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Review

Carbon Farming: Prospects and Challenges

Meenakshi Sharma [1], Rajesh Kaushal [2], Prashant Kaushik [3,4,*] and Seeram Ramakrishna [5,*]

[1] Department of Chemistry, Kurukshetra University, Kurukshetra 136119, India; meenakshiskkr@gmail.com
[2] Division of Plant Science, ICAR-Indian Institute of Soil and Water Conservation, Dehradun 248195, India; kaushalrajesh1@rediffmail.com
[3] Kikugawa Research Station, Yokohama Ueki, 2265 Kamo, Kikugawa 439-0031, Japan
[4] Instituto de Conservación y Mejora de la Agrodiversidad Valenciana, Universitat Politècnica de València, 46022 Valencia, Spain
[5] Center for Nanotechnology and Sustainability, Department of Mechanical Engineering, National University of Singapore, Singapore 117576, Singapore
* Correspondence: prashantumri@gmail.com (P.K.); seeram@nus.edu.sg (S.R.)

Abstract: Carbon farming is a capable strategy for more sustainable production of food and other related products. It seeks to produce a diverse array of natural farming methods and marketable products simultaneously. According to the food and agriculture organization (FAO), agriculture, forestry, and other land-use practices account for 24% of global greenhouse gas (GHG) emissions and total global livestock emissions of 7.1 gigatons of CO_2-equivalent per year, representing 14.5% of total anthropogenic GHG emissions. For example, an agroforestry system that deliberately integrates trees and crops with livestock in agricultural production could potentially increase carbon sequestration and decrease GHG emissions from terrestrial ecosystems, thus helping to mitigate global climatic change. Also, agroforestry is capable of generating huge amounts of bio-mass and is believed to be particularly suitable for replenishing soil organic carbon (SOC). SOC is a crucial indicator for soil fertility since the change in SOC can explain whether the land use pattern degrades or improves soil fertility. Moreover, SOC found in soil in the form of soil organic matter (SOM) helps to improve soil health either directly or indirectly. Thus, efforts should be made to convince farmers to increase their resource-use efficiency and soil conserving ability to get maximum benefits from agriculture. Therefore, this review aimed at clarification about carbon farming, modifications in carbon cycle and carbon sequestration during agricultural development, and benefits of agroforestry.

Keywords: carbon farming; carbon foot printing; low carbon agriculture; carbon sequestration; carbon economy

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1. Introduction

Novel approaches to cropping systems and soil management are being developed to cope with the abundance of CO_2 in the environment while improving water use efficiency and soil quality at the same time. Different management practices affect the amount of organic matter in the soil, composition, and water retention capacity [1,2]. However, satisfying human needs and protecting environmental resources simultaneously is key to effective planning strategies. Soil quality research aims to understand the management of soil to take advantage of its inherent qualities. Therefore, it becomes necessary to recognize the factors affecting the health of soil, among which organic matter is critically important [3,4]. Easily manipulated by land management activities, organic matter is found in most agricultural settings. Because organic matter increases the water-retaining capacity and strengthens the soil structure [5,6], it helps to improve agricultural productivity, in addition to reduced incidences of drought and diseases [7,8]. Furthermore, agricultural activities that deposit organic matter into the soil are necessary to limit the environmental CO_2 [9,10].

It has also been demonstrated that activities related to soil management are essential for conserving and restoring soil carbon. However, many farming fields, though not all, have substantial carbon deficiency because of soil erosion and breakdown [11,12]. It is widely accepted that various governments employ possible measures to incentivize ecologically sustainable farming methods to conserve soil carbon. In low-input areas, agroforests struggle to increase crop productivity and help farmers maintain soil quality. In combination with crops, particular tree species in agroforest-management systems may be feasible to solve numerous agricultural challenges [13,14]. Another government project is the implementation of environmental policies that attempt to maintain a low carbon footprint. In addition to traditional tillage, terracing, and no-mulching systems, farmers are advised to use other systems such as biofertilizers, no-till, and vegetal mulch, along with the systems operating under agroforestry [15,16].

