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Rational Outlook on Carbon Credit and Carbon Footprints in Indian Agricultural System: A Comprehensive Review

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Review Article

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ABSTRACT

Global population is expected to rise about 9 billion by 2050, and thus will bring significant and devastating changes to the earth. CO_2 levels have been found to be sharply increased by 31 per cent since 1750, due to numerous land use alterations, faulty and intensive agricultural practices which lead to soil degradation. If such development prevails then it demands innovative and modern management strategies to mitigate the risks associated with climatic change. Earth's surface is continuously warming up due to an irrational land use system, intensive farming without considering the soil health and a surge in global CO_2 emissions. Moreover, these adverse

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conditions can be exacerbated by soil mismanagement, degradation and land exploitation which leads to significant soil carbon depletion. The primary source of carbon emissions is human based activities including land use changes, burning natural biomass, excessive exploitation of renewable natural resources. In the agricultural system, soil plays a crucial role in mitigating the emissions and maintaing food safety and security equilibrium, irrigation water quality and thus impacts the climate positively. Implementation of soil health management strategies not only support the land restoration and crop production levels but also increases the soil carbon sequestration capacity. The key to harnessing the soil hidden potential lies in the adoption of best management practices and restorative land-use strategies. Most of the carbon lost from soil carbon pools due to mismanagement can be reclaimed through conservation practices. Therefore, the present review delves into constructing an understanding on mechanism and role of soil C credit and C sequestration and its impact on the agricultural sector.

Keywords: Carbon credit; carbon sequestration; soil health; ecological balance; climate change; crops.

1. INTRODUCTION

India's agricultural sector, pivotal to its economy and the sustenance of its visiting population has undergone significant transformations over the years, impacting its carbon footprints. As the country strives to balance the food security with sustainable practices, understanding the carbon footprint in agriculture- its past, present and future scenarios become crucial for farming effective policies and interventions. If we see the past scenario, India's agriculture was characterized by traditional farming methods with minimal mechanization and chemical inputs. The carbon footprints during that period were relatively low due to practices such as crop rotation, organic fertilization and manual labor, which might have promoted soil health and minimized C emissions [1]. However, the green revolution in the 1960's marked a paradigm shift by introducing high-yielding variety HYV seeds, synthetic fertilizers and pesticides along with improved irrigation practices. While this revolution significantly boosted food production, it also led to an increase in greenhouse gas (GHG) emissions. The use of nitrogen-based fertilizers, in particular, resulted in the release of nitrous oxide(N_2O), a potent greenhouse gas. Additionally, the expansion of irrigation infrastructure and increased mechanization further contributed to the carbon footprint through the consumption of fossil fuels and energy [2]. If we see the present scenario, the agricultural sector in India is a significant contributor to the country's GHG emissions. According to recent estimates, agriculture accounts for about 18 per cent of India's total GHG emissions [3]. Key sources include methane emission from enteric fermentation in livestock and rice paddies, nitrous oxide emission from fertilized soils, and carbon dioxide emissions from the use of fossil fuels in machinery and irrigation. Modern agricultural practices, while increasing productivity, have also led to soil degradation, water scarcity, and a high dependency on chemical inputs, exacerbating the environment impact. Additionally, the burning of crop residues, particularly in northern India, contributes to seasonal air pollution and significant CO_2 emissions [2]. Looking ahead, India faces the challenge of reducing the carbon footprint of its agricultural sector while ensuring food security for its growing population. Several strategies are being explored and implemented to achieve this balance. Sustainable agricultural practices, such as precision farming, conservation agriculture, and IPM, are being promoted to enhance resource efficiency and reduce emissions Mahato., 2018. The adaptation of renewable energy sources such as solar-powered irrigation can significantly cut down on fossil fuel use. Advances in biotechnology including the development of climate-resilient and low emission crop varieties holds promise for reducing the sector's carbon footprint. Moreover, policy measures such as incentivizing organic farming, implementing stricter regulations on residue burning and enhancing carbon sequestration through agroforestry and soil management practices are critical [4]. The future scenario also envisions a greater role for digital technologies and data analytics in agriculture. Precision agriculture enabled by GPS, remote sensing and IoT can optimize the input use and enhance productivity with minimal environmental impact. Blockchain technology can improve supply chain transparency and thus reducing waste and ensuring that sustainable practices are rewarded [1]. Furthermore, the integration of AI and machine learning can provide real-time insights and predictive analytics, aiding farmers in making informed decisions that align with sustainable practices [5].

