Review Article
Carbon Neutral Farming- A Strategy for Abating Climate Change

ABSTRACT

The review highlights the critical role of carbon neutral farming in mitigating climate change, highlighting agriculture's significant contribution to greenhouse gas (GHG) emission and its underutilized potential for emission reduction. Agriculture uniquely serves as both a source and a potential sink for GHGs. Carbon neutral farming offers a promising pathway to transform agriculture into a sustainable, climate-resilient sector. By reducing emissions, enhancing sequestration, and offsetting remaining carbon footprints, this approach significantly contributes to global climate change mitigation efforts while also improving soil health, increasing biodiversity, and fostering economic viability in farming communities.

Keywords: Carbon neutral farming, Greenhouse gas emission, Methane, Fossil fuel, carbon dioxide equivalent

1. INTRODUCTION

The increase in atmospheric greenhouse gas (GHG) levels has intensified global concern over climate change and its impacts. The surge in GHG emissions during the last couple of centuries has led to notable alterations in global climate, leading to environmental catastrophes such as extensive flooding, prolonged droughts, and devastating wildfires.

According to FAO [1] the global agriculture and associated land use have contributed to an emission of 9.3×10^9tonnes of carbon dioxide equivalent (CO_2-eq), and more than half of this (5.3×10^9 tonnes CO_2-eq) is attributed to crop and livestock activities within the farm gate, while land use and land use change activities account for nearly 4 $\times 10^9$tonnes CO_2-eq. The food production is anticipated to rise by 70 per cent between 2005 and 2050 in order to feed an estimated global population of 9.1 billion individuals while maintaining present dietary habits. This growth is expected to have significant consequences, including a 30 per cent rise in global GHG emissions from agriculture [2]. Based on empirical evidence, in the long run, a one per cent increase in agricultural land, crop production index, livestock production index, fisheries production, energy use in agriculture, and fertilizer consumption, GHG emissions will be increased by 0.25, 0.29, 0.40, 0.18, 0.46, and 0.28 per cent respectively [3].

2. CONCEPT OF CARBON NEUTRAL FARMING

Agriculture sector plays a dual role in decarbonizing economy, serving both as a source and a sink for GHGs. According to the Carbon Cycle Institute [4], agriculture stands out as the only sector which can switch from a net CO_2 emitter to net CO_2sequesterer, a potential unmatched by any other human managed domain. The estimated global mitigation potential from agriculture (excluding fossil fuel offsets from biomass) by 2030 is nearly 5500-6,000 $MtCO_2$-eq y^{-1} [5].

Carbon neutral farming aims to balance the carbon emissions produced by farming activities with equivalent carbon removals or sequestration, resulting in a net-zero carbon footprint. Carbon-neutral farming involves implementing a scientifically proven methodology that effectively reduce carbon emissions while maintaining agricultural productivity.

3. SOURCES OF EMISSION OF GHG IN AGRICULTURE

Agricultural activities release three primary GHGs viz., carbon dioxide, nitrous oxide and methane. Among all anthropogenic sources, agriculture is the major cause for 39 per cent of CH_4 and 76 per cent of N_2O emissions [6]. The radiative forcing potential of CH_4 and N_2O are considerably higher than that of CO_2 over short time frames, intensifying their impact on global warming potential (GWP).

3.1Emission from the Livestock sector

3.1.1 Enteric fermentation

The emissions from agriculture sector are primarily attributed to enteric fermentation in livestock, constituting nearly 63 per cent of the sector's total emissions [7]. Enteric fermentation is an inherent aspect of the digestion in ruminants, involving fermentation and break down of plant biomass eaten by animals through the actions of bacteria, fungi, and protozoa in the rumen. The resulting gaseous by products, mainly CO_2 and CH_4 are released from the rumen by eructation. Methane plays a significant role in global warming, as it effectively traps infrared radiation leading to significant increase in mean surface temperatures. Around 30 to 50 percent of recent rise in temperature has been linked to methane emissions [8].

3.1.2 Manure management

Decisions made regarding storage and disposal of manure can affect emissions of CH_4 and N_2O, which are formed during the decomposition process of manures. In India, management of manure contributes to annual emissions of 120.44 thousand tonnes of CH_4 and 0.08 thousand tonnes of N_2O [9].

3.2 Emission from the rice fields

Rice farming in India is a significant contributor to GHG emissions, releasing an estimated 97 Mt CO_2-eq into the environment [10].