The density of forests constitutes another major factor influencing the soil carbon content. On the other hand, deforestation substantially affects the flow of rivers and land use patterns [17,18]. Agriculture, forestry, and other land-use practices account for 24 percent of global greenhouse gas (GHG) emissions, with total global livestock emissions of 7.1 gigatons of CO_2-equivalent per year, accounting for 14.5 percent of total anthropogenic GHG emissions, according to the Food and Agriculture Organization (FAO) [19]. Forests, however, provide significant scope for a net reduction in global warming (as a consequence of GHG emissions) through CO_2 sequestration [20]. Since injecting flue gas into aquifers for storage and disposal of CO_2 poses the risk of carbon leakage over time, it offers little economic advantage, making the carbon sequestration technique more attractive [21,22]. Furthermore, planning and management of forests must also consider how they relate to other aspects of the ecosystem. Besides, microalgae exhibit a highly productive photosynthesis, resulting in large amounts of CO_2 as organically bound carbon in their cells [23,24]. Therefore, for biomass sourced from fossil fuels, CO_2 pollution per unit may be lowered due to the CO_2 that is recycled and then reused by algae [25].

2. Material and Methods

The literature was systematically reviewed based on the PRISMA (Preferred Reporting Items for Systematic Meta-Analysis) approach [26]. The research goals were investigated through related studies using Google Scholar with the keywords: carbon farming and soil management, carbon foot-printing and carbon economy, carbon sequestration, carbon farming and challenges. Further, the studies were investigated for the years 2000–2020. In total, 360 documents were analyzed, out of which 190 papers were found relevant for the present review (Figure 1). Finally, the research papers published in journals with an impact factor were carefully selected, and their findings are reported in this review.

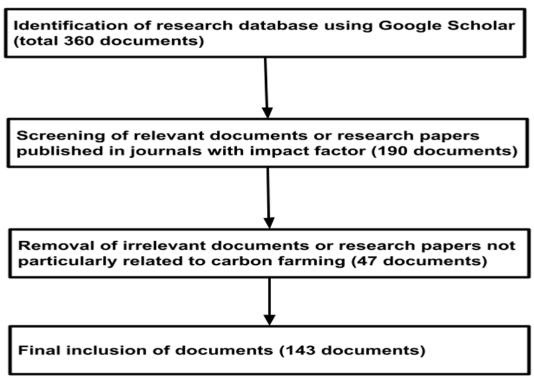

Figure 1. The methodological framework of research analysis.

3. Low Carbon Agriculture

Minimal soil disturbance, consistent soil coverage, and crop rotation are essential for soil conservation practices [27]. According to their availability, managing diverse plant species (allocating nutrients at varying levels) allows for sustainable nutrient management in nutrient-depleted soils [28,29]. Agroforestry, in this context, has been found to be useful in creating environmental, economic, and ecological values for agricultural areas in temperate and tropical ecosystems [30]. These may include an increase in nutrient utilization, creating habitats for plants, insects, and animals, and protecting soil from erosion in hilly locations [31,32]. Furthermore, litter and tree roots constitute a highly sustainable way of forming and enhancing the quality of soil organic matter (SOM) in agroforestry ecosystems [33,34]. Restoration systems have proven successful because of their capacity to improve soil structure and biomass stores in the long term [35]. Further, it has been observed that, in hot regions, organic matter tends to degrade quickly, with corresponding changes in the chemical, physical, and biological composition of soil [36]. In these regions, appropriate soil conservation and crop management are predicated on using little or no-tillage for crops with higher residue production [37,38].