2. IMPORTANCE AND ROLE OF CARBON FOOTPRINT

A carbon footprint refers to the total amount of greenhouse gasses emitted directly or indirectly by an individual, organization, event or product, typically expressed in equivalent tons of carbon dioxide. These emissions contribute to global warming and climate change by trapping heat in the Earth's atmosphere, leading to a range of environmental impacts such as rising temperatures, changing weather patterns, and increased frequency of extreme weather events. The concept of a carbon footprint encompasses various activities that release GHGs, including carbon dioxide, methane, nitrous oxide, and other fluorinated gasses [3]. These gasses are produced through a wide array of human activities, such as burning fossil fuels for electricity, heating, and transportation, industrial processes, agriculture, deforestation, and waste management. The calculation of carbon footprint takes into account both direct and indirect emissions Mahato., 2018. Direct emissions come from sources that are owned or controlled by an individual or organization, such as emissions from vehicles, heating systems, and industrial processes. Indirect emissions result from the consumption of purchased goods and services, such as electricity, food, and manufactured products, which require energy and resources to produce and transport [2]. For individuals, a carbon footprint is influenced by lifestyle choices such as energy use at home, travel habits, dietary preferences, and consumption patterns. For instance, driving a gasoline-powered car, taking frequent flights, using energy-intensive appliances, and consuming meat and dairy products can significantly increase one's carbon footprint. Conversely, adopting energy-efficient technologies, reducing car travel, using public transportation, and consuming plant-based foods can help reduce it Sharma et al., [4].

Organizations also have carbon footprints, which are often more complex due to the scale of operations. Companies are increasingly being held accountable for their carbon emissions, and many are taking steps to measure, reduce, and offsets their carbon footprints as part of corporate social responsibility (CSR) initiatives [1]. This can include improving energy efficiency, switching to renewable energy sources, optimizing supply chains, and investing in carbon offset projects like reforestation or renewable energy development. Products, too, have carbon footprints, which are determined by the emissions generated throughout their life cycle-from the extraction of raw materials, manufacturing and transportation to usage and disposal [2]. Life cycle assessments (LCA) are often used to evaluate the carbon footprint of products, helping consumers and companies make more sustainable choices. Reducing the global carbon footprint is crucial for mitigating climate change and achieving international goals such as those outlined in the Paris Agreement, which aims to limit global warming to well below 2 degrees Celsius above pre-industrial levels. Individuals, business, and governments all play a role in reducing carbon footprints by adopting sustainable practices, promoting energy efficiency, and supporting policies that encourage low-carbon technologies and behaviors [6].

2.1 Carbon Credit

Carbon credits are a key component in global efforts to reduce greenhouse gas emissions and combat climate change. They represent a permit that allows a country or organization to emit a certain amount of carbon dioxide or other greenhouse gasses. Each carbon credit typically allows the emission of one metric ton of CO2 or the equivalent amount of other GHGs, such as methane [6].

How Carbon Credit works: Carbon credits are used in "cap-and-trade" systems. Under such systems, a government sets a cap on the total amount of GHFs that can be emitted. Companies are given or can purchase a certain number of carbon credits, depending on their emissions needs. If a company emits less than its allowance, it can sell its unused credits to other companies. Conversely, if it exceeds its limit, it must buy additional credits from others or face penalties [7].

2.2 Types of Carbon Credits

1. Compliance carbon credits: These are credits used in regulatory cap-and -trade systems like the European Union Emission Trading Systems (EU ETS) or the California Cap-and-Trade Program.

2. Voluntary carbon credits: These are purchased by individuals or companies that wish to offset their carbon footprint voluntarily, outside of government-regulated markets. These credits are often used by corporations aiming to be “carbon-neutral” by offsetting emissions from business operations, travel, or manufacturing.

2.3 Example

1. Forestation projects: A company might invest in a reforestation project that absorbs CO2 from the atmosphere. The carbon absorbed by the trees is calculated, and the company is awarded carbon credits for the amount of CO_2 captured. They can then use these credits to offset their emissions.
2. Renewable energy: A company may invest in renewable energy projects such as wind, solar, or hydroelectric power. These projects reduce the need for fossil fuel-based power generation, lowering GHG emissions. This reduced emissions generate carbon credits for the company to trade or use.

3. OVERVIEW ON CARBON POOLS IN SOIL

Carbon plays a vital role in sustaining life on Earth, with absorbing Carbon dioxide from the atmosphere during photosynthesis, using it as an energy source. When plants die, their foliage and stems decompose, returning carbon to the soil, where microorganisms break it down, recycling the carbon back into the atmosphere [5]. However, some organic matter remains in the soil, becoming part of the carbon reservoir known as the soil carbon pool, which is a significant component of Earth’s overall carbon storage. Carbon exists in four pools: the lithosphere (Earth’s crust), oceans, atmosphere, and terrestrial ecosystems [6]. The soil within the terrestrial ecosystem is especially important in the carbon cycle, serving as both a sink and a flux within the soil-plant-atmosphere systems. Carbon is found in various forms within trees, plants, animals, soils, and microorganisms, with the plant-soil system holding the largest fractions of carbon. In the terrestrial ecosystem, most carbon exists in organic forms, largely derived from dead plant materials and microorganisms. The global soil carbon pool is estimated to contain around 1500 petagrams(Pg) of carbon, making soil a crucial component in the global carbon cycle. Organic carbon (OC) is most prevalent in the upper layers of soil, but its abundance decreases with depth [4]. The top one meter of soil often contains a significant fraction of sequestered carbon, though this can vary depending on soil types and environmental conditions. Most soil carbon enters the system as dead plant material, which is decomposed by soil microorganism, primarily bacteria and fungi. This decomposition process releases carbon back into the atmosphere through microbial respiration [8].