3.2.1 Methane emission

Organic materials upon anaerobic decomposition in flooded rice fields generates CH_4. Globally, emissions of CH_4 from paddy fields range from 31 to 280 Tg y^{-1}, constituting for 10 to 20 per cent of anthropogenic CH_4 emissions [11]. Methane emissions from major paddy growing regions of the country under different rice environments were assessed for the whole cropping period, and estimated CH_4 emission from paddy cultivation in India is approximately 4 million tonnes per year [12].

3.2.2Nitrous oxide emission due to unscientific nitrogen management

Agriculture accounts for 75 per cent of anthropogenic N_2O emissions. Nitrous oxide is formed as an intermediate product of microbial nitrogen conversion in the soil i.e., nitrification and denitrification. Flushes of N_2O can occur when soils, which are previously well-aerated, become moistened or saturated due to precipitation or irrigation. The main driver of N_2O emission is the lack of synchronisation between N supply and N demand by plants, leading to excess N in soil.

3.3Emission due to land use changes

Alterations in land use, such as deforestation for agricultural expansion also lead to release of GHGs. Land use and land use change activities contribute to an emission of about 4 Gt CO_2 equivalent [1]. If current patterns continue, with richer nations intensifying agricultural practices and poorer nations engaging in extensive land clearing, nearly 1 billion ha of land are projected to undergo clearance globally by 2050, which would result in GHG emissions reaching nearly 3 Gt CO_2-C equivalent y^{-1} [13].

3.4 Emissions from the crop residue burning

Indian agriculture generates approximately 500 to 550 million tonnes (Mt) of crop residues each year. About 90-140 Mt of these residues are burned on-farm annually mainly to clear the field for sowing the next crop, making this practice is a major source of CO_2 emission from agriculture sector [9]. In India, burning of crop residues in fields result in emissions of 257.21×10^3tonnes of CH_4 and 6.67×10^3tonnes of N_2O emissions annually [14].

3.5Emission from the fossil fuel

According to FAO, the emissions arising from energy use in agriculture were 0.9 Gt CO_2 equivalent in 2018, marking a 23 per cent rise since 2000 [1]. Use of LPG, natural gas, residual fuel oil and other bituminous coal in the agriculture and fisheries sector together with use of electricity result in an emission of more than 1 billion tonnes of CO_2 equivalent per year [15].

4. HOW TO ACHIEVE CARBON NEUTRALITY

Carbon neutrality in agriculture can be achieved through various practices that maintain and enhance the carbon levels in soils, minimize GHG emission from crop and livestock production, and adoption of farming systems like mixed farming and agro-forestry that reduces emissions while promoting biodiversity. Efficient utilization of fertilizers, energy sources and other farm inputs is crucial, alongside efforts to revitalize soil health. The lifecycle perspective of the carbon balance in a farming system encompasses both direct emissions that occur in the farm and indirect emissions that originate from the inputs utilized on the farm. Achieving carbon neutrality necessitates an integrated approach focused on mitigating emissions, enhancing carbon sinks, and minimizing the overall carbon footprint of agricultural operations. Methods and tools to evaluate emissions and carbon sequestration at farm level are also required.

4.1 Reducing emission from cropland

4.1.1 Agronomic intervention

Improved agronomic practices have significant role in reducing emission from cropland.