An agroforestry or alley cropping system, in general, combines trees and grassland farming. The trees are used to make quality wood products while also providing forage and shelter at the same time. On the other hand, grasslands can serve to preserve biodiversity [39]. Most treeless savanna systems can sequester carbon, in addition to extraction or remediation of nutrients [40]. Alley cropping has been used in temperate and tropical regions to grow trees and coffee, cocoa, and livestock [41,42]. Cultivated vegetation in alley cropping systems has been shown to improve soil nutrient cycling [43], reduce nutrient losses [44], promote fauna activity [45], enhance fertility [46], and control soil erosion [47]. Besides, interest in developing alleys as alternative crops and as a carbon sink has risen because of the development of species like *Robinia pseudoacacia*, as a great potential to offset GHG emissions [48]. Improving soil characteristics due to N2 fixation and increasing SOM in the litterfall may contribute to *R. pseudoacacia's* overall success [49,50]. Therefore, integrating three elements, i.e., farming, livestock, and forestry via agroforestry with various conservation practices, revitalize soils while increasing carbon sequestration in the long term [51,52]. In a crop-livestock system, forests are involved simultaneously as livestock-grazing land after the crops have been harvested.

Moreover, an integrated crop-livestock-forest system may improve soil biodiversity, nutrient depletion, and nutrient recycling, as withstanding capacities [53,54]. These systems maximize total production, lower the real risk, and increase the cultivation alternatives rendering them economically favourable to monoculture [53,55]. However, some researchers have suggested that alley cropping systems may influence soil use efficiency [56]. The labile organic fraction also decreased with the continued use of alley cropping [46,57]. Therefore, more research needs to be done in order to discover the possible impacts of agroforests on the quality of soils in different ecosystems. Also, studies of the annual litterfall and non-tree elements of alley-based agriculture should be done.

4. Carbon Cycle in Agriculture

The main sources of carbon circulating actively in the ecosystem are atmospheric CO_2, biomass (generally vegetation), soil organic matter, and the oceans [58,59]. Among these, the oceans comprise the most extensive carbon reserves. However, most of the carbon lies in deep ocean layers (not involved in active carbon circulation) [60,61]. Carbon stocks in biomass or biota are less certain, however, they are almost equivalent to the atmospheric sources [62]. About 75% of biomass is found in forests [63]. Plants found in the ocean, primarily algae, possess less than 1% global carbon biomass [64].

Furthermore, the largest source of carbon circulating actively in the terrestrial ecosystem is the soil [65]. It contains carbon in different organic forms, such as plant litter, charcoal, or fossils [66]. About one-third of the organic carbon in soil is found in forests, another one third in savannas and grasslands, and the rest in wetlands and other biomes [67].

All of these carbon sources, i.e., the atmosphere, the vegetation, the soil, and the oceans, are interconnected. Atmospheric CO_2 enters the terrestrial bio-mass through photosynthesis in plants. However, about half of the CO_2 is released through respiration [68].

The amount of CO_2 left or net primary production (NPP) is stored provisionally in vegetative tissues, which eventually enters the soil after attaining senescence [69]. Simultaneously, heterotrophic respiration performed mainly by soil micro-organisms and other anthropogenic activities returns roughly equivalent NPP to the atmosphere, closing the loop [69]. CO_2 exchange between the atmosphere and the ocean is even more prominent. Some of this occurs by physical processes involving the CO_2-carbonate equilibria, but a surprisingly large exchange also occurs via biological processes [70].

5. Effects of Plant Residue Quality on Carbon Dynamics

The added plant residue, microbial biomass, mineralization, and organic matter production rates are important in different ecosystems [71,72]. The quality of plant residues and, essentially the soil mineralogy (such as acidity, biological readiness and mineral contents) are mainly determined by the rates of residual mineralization [73,74]. The plant residues are also affected by variations in their biochemical compositions [75,76]. The composition of residue minerals and their chemical profile in controlled environments decides the extent of decomposition, or in other words, the biochemical composition of residue controls the rate of decay [77,78]. Further, various studies have revealed that plant species with distinct abilities are especially important for agricultural systems with limited fertilizer inputs [79,80]. The amount, location, and bio-degradability of plant residues significantly affect the SOC [81,82]. Therefore, the adequate management of plant residues is necessary to increase the processing of biological nutrients and minerals in the soil.