Soil has the potential to store approximately 2500 gigatons (Gt) of carbon, with the global soil carbon pool holding more than three times the amount of carbon found in the atmosphere. Soil organic matter (SOM), the organic fraction of soil, is composed of decomposing plant and animal materials, as well as microbial cells and tissues. SOM is crucial for maintaining various physicochemical properties of soil, including soil structure, water retention capacity, biodiversity, fertility, nutrient availability, aeration, and resistance to water erosion [8]. These properties make SOM an important indicator of soil health, contributing to ecosystem growth and sustainability. There are four main pools of SOM: plant residue, particulate organic carbon (OC), humus, and recalcitrant organic carbon (OC). These pools differ in their chemical composition, stage of decomposition, and role in soil functioning and health. Soil carbon pools can be broadly divided into two fractions: soil organic carbon (SOC) and soil inorganic carbon (SIC). The SIC pool is particularly important in dry regions. The concentration of SOC varies widely, ranging from low levels in arid regions to high levels in organic or peat soils [9]. Management practices significantly influence the total organic carbon (TOC) stocks and the composition of carbon in these pools. Understanding how carbon pools respond to different management practices provides valuable insight into the likely functioning and health of soils. Each carbon pool decomposes or transforms at different rates and over different periods, driven by various soil processes. This dynamic nature of soil carbon pools underscores the importance of effective management to maintain soil health and optimize carbon storage in terrestrial ecosystems [5].

Carbon credits are a form of tradable certificates or permits that represent the removal or reduction of one metric ton of carbon dioxide or its equivalent in other greenhouse gasses from the atmosphere [10]. In agriculture, these credits are earned by adopting practices that either reduce GHG emissions or enhance carbon sequestration in soils and vegetation. For example, practices such as no-till farming, cover cropping, agroforestry, and improved manure management can increase soil carbon soil carbon storage and reduce methane and nitrous oxide, which are potent greenhouse gasses.

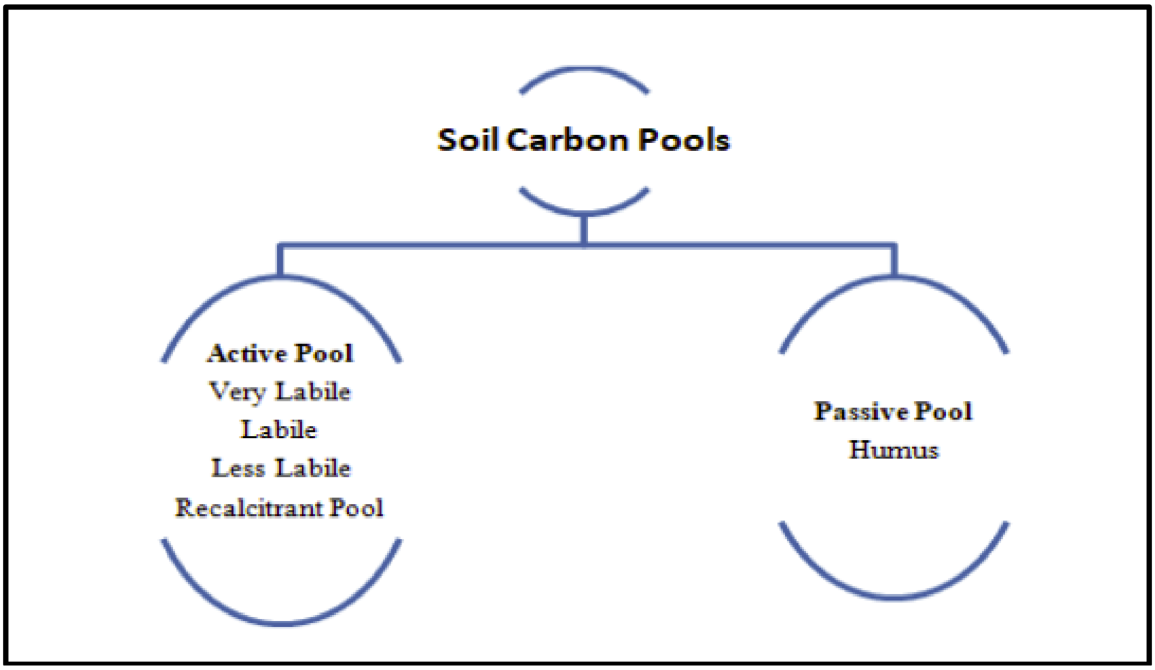

Fig. 1. Two types of soil carbon pools
(Bouwman et al., 2002)