4.1.1.1Crop varieties

Crop varieties with improved resource use efficiency, pest and disease tolerance, climate resilience, indirectly result in lowering GHG emission. Crop varieties possessing resistance to pests and diseases can decrease the dependency on chemical pesticides. Heimpel*et al.* [16] reported that the manufacture, transport, and application of insecticides against soybean aphid results in a GHG emission of 10.6 kg CO_2-eq ha^{-1} being emitted per hectare of soybeans treated. By using fewer pesticides, farmers can help mitigate emissions linked to the production and usage of such chemicals. Crop varieties with improved nutrient and water use efficiency reduce the need for synthetic fertilizers and irrigation, indirectly leading to lower emissions associated with such practices.
Rice varieties affect soil CH_4 emission by facilitating the movement of CH_4 and O_2 through the aerenchyma [17], as well as by providing substrates for methanogens and methanotrophs through root exudates [18]. Hence, the genetic characters of the rice cultivars could significantly influence the regulation of soil CH_4 emissions from paddy fields. Zou et al. [19] reported that, cultivation of rice varieties with poor aerenchyma tissue is an important mitigation strategy for reducing soil CH_4 emission. Mutant rice plant (oslsd1.1-m12) recorded significant reductions in several traits; aerenchyma formation (20–60 per cent), root development (25 per cent), diffusion of O_2 (50 per cent) and emission of methane (27–36 per cent) as compared to wild type [20].
According to Bloom and Swisher [21] super rice varieties exhibit lower CH_4 emission compared to conventional rice and hybrid rice. This difference may be attributed to the ability of super rice varieties to retain more substrates within rice plants, thus reducing soil CH_4 emissions. Certain research findings indicate that the cultivation of early maturing varieties significantly altered the abundance of methanogens and methanotrophs in soil, consequently affecting CH_4 fluxes [22]. Biochemists in Sweden, China and the United States have collaborated on the development of a novel rice cultivar named SUSIBA2, hailed as world's first 'climate-friendly rice'. Introduction of barley SUSIBA2 gene in rice resulted in a change in carbon flux, directing more photosynthates towards aboveground biomass instead of roots, and suppressed methanogenesis, mainly through a reduction in root exudates [23].

4.1.1.2 Sowing methods

Compared with transplanting, throwing of rice seedlings significantly reduced seasonal total CH_4 and CO_2 emissions by 15-40 per cent and 19-33 per cent for early rice, and by 38-47 per cent and 19-22 per cent for late rice, respectively [24].
Susilawati*et al.* [25] noted that compared to transplanted rice, CH_4 emissions and GWP were reduced by 47 per cent and 46.4 per cent in direct seeded rice, and no significant differences were observed among crop establishments on N_2O emissions. Since the above crop-establishment methods did not influence grain yield, direct seeding was suggested as an alternative method of establishing lowland rice with low GHG emissions. Continuous flooding under transplanted rice created anaerobic condition resulting in higher CH_4 emission.

4.1.1.3 Spacing/ seed rate

Increasing row width or decreasing the seed rate could lead to greater exposure of surface soils to precipitation, solar radiation and wind, leading changes in microclimate that affect soil temperature and moisture, influencing GHG emissions. O'Neill, *et al.* [26] reported that cumulative CO_2 emissions were greater in rape seed when planted at a density of 10 seeds m^{-2} compared to 60 seeds m^{-2} for both variety Compass and Troy. This disparity was attributed to increased decomposition of organic matter, likely caused by reduced shading at lower seed densities.

4.1.1.4 Tillage/residue management

Conventional tillage involves physically turning soils and residues, altering the physical, chemical, and biological properties of the soil, and hastening organic matter decomposition. Ploughing results in better distribution of crop residues and its exposure to oxygen thereby increasing CO_2-evolution [27].
Reducing tillage intensity is likely to enhance soil organic carbon storage compared to conventional tillage, as these practices minimize soil erosion by promoting the development of a protective litter layer. In fact, reduced tillage retains at least 30 per cent of crop residue on the soil surface leading to an increase in soil carbon. No‐tillage minimizes soil disturbance resulting in slower decomposition of residues on the soil surface. Conservation tillage practices even require farmers to reduce the frequency of tractor passes and reliance on fossil fuels. Improved soil porosity and gas diffusivity facilitates the transport of CH_4 to methanotrophs, potentially reducing CH_4 emissions [28]. Factors such as improved soil structure, reduced soil temperature, limited pool of decomposable organic carbon and lower mineral nitrogen availability due to slower soil organic matter (SOM) mineralization can contribute to a decrease in N_2O emissions [29].
Transitioning to minimum tillage has been shown to decrease C emissions from farm during soil preparation by 0.1 t C ha^{-1} y^{-1} [30]. A meta-analysis, comprising 90 peer-reviewed articles was carried out to evaluate the effect of no-tillage on GHG emissions, and GWP of major cereal cropping systems. The results shows that, compared to conventional tillage no tillage recorded lower GHG emissions in dry climate and lower GWP in areas with acidic soils. No-tillage resulted in 22 per cent reduction in the GWP of rice fields by lowering both CO_2 and CH_4 emissions [31].

4.1.1.5 Diversified cropping system

Diversified cropping systems involving crop rotation, cover crops, and climate resilient crops can boost soil organic carbon. This increase is attributed to the greater amount of crop residue incorporated in to the soil compared than that of less diversified systems, like monocropping, crop-fallow, and those without cover crops [32].