However, plant residue management alone may not be sufficient to ensure enough carbon reserves in the soil since it is also associated with the physical soil structure [83,84]. It has been found that the soil carbon levels decreased considerably as a result of conversion of the forest land to agricultural land [85,86]. The loss in soil inputs, nutrients, and decomposition can be attributed to changes in forest carbon and ecosystem disturbance [87,88]. The carbon isotope composition in the soil is a valuable technique for quantifying the rate of organic and/or non-biological processes [89]. A number of ecosystems have been investigated using C-isotopic techniques for SOM concentrations. Most of these studies have investigated the 13C (isotopic) properties of SOM that have emerged through vegetation changes between the C3 plants and the C4 plants [90,91]. Changes in the 13C concentration of these fractions can, thus, tell us about SOM consumption rates and provide helpful information about the different control systems of management. Depending on the location and environmental exposure, different results are obtained.

6. Carbon Sequestration

As a matter of environmental concern, there has been increased interest in carbon sequestration techniques for reducing CO_2 emissions. Human activities are known to have substantial effects on the terrestrial carbon cycle (approximately 50% CO_2 sequestration) both directly and indirectly [92,93]. The burning of fossil fuels constitutes a significant proportion of total anthropogenic CO_2 emissions [94,95], and with the demand for energy increasing rapidly, particularly in developing countries, such emissions are expected to increase even more. The overwhelming body of scientific evidence has indicated that elevated CO_2 levels in the atmosphere are highly detrimental to the environment [96,97]. According to researchers, increased CO_2 levels in environment produce greenhouse effect resulting in increased temperatures and hence global warming [98,99]. The oceans, in this regard, can provide a solution since they are known to absorb about a quarter of all the anthropogenic CO_2 emissions [100,101]. This could be beneficial, but at a cost, since increased CO_2 levels in seawater forms carbonic acid [102,103]. It is worth mentioning here that ocean acidity has increased by 30% since the industrial revolution began. Increased water acidity impairs the development of marine shells and skeletons, primarily affecting deep-sea organisms such as benthic and anadromous fauna [101,102]. Additional increases in oceanic acidity are believed to hasten the demise of marine life. Therefore, stringent post-combustion carbon sequestration management will be required to meet the energy demand while minimizing CO_2 emissions.

Carbon capture and storage is a process that absorbs CO_2 from flue gaseous emissions and stores it for extended periods [104,105]. Carbon is found in all biological media, including peat and seawater [106,107]. Besides, organic carbon can be produced by autotrophic organisms through photosynthesis which involves the reduction of CO_2 [108,109]. Carbon sequestration is defined as the deliberate or intentional separation and disposal of CO_2 as a by-product of combustion in non-atmospheric reservoirs [110]. It has been further defined as increasing natural processes, such as CO_2 absorption by living organisms, to offset any additional CO_2 emitted [21,111]. Energy crops such as biofuels, in this context, may be used in a variety of ways [112,113]. CO_2 can be recycled during the biofuel production, and biomass can be potentially used in place of fossil fuels [114,115]. If the process is carried out properly, it will result in massive amounts of value-added biomass and materials that can be further used to make bio-ethanol. In addition to these carbon management strategies, the biological carbon mitigation technology (BCM) in CO_2 sequestration has also been investigated (as is the applicability of microalgae) to ascertain the fate of mitigated carbon [21,116]. Thus, appropriate carbon management is necessary to ensure that biomass can be used for various commercial purposes while also sequestering additional carbon simultaneously in biological media to keep the air safe.