4. SIGNIFICANCE OF CARBON CREDIT IN AGRICULTURAL AREA

Carbon-credits are a market based mechanism designed to incentivize the reduction of greenhouse gas (GHG) emissions [11]. Each carbon credit represents the removal or reduction of one metric ton of carbon dioxide or its equivalent in other greenhouse gasses from the atmosphere. These credits can be earned by entities- such as business, governments, or individuals- through activities that lower emissions or enhance carbon sequestration, such as renewable energy projects, reforestation, or improved agricultural practices [9]. Once earned, carbon credits can be treated on carbon markets. Companies or organizations that exceed their emissions limits or seek to voluntarily offset their carbon footprint can purchase these credits to balance their emissions. This creates a financial incentive for those who can reduce emission or sequester carbon to do so, as they can sell the credits for profit. In agriculture, Carbon-credits can be generated by adopting practices that increase soil carbon storage, reduce methane emissions from livestocks, or enhance or agroforestry not only improve soil health but also capture and store carbon, allowing farmers to earn credits [10]. These credits can then be sold, providing an additional revenue stream and promoting sustainable farming practices. The carbon credit system is crucial for achieving global climate goals by encouraging the reduction of GHG emissions across various sectors. However, the effectiveness of carbon credits depends on accurate measurement, verification, and robust market structures to ensure that the credits represent genuine environmental benefits. When properly implemented, carbon credits can be a powerful tool in the global effort to combat climate change [11].

India’s agricultural sector, integral to its economy and livelihood, is increasingly recognizing the potential of carbon-credit systems as a tool for promoting sustainable farming practices and mitigating climate change. Carbon-credit systems reward farmers for adopting practices that reduce greenhouse gas (GHG) emission or enhance carbon sequestration. This approach not only contributes to climate goals but also provides economic benefits to farmers [12]. A carbon credit represents a reduction of a metric ton of CO2 or its equivalent in other GHGs. These credits can be traded in carbon markets, when entities with high emissions purchase credits to offset their carbon footprint. In agriculture, carbon credits can be generated through practices that sequester carbon in soils or reduce emissions from farming activities [13].

4.1 Impact of Climate Change on Agriculture

Climate change and environmental factors have a significant impact on agriculture, leading to a range of challenges for farming communities worldwide. One of the most pressing issues is the increased frequency and intensity of floods due to rising sea levels, particularly in coastal regions. These floods cause extensive damage to livestock and crops, accelerate soil erosion, and lead to water pollution, all of which contribute to a decline in agricultural productivity and increased costs for farmers. Conversely, the lack of adequate water supply presents an equally daunting challenge. Severe droughts have already affected many parts of the world, damaging crops and livestock, and placing a strain on farmers [5]. As global temperatures continue to rise, the frequency and severity of droughts are expected to increase, exacerbating these problems and making it more difficult for farming communities to sustain their livelihoods [14]. The viability of traditional crops and livestock is also being threatened by these changes. As environmental conditions shift rapidly, farmers are increasingly forced to select crop varieties and animal breeds that are better suited to the new conditions. This often requires significant investments in new technologies, practices, and markets, placing an additional financial burden on farmers who are already struggling to adapt [13].

Moreover, the introduction of new crops, animals and farming practices can lead to the emergence of new pests, pathogens, and weed problems. These new threats require farmers to develop and implement new strategies for managing their crops and livestock, further increasing the complexity and cost of farming. Soil health has also been severely impacted by various environmental changes [14]. Alterations in soil composition, such as reduced fertility, decreased water-holding capacity, and increased vulnerability to erosion and water pollution, have led to a decline in soil health. This, in turn, has resulted in reduced agricultural productivity and lower production levels, further exacerbating the challenges faced by farmers. The shift towards industrial agriculture has also simplified farm landscapes, treating them as mere crops production areas rather than managed ecosystems. This approach has led to a significant reduction in biodiversity on farms, increasing the risk of crop failure and making farming systems more vulnerable to environmental changes [15]. Finally, the heavy reliance on synthetic pesticides, weedicides, and fertilizers in modern agriculture has increased the initial costs of farming, placing a further financial burden on farmers. This use of these inputs has also contributed to environmental degradation, further complicating the challenges faced by farming communities.

4.2 Influence of Anthropogenic Activities on Climate Change

Over the centuries, human activities have led to significant changes on the Earth’s surface. Actions such as intensive agriculture, construction, and the development of pastures have transformed the landscape extensively. With the growing human population, nearly all available land is being utilized, putting increasing pressure on the Earth’s resources. These human-induced changes have altered the Earth’s radiative balance on various timescales and spatial scales, which has had a profound impact on global surface temperatures [16]. One of the most significant anthropogenic effects is elevated concentration of greenhouse gasses in the atmosphere. These gasses, including carbon dioxide, methane, and nitrous oxide, trap heat in Earth’s atmosphere, leading to global warming and contributing to climate change. Beyond greenhouse gasses, human activities also influence the climate by altering concentration of aerosols and ozone. Aerosols, which are tiny particles suspended in the atmosphere, can either cool or warm the Earth depending on their [2]. For instance, sulfate aerosols typically have cooling effects by reflecting sunlight back into space, whereas black carbon (soot) can absorb sunlight and contribute to warming. Human activities such as burning fossil fuels, industrial processes, and deforestation have significantly increased the amount of aerosols in the atmosphere, thereby affecting the climate.