4.1.1.5.1 Crop rotation

Crop rotation particularly when integrated with legumes has the potential to promote climate targets compared to monoculture practices. The favourable climate outcomes associated with legumes in crop rotations can be linked to their nitrogen fixing ability. Legumes reduces the need for synthetic nitrogen fertilizers which are energy intensive to produce [33], and avoid the associated emissions of N_2O. Reckling *et al.* [34] also reported that cropping systems involving legumes exhibit lower nitrate-nitrogen runoff and N_2O emissions than systems without legumes. The addition of nitrogen-rich residues from pulse crops improves soil organic carbon content, thereby promoting long-term carbon storage in agricultural soils. Pulse crop residues contribute to enhancement in soil structure and microbial activity, reducing the susceptibility of soils to erosion and degradation. This indirectly prevents the release of stored carbon as CO_2.

4.1.1.5.2 Cover crops

Through photosynthesis cover crops absorb carbon dioxide from atmosphere and store the carbon in the soil, contributing to climate change mitigation efforts. Studies suggest that approximately 8.1 million hectares of cover crops have the ability to annually sequester over 66 million tonnes of CO_2 equivalent, equal to the emissions generated by around 13 million vehicles [35].

4.1.1.5.3 Cultivation of climate resilient crops

Millets and tuber crops have been considered as climate resilient crops with
low carbon foot prints. In comparison to wheat and rice, millets have low carbon footprint of 3,218- kg CO_2 equivalent ha^{-1}, as against 3,968 kg and 3,401 kg, for wheat and rice respectively [36].
A study by John *et al*. [37] revealed the potential of cassava in C sequestration and GHG mitigation. The long term fertilizer experiment (LTFE) (over 20 years) revealed that the crop has shown the ability to sustain a yield of 10-15 t ha^{-1} without the application of any manures and fertilizers in the same field, which could be attributed to the climate resilient

traits and C sequestration potential, such as high leaf dry matter production, leaf shedding in response to water stress and high nutrient content of leaves. By assimilating 60.38 ppm of atmospheric CO_2, crop attained a leaf dry matter production of 3.573 t ha^{-1}, concurrently lowering the atmospheric CO_2 level to 317 ppm while increasing the SOC by 2780 ppm.

4.1.1.6 Nutrient management

Efficient utilization of applied nitrogen by crop is not always achieved, leading to surplus N susceptible to emission as N_2O. Loses of nitrogen through N leaching, NH_4 volatilization, and urea hydrolysis can also offset the mitigation potential [38]. As a result, enhancing N use efficiency can decrease the emission of N_2O as well as indirectly mitigate GHG emissions from the manufacturing of N fertilizer.

Fertilizer plays significant role in influencing methane emissions from paddy fields. This influence is mainly due to the increase in substrate sources for methanogens, and decrease in soil redox potential, both of which provides favourable environmental conditions for methanogens [39]. Compared with no fertilizer application, the use of fertilizer promoted soil CH_4 emissions, resulting in a notable increase of 32.98 per cent [40].

4.1.1.6.1 Fertilizer dose

In rice, N_2O emission was positively correlated with application rate of N [41] N application at 200 kg ha^{-1} reduced methane emissions from rice crop by 25–30 per cent compared to N application at 400 kg ha^{-1} [42]. Sapkota *et al.* [43] reported that site-specific nutrient management (SSNM) using nutrient expert tool in rice and wheat could lead to a reduction in GWP by about 2.5 per cent in rice, and 12-20 per cent in wheat over conventional farmers' fertilization practices.

4.1.1.6.2Method of application

Application of fertilizer in multiple split doses at various crop stages ensures continuous N availability, leading to improved NUE and decreased N_2O emissions. Split application of fertilizer at different growth stages of wheat (30 per cent at planting and 70 per cent at GS_4) resulted in lower cumulative N_2O flux (0.49 kg N ha^{-1}) compared to application of 100 per cent of fertilizer at planting (0.53 kg N ha^{-1}) [44]. Rutkowska *et al.* [45] observed a significant reduction in N_2O emission from sandy soils upon deep placement of N fertilizers.

4.1.1.6.3 Time of fertilizer application

Delaying fertilizer application until a week after sowing, rather than applying fertilizers prior to sowing, results in better utilization of applied N by crop instead of getting lost to atmosphere and ground water.