7. Carbon Foot Printing

To reduce GHG emissions and increase GHG sinks in a particular system, carbon footprint (CF) identifies the source, quantity, and sink of GHGs released from on-farm and off-farm activities [117]. A CF takes into account all the inputs and processes within the confines of a defined system. The friction coefficient is calculated within a system limit, a hypothetical line based on the activity and materials used [118]. Although the findings of CF research may provide helpful information to make effective choices, the methods used to calculate CF for agricultural systems are, at present, lacking in consistency [119]. For instance, in several areas, consistency including the choice of functional units, system limits and emission factor specificity (EFS) is missing. Moreover, it is difficult for a variety of reasons to estimate soil GHG emissions from diverse farm activities. There are significant variations amongst other factors in soil carbon (C), global and field-scale estimates [120]. In addition, the dynamics and interactions of labile and recalcitrant carbon stores give a combined strategy to develop consistent methods and models for site-specific information. Adewale et al. quantified carbon loss and gained in soil, and found that 13% of CF net soil emissions were produced from a small production of vegetables [117]. Therefore, a full CF assessment must cover carbon (CO_2 released or sequestered) and the net GHG emissions of a particular farm or farm product or field operations [121] to determine whether agricultural techniques can help implement a GHG reduction strategy successfully. Organic agriculture, in this regard, is a beneficial subset of CF agriculture since it involves the conservation of natural resources and annual certification [122]. Numerous studies were carried out to determine the environmental impacts of organic farming, most of which demonstrated advantages over conventional farming methods, including increased soil content, lowering nutrient performance and lower consumption of energy [123,124].

However, whether organic farming produces more or less GHGs than conventional farming is not answered since the findings vary depending on the product and farm activity. According to a study, organic farming techniques emit more ammonia, nitrogen and N2O per Product Unit than conventional farming systems [125]. Organic dairy and organic pig farmers are often responsible for more GHG emissions by a unit than conventional systems, while organic beef production generates fewer GHGs per kilogram of meat [126]. Due to many results, satisfactory conclusions cannot be drawn regarding the CF of different systems. However, many studies advocate using Tier3 EFS to improve the precision and usefulness of methods for estimating agricultural GHGs [127]. Given the potential to contribute significantly to GHG reduction efforts by organic fertilizers and technology, it is critically needed that Tier 3 EFS, particularly for organic inputs, be established. The limits of an agricultural system include farm infrastructure and machinery, pesticides and other chemical inputs, soil-use changes, soil emissions and sequestration of carbon and livestock enteric fermentation, in combination with more traditional inputs such as fertilizer, fuel and electricity [128]. Any such factor could be critical in determining systems differentiation or the most effective CF prevention and reduction strategies.

Furthermore, agricultural operations need adequate monitoring so that farmers can make informed decisions regarding equipment and use of fuel and soil carbon changes [129]. Organic farming frequently has a lower carbon footprint (CF) than conventional agriculture when measured by area and sometimes by-product unit [121]. The future use of certified organic farms as a longitudinal national or global population study would be justified due to their potential benefits and the annual inspection and certification process. In this direction, the representative concentration pathway (RCP) is a GHG concentration trajectory approved by the Intergovernmental Panel on Climate Change (IPCC). In 2014, the IPCC's fifth assessment report took four distinct climate modelling and research [130]. The paths illustrated possible climate futures, and each is considered plausible considering CO_2 generated in the coming years. RCP2.6, RCP4.5, RCP6.0, and RCP8.5 refer to radiative forcing values for the year 2100 (Figure 2).