Ozone, a gas that exists in the Earth’s stratosphere and at ground level, also plays a crucial role in the climate systems. Stratospheric ozone protects life on Earth by absorbing harmful ultraviolet radiation from the sun. However, human activities have led to the depletion of this protective layer, particularly through the release of chlorofluorocarbons (CFCs) [16]. At ground level, ozone acts as a greenhouse gas, contributing to warming, and is a major component of urban smog, which poses health risks. In addition to atmospheric changes, human actions have drastically altered the terrestrial surface of the Earth [17]. Land-use changes, such as deforestation, urbanization, and the expansion of agricultural lands, have reduced the Earth's capacity to absorb carbon dioxide, further exacerbating the greenhouse effect. Forests, which act as significant carbon sinks, have been cleared for agriculture and urban development, leading to a loss of biodiversity and disruption of ecosystems [18]. The land-use changes not only contribute to the increase in greenhouse gas concentrations but also affect the Earth's albedo, which is the reflectivity of the Earth's surface. Lighter surfaces, such as ice and snow, reflect more sunlight, while darker surfaces, such as forests and oceans, absorb more heat. As ice and snow cover decrease due to warming, more heat is absorbed by Earth's surface, further accelerating global warming in a feedback loop.

5. METHODS ASSOCIATED WITH CO_2 REMOVALS WITH SOIL C STOCK CHANGES

Biotic carbon stocks maintain a dynamic equilibrium through the continuous inflow and outflow of carbon. For effective carbon sequestration, the key metric is the net amount of CO_2 removed from the atmosphere and incorporated into the soil. The net value represents the balance between two significant fluxes: the uptake of CO_2 by plants and the emission of CO_2 via respiration from plants and soil organisms [18]. Because the net annual flux of CO2 is usually small compared to gross fluxes, accurately measuring net gains or losses of carbon from the ecosystem is challenging and requires sophisticated research instrumentation. An alternative approach to tracking these changes is to monitor the variations in ecosystem carbon stocks over time [5]. The main carbon exchange in the terrestrial ecosystem occurs between the atmosphere and the plant/soil system. Therefore, an increase in biotic organic carbon stocks over time serves as a good proxy for the net uptake of carbon from the atmosphere. Conversely, if there is no erosion or lateral transport processes, a decrease in ecosystem carbon stocks over time indicates a net flux of carbon to the atmosphere [17]. In forests and shrublands, a significant amount of carbon is stored in woody biomass, which can accumulate and persist over many decades. Thus, it is crucial to consider plant biomass carbon in any net CO_2 accounting method. However, in agricultural systems that lack long - lived woody biomass (such as annual cropland and non-wooded grassland), plant biomass stocks are relatively small and mostly short-lived due to annual harvesting and grazing [19]. Consequently the only large and persistent organic carbon stock accounting is vital for assessing whether agricultural ecosystems act as net sources or sinks of carbon. Direct measurement of CO_2 fluxes is complex and is only briefly mentioned here. Instead, the primary focus is on determining changes in SOC stocks over time. In agricultural systems, monitoring SOC stocks provides a reliable indicator of carbon sequestration because plant biomass in these systems doesn't contribute significantly to long-term carbon storage due to its ephemeral nature.

5.1 Economic Incentives and Environmental Aspects of Carbon Credit in the Agricultural Area

The integration of carbon credits into agriculture provides farmers with a new revenue stream. By implementing sustainable practices that generate carbon credits, farmers can sell these credits in carbon markets. Buyers of these credits are often companies or governments looking to offset their own emissions as part of compliance with regulatory requirements or voluntary commitments to reduce their carbon footprint [19]. This creates a financial incentive for farmers to adopt environmentally friendly practices, which might otherwise be cost-prohibitive. The adoption of carbon-credit generating practices in agriculture contributes significantly to climate change mitigation. Soil is a major carbon sink, and practices that enhance soil health and increase its carbon content can sequester large amounts of CO_2 from the atmosphere. Moreover, reducing emissions of methane and nitrous oxide- both of which have much higher global warming potentials than CO_2 through improved livestock and fertilizer management, respectively, further strengthens agriculture's role in combating change [20]. In addition to climate benefits, these practices often lead to improved soil fertility, water retention, and biodiversity, which can enhance the resilience of farming systems to climate extremes such as droughts and floods. Thus, carbon credits in agriculture have the potential to deliver both climate mitigation and adaptation benefits, making agriculture more sustainable in the long term.

