application of the same amount of nitrogen fertilizer as aqueous ammonia or urea.

Controlled release of fertilizers- Minami (2005) reported that the application of controlled release fertilizers reduced N_2O emissions. A reduction in N_2O emissions has been reported by using polyolefin-coated ammonium nitrate with uncoated ammonium sulphate (Swify *et al*., 2023, Azeem *et al*., 2014) [113, 6]. By implementing appropriate agronomic management practices to increase the efficiency of nutrient use in crops.

Water management practices- Various water management practices can reduce CH_4 and N_2O emissions. For example, more CH_4 emissions were recorded in submerged rice cultivation than in dry rice cultivation. Crop should be selected based on water use efficiency (Vorosmarty *et al*., 2004) [117]. Water-intensive crops need to be replaced by less water intentive crop varieties (De Fraiture and Wichelns, 2010) [21] as the problem of water scarcity may worsen in the coming years (Mahato *et al*., 2022) [69]. This will help reduce irrigation needs, as water availability may decrease due to continuous consumption. This reduces the GHG emissions in terms of electricity demand.

Other management options: Some strategies to reduce GHG emission from agriculture are to practice an Integrated Plant Nutrient System (IPNS), which includes the use of nutrient-enriched organic fertilizers. Strategies should be developed to increase agricultural productivity (Islam *et al*., 2022) [45] by optimizing water consumption, conserving water resources and increasing productivity (Paramesh *et al*., 2023) [85]. Strategies should be developed to sustainably use part of the gray water for agricultural production (Sheikh *et al*., 2018, Salukazana *et al*., 2005) [105, 100]. Greater application of organic manure such as cow dung results in higher GHGs emissions.

Deep tillage: Deep tillage should be carried out for proper mixing of soil and organic matter. It also increases the content of free iron oxide and easily reducible manganese in the soil, as these accumulate in deeper soil layers through leaching (Kogel-Knabner *et al*. 2010) [54].

Soil manipulation: Reduced sandy soils with high organic carbon content produce more CH_4 than clay soils with similar carbon content (Sass *et al*., 1994) [101]. Sandy soils have less trapped CH_4, while clayey soils may have lower CH_4 fluxes because trapped CH_4 can be oxidized before escaping to the atmosphere (Majumdar *et al*., 1998) [72].

Agri-voltaic system: Giri & Mohanty (2022 a, b) [29, 30] have presented an interesting concept of an agri-voltaic system. With this system, a photovoltaic system is installed on agricultural land. To increase land productivity and farmers income, the researchers installed a portable and adjustable agri-voltaic system with an output of 0.675 kWp, with an underlying turmeric crop, on a land area of $11m^2$. It was observed that the temperature decreased by 1-1.5 °C, resulting in improvement in energy generation and agricultural production. This system can meet the twin goals of access to electricity and ensuring food security. This is an effective solution for densely populated areas, coastal areas and low-lying countries where land resources are scarce.

Millet as alternative option

Millet is an ideal solution for countries to increase their self-sufficiency and reduce dependence on imported cereal grains. Aside from being rich in fiber, vitamins, proteins, and minerals, they are an extremely nutritious crop. They are easy to digest and gluten-free. They require minimal inputs, are resistant to diseases and pests, and offer reduced reliance on synthetic fertilizers and pesticides. Because millet has more shoots or branches than corn and sorghum, it is also a better forage. Millet plants also have a good ability to sequester carbon, thus contributing to climate change adaptation, when considering water requirements and methane emissions from rice fields. Millet is a drought-tolerant crop that can be grown in dry and arid climates, requires less water and can thrive even in poor soil conditions.

The United Nations General Assembly declared 2023 the International Year of Millets at its 75th session in March 2021. Millet is one of the oldest cultivated grains in the world. India is the largest millet producing country in the world, accounting for 42% of global millet production. Some important millets are Foxtail millet (Kangni), Browntop millet (Andu korralu), Finger millet (Ragi), Pearl millet (Bajra), Buckwheat millet (Kuttu), Amaranth millet (Rajgira), Barnyard millet (Sanwa), Kodo millet etc.

Conclusion

Agricultural growth is very important to meet the ever-increasing food needs of people. The net cultivated area is continuously increasing and there is also pressure to increase productivity per hectare of land area as land resources are limited. Traditional agricultural methods lead to the emission of greenhouse gases such as methane, nitrous oxide and, in some cases, carbon dioxide. Due to the recent scenario of climate change, there is an urgent need to reduce to GHG emissions to limit warming to 2 °C, otherwise all life on earth will be at risk.

This is because agriculture contributes to around 80% of anthropogenic N_2O emissions, 40% of CH_4 emissions and 1% of CO_2 emissions. Agricultural activities offer enormous potential to reduce GHG emissions and mitigate the effects of global warming. Therefore, mitigation strategies include implementing better management options, selecting appropriate crop varieties, conservation agriculture, reducing food waste, preventing crop residue burning, etc.

Conflict of Interest: None

Abbreviations

CO_2- Carbon Dioxide, N- Nitrogen, N_2O-Nitrous Oxide, CH_4- Methane, FAO-Food and Agricultural Organization, GHG- Greenhouse gas, IPCC-Intergovernmental Panel on Climate Change, SOC- Soil Organic Carbon, HYV- High Yielding Varieties, CT- Conventional Tillage, NT- No Tillage.

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