4.1.1.6.4 Selection of suitable fertilizer

Vinzent *et al.* [46] found that selecting the suitable form of N and use of nitrification inhibitors aid in reducing nitrous oxide emissions. Application of ammonium sulphate nitrate resulted in higher nitrate values in soil compared to the treatment urea along with nitrification inhibitor, and might be reason for higher N_2O emissions in the ammonium sulphate nitrate treatment, particularly flowering to harvest stage of crop.

4.1.1.6.5 Nitrification inhibitors

Nitrification inhibitors (NI) or slow-release N fertilizers can lower both N_2O and CH_4 emissions [47]. The nitrification inhibitors not only reduces N_2O emission by inhibiting nitrification but also by reducing NO_3^- availability for denitrification [48]. Gilsanz*et al.* [49] reported a reduction potential of 42 per cent for the NI Dicyandiamide which varied significantly depending on soil and management factors.

4.1.1.6.6 Organic amendments

Biochar derived from plant biomass contains significant quantity of carbon which can be sequestered in soil with a mean residence time of 2000 years [50]. The modification of soil pH, aeration and water-holding capability by biochar is responsible for lowering N_2O emission [51]. Biochar application in rice reduced the emission of N_2O and NH_3 by 16.10 per cent and 89.60 per cent, respectively, compared to control [52].

Pallavi [53] evaluated the CO_2 evolution from different nutrient sources and found that organic sources resulted significantly higher CO_2 evolution (14.44 to 42.27 per cent) than chemical fertilizers, and was maximum for poultry manure (344.43 mg of CO_2 100 g^{-1} soil). Khosa *et al*. [54] reported the effectiveness of FYM in reducing CH_4 emissions from rice fields while also improving soil fertility and crop productivity.

4.1.1.6.7 Biofertilizers

As per the findings of Senthilraja*et al.* [55], the addition of BGA +Azolla in rice resulted in the most substantial reduction in CH_4 emission (37.9 per cent) compared to the control followed by application of BGA alone. The same treatment had a 50 per cent and 43 per cent increase in redox potential and dissolved oxygen content, respectively, over the control. Utilization of BGA and Azolla in flooded rice helps to reduce global warming by enhancing dissolved oxygen content and by suppressing the activity of methanogens.

4.1.1.7 Irrigation

While irrigation in intensive agriculture system result in higher yield, it also have adverse environmental impacts such as GHG emissions [13]. GHG emission attributed to fuel or electricity usage for irrigation purposes were found to be high [56].

Lagomarsino *et al.* [57] reported that alternate wetting and drying resulted in 97 per cent reduction in CH_4 emission, while simultaneously causing a five fold increase in N_2O emission in clayey soil.

Gu *et al.* [40] found that, water efficient irrigation methods significantly decreased soil CH_4 emissions by 71.25 per cent compared to traditional irrigation such as long-term flood irrigation. Among the practices, rainfed system had shown the greatest reduction (151.45 per cent), followed by moist irrigation (117.88 per cent). In contrast, the emission reduction rate of intermittent irrigation was the lowest (25.78 per cent). In a study conducted at Kerala Agricultural University by Jinsy [58], the effectiveness of aerobic rice cultivation in mitigating GHG emission from rice fields was evident from the significantly lower methane efflux (3.03 mg m^{-2} h^{-1}) under aerobic rice compared to flooded rice (6.16 mg m^{-2} h^{-1}). Though CH_4 emission did not exhibit significant variations among the varieties under flooded conditions, the variety Sarada recorded the lowest methane efflux (14.08 mg m^{-2} h^{-1}) under aerobic system.

4.1.2 Agroforestry

Agroforestry serves as a polycultural land use management system, where various combinations of trees are cultivated around or among crops or pasture. Agroforestry offers a promising alternative system for reducing and mitigating atmospheric CO_2 levels through carbon sequestration. As per the IPCC [59] report agroforestry systems possess a mitigation potential of 1.1-2.2 Pg C in terrestrial ecosystems over the forthcoming 50 years. Carbon stored in agroforestry range from 0.29-15.2 Mg C ha^{-1} y^{-1} above ground, and from 30-300 Mg C ha^{-1} up to 1 m below ground [60]. Carbon sequestration in agroforestry systems take place in both in aboveground biomass including stem, branch, and foliage, as well as in belowground biomass, such as roots and within soil. C sequestration primarily involves the uptake of atmospheric CO_2 during photosynthesis and subsequent transfer of captured C into vegetation, detritus, and soil pools for long-term storage [61].