5.2 Challenges and Considerations of Carbon Credit

Despite the potential benefits, there are challenges to effectively integrating carbon credits into the agricultural sector. One significant issue is the accurate measurement and verification of carbon sequestration and GHG reductions, which is critical for ensuring the integrity of carbon credits. The variability of carbon sequestration rates across different soil types, climates, and farming practices makes this a complex task [20]. Additionally, the carbon credit market is still evolving, and prices for credits can fluctuate, making it difficult for farmers to predict the financial returns of adopting carbon-sequestration practices. There are also concerns about the equitable distribution of benefits, as small-scale and resource-limited farmers may find it challenging to participate in carbon markets due to the upfront costs and technical knowledge required [21].

Climate change, when viewed through geological records, reveals a continuous and concerning trend. The rapid rate of change and its significant magnitude have become a global concern. India ranks as the fifth most vulnerable country to climate change, which poses severe risks due to a variety of factors [22]. For instance, a one-meter rise in sea level in India could displace around 7.1 million people, submerge approximately 5764 square kilometers of land, and result in the loss of about 4200 kilometers of roads [21]. This vulnerability is largely due to both human activities- such as deforestation, land-use changes, and intensive farming practices- and natural processes like soil organic matter decomposition, erosion, and natural fires. These factors contribute significantly to climate change, which is closely linked to the increase in greenhouse gasses, particularly carbon dioxide. CO_2 plays a vital role in climate change due to its ability to absorb long-wave radiation from the sun, contributing to the greenhouse effect. Historically, CO_2 emissions were part of the natural carbon cycle, which maintained a balance between the capture and release of CO_2 into the atmosphere. However, human activities have disrupted this balance, leading to a significant increase in CO_2 levels. A key approach to addressing this issue is carbon sequestration, which refers to the process of capturing and storing CO_2 from the atmosphere, measured in gigatons. Carbon sequestration can occur naturally or intentionally, and it play a crucial role in the global carbon cycle by acting as a carbon sink- an established process through which CO_2 is absorbed and stored in the earth’s systems, such as forests, soil, and oceans. However, countries like China and India, with their large populations and industrial activities, continue to be major sources of global carbon emissions [22]. Therefore, it is essential to focus on reducing CO_2 emissions, not just on sequestering carbon.

Projections suggest that by the twenty-first century, global carbon levels could exceed 600 petagrams, with carbon remaining in the atmosphere for centuries to millennia if the primary focus is on sequestration rather than eliminating emissions. Even a relatively small amount of carbon, around 2-3 Pg per year, if sequestered from one of the carbon pools, could have significant implications for long-term climate planning [23]. This highlights the dynamic and complex nature of climate change, which is influenced by various social, environmental, and economic factors, all of which contribute to a wide range of health risks. Globally, researchers are concentrating on assessing carbon fluxes, the capacity of different carbon pools, and the challenges associated with carbon sequestration methods. These efforts aim to mitigate the effects of climate change and reduce the risks associated with soil depletion. Understanding the processes of carbon sequestration and the mineralization of soil organic carbon (SOC) in soil aggregates is particularly important in this context. By elucidating these processes, we can better manage soil health, enhance carbon storage in soils, and ultimately contribute to reducing the impact of climate change [24]. Efforts to mitigate climate change must therefore involve a comprehensive approach that includes both reducing carbon emission and enhancing carbon sequestration. This dual strategy is essential to maintaining the balance of the carbon cycle and minimizing the long-term risks associated with climate change. Furthermore, addressing the social and environmental conditions that exacerbate these risks is crucial for developing effective and sustainable solutions to combat climate change on a global scale [23].

6. IMPLEMENTATION AND MANAGEMENT OF CARBON FOOTPRINT MEASURING EMISSION

Carbon Footprint Assessment: The first step is to assess the carbon footprint of agricultural activities. This involves calculating the GHG emissions from various sources, including energy use (fuel, electricity), fertilizer application, livestock management, and land-use changes [24]. Tools like carbon calculators and life cycle assessments (LCA) can help farmers quantify their emissions.

Data Collection: Accurate data collection is essential for measuring emissions. Farmers need to track inputs like fuel consumption, fertilizer use, crop yields, and livestock numbers. This data can then be used to estimate the carbon footprint of specific operations or the entire farm.

1. Reducing emissions:

A. **Adopting Sustainable Practices:** Farmers can reduce their carbon footprints by adopting sustainable agricultural practices. These include conservation tillage, crop rotation, organic farming, precision agriculture, and agroforestry. These practices not only reduce emission but also enhance soil health, water retention, and biodiversity.
B. **Efficient Use of Resources:** Optimizing the use of fertilizers, water, and energy can significantly reduce emissions. Precision agriculture technologies, such as GPS-guided machinery and variable rate technology (VRT), allow farmers to apply inputs more efficiently, reducing waste and emissions.
C. **Renewable Energy:** Integrating renewable energy resources, such as solar or wind power, into farming operations can reduce reliance on fossil fuels, further lowering the carbon footprint.