Saha *et al.* [62] compared soil C sequestration across different land-use systems and found that, overall SOC content up to 1m depth decreased in the order, forest (176.6 Mg ha^{-1}) > small home garden (<0.4 ha area) (119.3 Mg ha^{-1}) = rubber (119.2 Mg ha^{-1}) ≥ large home garden (> 0.4 ha area) (108.2 Mg ha^{-1}) ≥ coconut (91.7 Mg ha^{-1}) > paddy (55.6 Mg ha^{-1}). Mina *et al.* (2023) found that, rubber plantations exhibited highest tree carbon sequestration (13.8 t C ha^{-1} y^{-1}) followed by homestead AFS (2.68 t C ha^{-1} y^{-1}) and coconut tree plantation (2.08 ± 0.53 t C ha^{-1} y^{-1}). Regarding the SOC content, highest was recorded in homestead AFS (2.48 per cent).

4.1.3 Farm power intervention

The agricultural sector have significant contribution in global carbon emissions due to various practices, including the use of fossil fuels for machinery and equipment. Conventional farm machinery depends fossil fuels for operation, contributing to carbon emissions.

Carbon-neutral farms prioritize the use of renewable energy sources such as wind, solar, and bioenergy. Wind turbines and solar panels can be installed on-farm to generate electricity, which can power various farm operations, including irrigation systems, lighting, and machinery. Bioenergy, such as biogas generated from organic waste and livestock manure, can be harnessed for both electricity and heat production. Ou *et al.* [63] reported that biofuels derived from grain-based feedstock emit significantly lower carbon compared to conventional fuels. Biofuel produced from Jatropha also significantly reduced GHG emissions (by up to 90 per cent) compared to fossil diesel fuels. Replacing electrical energy with solar powered irrigation pumps and diesel-based machinery with biofuel-based machinery the total agricultural carbon footprint was reduced by 8.1 per cent and 3.9 per cent respectively in cotton cultivation [64].

Carbon-neutral farms invest in energy-efficient machinery and equipment. This includes using electric tractors, precision agriculture technologies, and smart irrigation systems that optimize water and energy usage. Electric motors for irrigation resulted in lower GHG emissions than diesel motors due to their greater pump efficiency. The energy required to pump one mm water per hectare was 36 MJ for electricity and 44 MJ for diesel [65].

4.2 Reducing Emissions due to changes in land use

Promoting the conversion of cropland back to land cover resembling native vegetation is found to be an effective method for mitigating GHG emission. The conversion can take place over the entire land area ('set-asides'), or in localized areas, like grassed waterways, field margins, or shelter belts [66]. Converting arable cropland to grassland enhances the soil carbon level as a result of lower soil disturbance and lower carbon removal in harvested products. Grasslands exhibit lower N_2O emissions compared to cultivated lands because of lower N inputs, as well as higher CH_4 oxidation rates [67].

4.3 Reducing emission from livestock sector

The global livestock sector is a major contributor to anthropogenic GHG emissions. According FAO [6] beef and dairy production are the primary contributors accounting for 41 per cent and 20 per cent of the sector's direct emissions respectively. These figures are much higher compared to poultry and pig production, which accounts for 9 and 8 per cent respectively. Apart from the environmental concerns, enteric CH_4 production in ruminants also impact their energy efficiency negatively. Around 11 per cent of the total energy in cattle feed can be lost through eructated CH_4 [68].

4.3.1 Feed and nutrition

Low-quality and low-digestibility feeds leads to relatively high enteric emissions per unit of meat or milk. Forages with high protein content and digestibility has lowered CH_4 emissions by 15-30 per cent in beef production [69]. Grazing management and enhancing forage quality through introduction of different forage species offer a proper diet formulation in extensive systems, leading to a reduction in emission intensity by 30 per cent [70]. Supplementing feed with antimethanogenic agents (e.g. antibiotics reducing methanogen populations) or electron (H+) acceptors (e.g. nitrate salts) or dietary lipids also helps in reducing methanogenesis. Recent research in cattle has shown that, with nitrate supplementation (21.5 g nitrate kg^{-1} dry matter intake), enteric CH_4 production was reduced by 17 per cent (4.43 g kg^{-1} dry matter intake), especially when supplemented with forage-based diets [71].

4.3.2 Animal genetics and breeding

Enhancing resource efficiency in animals and selecting those with lower GHG emissions per unit of feed intake are primary objectives through which breeding and genetics can aid in mitigating GHG emissions. Selective breeding for animals with low methane emissions per unit of feed consumed can lead to sustained 10 per cent reduction in methane emission without compromising productivity.

4.3.3 Rumen Modification

A practical and efficient option to reduce methane emissions is by modifying the rumen microbial ecosystem using vaccines which would stimulate the production of antibodies against methanogens in the host. Vaccination in an Australian sheep targeting specific methanogens resulted in reduction of CH_4 production by nearly 8 per cent [72].

4.3.4 Manure Management

Manure management includes the handling, storage and disposal of urine and faeces produced by livestock. Efficient collection and proper storage of manure are simple measures which can prevent nutrient leaching into the environment and reduce GHG emission. Manipulation of storage temperature, diet management, manure covering, anaerobic digestion of manure etc. were found to have significant influence on GHG emission.

5.CARBON NEURAL FARMING- A KERALA PERSPECTIVE

Through the transformation of atmospheric carbon into plant biomass and soil organic carbon, carbon sequestration significantly reduces the effects of climate change. Perennial plantations play crucial role in mitigating climate adversities due to the ability of trees to sequester more carbon in their biomass compared to other plant types. Kerala has a predominance of plantation based cropping system with coconut, rubber, pepper, coffee as the major cash crops. Studies have shown that these cropping systems have carbon sequestration potential and unexploited potential for paving way towards a carbon neutral ecosystem.

5.1 Coconut based cropping system

Coconut, a perennial crop with a life expectancy of 50-60 years, has the ability to store carbon for an extended period of time, particularly in the stem. The average carbon sequestration potential of coconut trees varies between 37 kg tree^{-1} y^{-1} (dwarf variety) up to 56 kg tree^{-1} y^{-1} (tall variety) [73]. The carbon sequestration potential of coconut plantation can be boosted through better utilisation of the space and solar radiation available in the understorey. Cultivation of coconut with other crops like tubers, vines, food crops, and tree crops can enhance the overall carbon sequestration potential [74]. Bhagya *et al.* [75], compared the carbon sequestration potential among coconut based cropping systems and found that cultivation of coconut in combination with jamun recorded the highest carbon sequestration (140.06 t ha^{-1}) followed by coconut with mango (138.91 t ha^{-1}), coconut with garcinia (131.72 t ha^{-1}), and the least under coconut monocrop (98.2 C t ha^{-1}).

5.2 Rubber plantations

Choudhary *et al.* [76] suggested the potential of rubber plantation in carbon sequestration, with a total C stock of 202.48 Mg ha^{-1}. The carbon stock of bulk soil, a measure of the sequestration potential, varied among different land use categories in the order; rubber > rice > vegetable > banana > homestead > tapioca > coconut [77]. The carbon sink loss was greatly affected by the removal of rubber plantation and the total sink loss for 23 and 30 year old rubber plantation were 214.2 t ha^{-1} and 342.5 t ha^{-1} respectively [78].

5.3 Coffee plantations

A study by Niguse *et al.* [79] revealed the carbon sequestration contribution of coffee in the entire coffee agroforestry system. On average coffee plants contributed 37.5 t C ha^{-1}, representing nearly 12.8 per cent of the total carbon sequestered within the coffee agroforestry systems.

Recently Government of Kerala has conceptualized the carbon neutral coffee park under carbon neutral Wayanad programme. The fundamental rationale of the coffee park is to double tribal and small coffee farmer's income sustainably through branding coffee as carbon neutral coffee. The main aim of the project is to establish an integrated coffee and agri-produce processing park in a 100 acre site near Kalpetta. Adopting sustainable agricultural practices will significantly improve the price for the produce.

5.4 Integrated Farming Systems and Wetland ecosystems

Integrated farming system (IFS) includes components such as dairy, fishery, poultry and duckery and hence often found to have increased emissions of GHGs. Conversely, the systems with a greater variety of complementary enterprises exhibited lower greenhouse gas intensity (GHGI) [80]. In the study, the integration of crop, dairy, poultry, fishery, apiary, duckery, boundary plantation, vermicompost and biogas unit demonstrated notably higher energy output (517.6 × 103 MJ ha^{-1}), and the lowest GHGI (0.164 kg CO_2 eq. per kg food production).