2. Offsetting Emission:

Carbon Sequestration: Agriculture has the potential to sequester carbon in soils and vegetation. Practices like cover cropping, reforestation, and maintaining grasslands can capture and store carbon, offsetting emissions from other farm activities [22].

Carbon Credits: Farmers can participate in carbon credit markets by implementing practices that reduce or sequester carbon. These credits can be sold to companies seeking to offset their emissions, providing an additional income stream for farmers.

6.1 Benefits of Carbon Footprint

The implementation of carbon footprint management in agriculture involves measuring, reducing, and offsetting greenhouse gas (GHG) emissions associated with farming practices. Agriculture is a significant contributor to global GHG emissions, primarily through activities like livestock production, soil cultivation, fertilizer use, and land-use changes. By managing carbon footprints, the agricultural sector can play a critical role in mitigating climate change while also benefiting from improved sustainability and efficiency [25].

1. Environmental Benefits:

1) **Climate Change:** By reducing emissions and sequestering carbon, agriculture can play a significant role in mitigating climate change. This helps protect ecosystems, biodiversity, and water resources, contributing to global environmental sustainability.
2) **Improved Soil Health:** Practices that reduce carbon footprints, such as conservation tillage and cover cropping, also enhance soil health. Healthy soils are more resilient to climate change, better at retaining water, and can increase crop yields.

2. Economic Benefits:

1) **Cost Savings:** Reducing input use and improving efficiency can lower costs for farmers. For example, precision agriculture reduces the amount of fertilizer and fuel needed, leading to direct savings.
2) **Access to New Markets:** Farmers who manage their carbon footprints may gain access to new markets, particularly those focused on sustainable and organic products. Consumers are increasingly demanding low-carbon and environmentally friendly products, providing opportunities for farmers to differentiate themselves.
3) **Carbon Credit Revenue:** By participating in carbon credit markets, farmers can earn additional income from carbon offsets, which can be particularly valuable in times of economic uncertainty.

3. Social and Ethical Benefits:

1) **Sustainable Farming Practices:** Implementing carbon footprint management aligns with sustainable farming practices that support long-term food security and the well-being of rural communities.
2) **Positive Brand Image:** Farmers and agricultural businesses that actively manage their carbon footprints can enhance their reputation and brand image,

attracting environmentally conscious consumers and investors.

6.2 Measurement of Carbon Footprint

The carbon footprint of the crop cultivation process in agriculture refers to the total amount of greenhouse gases emitted during the cultivation of a specific crop, expressed in carbon equivalent units. This CF is calculated by using formula as described by Nobre., [3].

Carbon Footprint = Agricultural Input* Emission Factor

In this formula, the “carbon footprint” represents the GHG emissions generated by a specific agricultural input. “Agricultural Input” refers to the quantity of various inputs such as fertilizers, pesticides, fuel consumption like petrol or diesel, and electricity usage. The “Emission Factor” represents the carbon equivalent of each individual input. To estimate the total carbon footprint involved in producing a crop, one must sum up the individual carbon costs from all the inputs used. The relationship is expressed as:

CFt = CFF + CFN + CFP + CFIR + CFD + CFM

In this equation:

CFF represents the carbon footprint from fertilizers.
CFN represents the direct emissions of nitrous oxide from nitrogen fertilizer application.
CFP is the carbon footprint from pesticides.
CFIR refers to the carbon footprint from irrigation.
CFD accounts for the carbon footprint from mechanical operations involved in crop production.

Additionally, CFM is an extra factor used specifically in rice cultivation to account for methane emissions, which are significant in this crop due to the anaerobic conditions prevalent in paddy fields. The carbon footprint resulting from N2O emissions due to nitrogen fertilizer application (CFN) is estimated using the following equations:

CFN = FN X dN X 44/28 X 298 X 12/44

In this equation:

CFN is the carbon footprint from direct N2O emissions due to nitrogen fertilizer application, expressed in tons of carbon equivalent.

FN is the quantity of nitrogen fertilizers applied during crop production.

dN is the emission factor for N2O emissions induced by the application of nitrogen fertilizers, measured in tons of N2O emitted per ton of nitrogen fertilizer applied.

44/28 is the molecular weight ratio of N2o to N2.
298 represents the global warming potential (GWP) of N2O over a 100-year time horizon.

12/44 is the molecular weight ratio of CO_2 to N_2O, used to convert N_2O emissions into carbon equivalents.

Both N_2O and CH_4 emissions are converted into carbon equivalents (CE) to provide a common unit for all GHGs, facilitating a more straightforward comparison and aggregation of the various emissions involved in agricultural processes.