Recently, scientists have identified immense potential for C sequestration in paddy soils than upland soils. This is mainly attributed to the slower decomposition of organic matter under submergence. Nideesh *et al*. [81] reported that entire *Kole* land wetland ecosystem in Kerala have the potential to sequester approximately 229.63 Tg organic carbon in its 150 cm top soil layer.

5.5 Carbon neutral Kerala -Case studies

The State of Kerala is gearing to make it completely carbon neutral by the year 2050 and efforts are being taken in this direction by the Government. In the first phase, carbon-neutral farming will be initiated across 13 farms under the Agriculture Department and tribal areas and in the second phase, model carbon-neutral farms will be established in all the 140 Assembly Constituencies.

5.5.1 Carbon neutral Meenagadi

Wayanad district, identified as a "climate change hotspot" in the state, was chosen for a community-driven initiative named "Carbon Neutral Wayanad". This project aimed to transform the Meenangadi Gram Panchayat of Wayanad district as the first 'Carbon Neutral Panchayat'. The objective of this project is to suggest sector-wise adaptation and mitigation strategies in Meenangadi by assessing its GHG emissions and carbon sequestration for the baseline year of 2017. The estimate indicated a net GHG emission (the difference between total emissions and total sequestration) of 11,412.57 tonnes of CO_2 equivalent in 2016-17. The Implementation of the 'Tree-banking scheme' has resulted in financial gains for farmers by providing incentives for individuals who plant and protect trees. Bamboo is also being encouraged due to its high carbon sequestration potential, particularly in riverbanks for soil and water conservation. Meenangadi has also initiated adoption of energy-efficient measures like energy audition, promotion of LED bulbs, waste management plants and vermicomposting, etc.

5.5.2 Kerala seed farm declared as first carbon neutral farm in the country

On December 10, 2022 Kerala's State Seed Farm in Aluva was officially declared as carbon neutral. The seed farm has achieved the carbon neutrality through a significant reduction in carbon emissions. Estimates showed that the farm emitted 43 tonnes of carbon and while storing 213 tonnes, indicating that the farm is not only carbon neutral but also carbon negative. Organic agricultural activities which improves soil health, intercropping systems, integrated farming system (comprising crop (mainly rice), livestock, ducks and fishes), proper waste management through composting, and usage of renewable energy (solar) were the practices followed for carbon neutrality.

6. BENEFITS AND CHALLENGES

As agriculture is a significant contributor to emissions, adoption of practices that offset or balance emissions with carbon removal helps in limiting the accumulation of atmospheric GHGs. Many carbon sequestration practices, improve soil structure, soil fertility, and soil organic matter content. Carbon neutral farming practices often involve planting trees, maintaining diverse landscapes, and creating habitat niches for various species. Improved soil fertility, reduced input costs, and access to carbon offset markets can enhance farm profitability and financial stability. Carbon neutral farming can enhance the marketability of agricultural products and cater to consumer demand for environmentally friendly choices. The major challenges in scaling up of carbon farming are ensuring accurate monitoring, reporting and verification. The carbon sequestered can be intentionally or unintentionally released back into the atmosphere thus diminishing the benefits from carbon farming. Effectiveness of the management practices is determined by several factors like soil and climatic conditions. A practice that effectively reduce emissions at one site may not yield same results elsewhere. Therefore it is essential to evaluate practices for individual agricultural systems based on climate, soil characteristics, social context, and historical land use patterns and management. Accurate measurement and tracking of emissions and sequestration are essential for achieving carbon neutrality. Advanced tools such as carbon footprint calculators, remote sensing, and soil carbon assessment methods aid in quantifying progress.

7. CONCLUSION

Agriculture's role in climate change is significant due to its substantial greenhouse gas emissions. As climate change continues to pose challenges, the agricultural sector must adopt sustainable practices that simultaneously ensure food security and reduce emissions. Carbon neutral farming presents a promising pathway to transform agriculture into a sustainable, climate-resilient sector. By reducing emissions, enhancing sequestration, and offsetting remaining carbon footprints, this approach contributes to global climate change mitigation efforts while also improving soil health, increasing biodiversity, and fostering economic viability in farming communities.

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