6.3 Mechanism of Carbon Emission and C Sequestration

1. **Soil Organic Carbon (SOC) Management:** Improving SOC levels through practices such as no-till farming, cover cropping, and crop rotation can sequester significant amounts of carbon in the soil. These methods enhance soil health and fertility, leading to sustainable agricultural productivity.
2. **Agroforestry:** Integrating trees into farming systems can sequester carbon both in biomass and soil. Agroforestry practices provide additional benefits like improved biodiversity, enhanced water retention, and diversified income sources for farmers.
3. **Methane Reduction:** Rice paddies are a major source of methane emissions. Alternate wetting and drying (AWD) techniques in rice cultivation can reduce methane emission. Additionally, improving livestocks management through better feed and manure management can also lower methane emissions.
4. **Efficient Fertilizer Use:** Precision farming techniques and the use of organic fertilizers can reduce nitrous oxide emissions from soil. Implementing these practices not only cuts down GHG emissions but also enhances nutrient use efficiency, reducing input costs for farmers.

To implement carbon-credit systems effectively, a robust framework for measurement, reporting and verification (MRV) is essential [25]. This ensures that carbon credits generated are real, quantifiable, and verifiable. Several pilot projects in India have demonstrated the feasibility and benefits of carbon-credit systems [26,27].

1. **Case Studies:** Projects in states like Andhra Pradesh and Punjab have shown that adopting sustainable agricultural practices can lead to significant carbon sequestration and emission reductions. These projects have successfully engaged farmers, provided them with technical support, and facilitated their participation in carbon markets [28].
2. **Economic Incentives:** Carbon-credit systems provide an additional revenue stream for farmers. By selling carbon credits, farmers can supplement their income, making sustainable practices economically viable. This financial incentive is crucial in encouraging widespread adoption of climate-smart agriculture [29].
3. **Policy Support:** The Indian government and various non-governmental organizations (NGOs) are promoting carbon-credit systems through policies and programs that support sustainable agriculture. Initiatives like the National Mission for Sustainable Agriculture (NMSA) and the Soil Health Card Scheme are aligned with the goals of enhancing soil carbon sequestration and reducing emissions.

6.4 Challenges and Future Directions

Despite the potential, several challenges need to be addressed to scale up carbon-credit systems in Indian agriculture:

1. **Awareness and Education:** Farmers need to be educated about the benefits and practices of carbon sequestration and emission reduction. Extension services and farmer training programs are vital for this.
2. **Technical and Financial Support:** Smallholder farmers require access to affordable technologies and financial assistance to adopt sustainable practices. Microfinance and subsidies can play a significant role.
3. **Market Access:** Establishing and accessing carbon markets can be complex. Support from governmental and non-governmental entities is necessary to streamline the process and ensure fair compensation for farmers.

7. CONCLUSION

The major greenhouse gas, CO2 can be significantly reduced through carbon sequestration mechanisms, particularly within terrestrial sinks such as soil. Currently, natural terrestrial sinks absorb about 60% of the 8.6pg C emitted annually, but their capacity and efficiency are not sufficient to fully assimilate the anticipated anthropogenic CO2 emissions throughout the 21st century. This shortfall will persist until carbon-neutral energy sources are fully implemented. However, the potential of managed habitats, such as forests, farmland, and wetlands, to act as carbon sinks can be enhanced by adopting careful land use and implementing effective management practices in forestry, agriculture, and pastureland. Various sustainable agricultural practices, including tillage operations, cover cropping, crop rotation, biochar application, integrated nutrient management, and microbial biomass management, are key strategies for controlling CO2 emissions. By deliberately managing biological processes, we can accelerate carbon sequestration, improve soil health, boost food production for the growing population, and enhance land sustainability as a resource. Achieving these benefits will require regulatory actions and policy incentives to support the adoption of these practices. For these management systems to be effective, an integrated structural approach is essential. There is sustainable potential for humanity to mitigate climate change through carbon sequestration. However, recent trends in agriculture reveal some challenges. For instance, the area under-intensive rice cultivation has increased, while the area devoted to less carbon-intensive crops like finger millet, pearl millet, sorghum and barley has declined. Among the various inputs used in agriculture, inorganic nitrogenous fertilizers are a major source of CO2 emissions. Therefore, improving the efficiency of nitrogen use by amending the application of chemical nitrogen fertilizers is critical to reducing the carbon footprint of agriculture.

To further reduce emissions, it is necessary to increase the efficiency of other agricultural inputs. This can be achieved by adopting recommended practices meticulously, such as applying input based on soil analysis and timing them with critical crop growth stages. Incorporating legumes into crop rotations, adopting integrated farming practices, using organic fertilizers, and implementing moisture conservation technologies in rice cultivation are also effective strategies. Quantifying greenhouse gas emissions from the production of various agricultural crops is crucial for helping farmers, researchers, and policymakers understand and manage these emissions. This understanding will enable the development of strategies to achieve food security while stabilizing the environment. By focusing on reducing the carbon footprint of agriculture, we can make significant strides toward mitigating climate change and ensuring the sustainability of food production systems.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declares that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript. There is NO use of AI technologies.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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