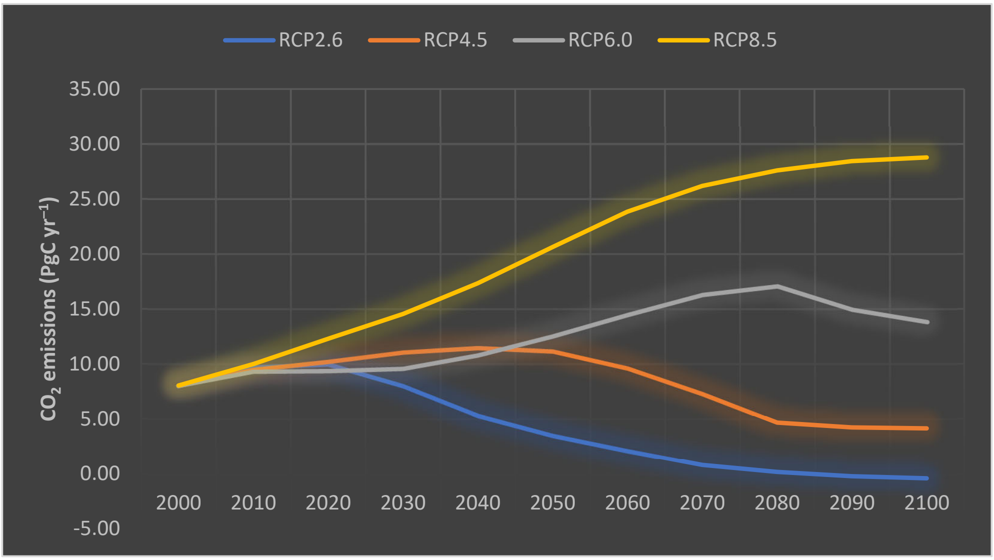

Figure 2. Anthropogenic total CO_2 emissions (PgC yr^{-1}) from farming and its projection until 2100.

8. Carbon Economy

Instead of colonizing the governance spaces created by calculating a product's carbon footprint, retailers establish new corporate responsibility regimes to measure and manage carbon emissions. Here, certain behaviors are encouraged, legitimized, and/or eliminated in order to force individual suppliers to become active participants in their own governance [131,132]. Similar is the case for carbon reduction from agricultural products, with the values and ambitions of their supply chain partners. Concerning climate change, retailers take on a more significant and more extensive role in measuring and reducing the carbon footprint of the products in order to strengthen their place in society, ensuring their long-term viability and license to operate [133]. While global retailers have received platitudes for their role in mitigating climate change, the actual responsibility of such climate change mitigation programs and the risk associated with them is positioned with the government [134]. However, by taking this approach, retailers have sparked a radical reimagining of the carbon economy due to their size and ubiquity at the intersection of daily consumption–production practices [132,133]. Retailers reframe their supply chain models by looking into the product's entire life cycle through carbon footprinting and introducing new norms and priorities into the existing relationships [135,136]. In carbon footprint printing, suppliers have independently adopted new measurement techniques, collected and disclosed data, and made corresponding carbon reductions.

The product carbon footprint necessitates the suppliers to take responsibility for the environmental and social impacts of the products they deliver to the next stage of the supply chain [137,138]. Suppliers at all the levels and tiers of a product's supply chain are encouraged to collect and share their best carbon footprint data [139,140]. Furthermore, the priorities, ambitions, and responsibilities assumed by multinational corporations, from halting deforestation to reducing carbon emissions, have a profound impact on the lives of consumers, suppliers, society, and global ecologies [132,141]. In the absence of well-defined and well-enforced international environmental standards, these actors are increasingly defining sustainability in corporate terms [142]. When it comes to mitigating climate change, this has resulted in retailers gradually reimagining the transition to a low-carbon economy in ways that align with their commercial and risk-averse interests [143,144]. Therefore, it becomes inevitable to address the fundamental questions relating to consumption (at the expense of global environmental changes) and the expanding power of these corporate citizens in creating a sustainable market for low-carbon products.

9. Challenges in Carbon Farming

The carbon farming initiatives (CFI) demand agro-environmental policies to incentivize farmers to adopt best farm management practices. However, it is usually difficult to get farmers involved in such programs mainly because of the complex scheme-design and its implementation or conflicting targets of policy-makers and the farmers [145]. Various other factors are also known to affect the adoption and implementation of new farm management practices, which include personal interests of landholders, farm or land features [146,147]. Some of the barriers in carbon farming are directly associated with the landholders' interests, in addition to inadequate skills or management abilities. Political instability also substantially affects the acceptance and implementation of such practices [148]. Besides, uncertainty about environment related impacts and lack of awareness of such schemes and policies may also undermine their adoption [149,150]. Farmers have agreed that they have insufficient access to information regarding available options for carbon farming [150,151]. In fact, many farmers don't understand the exact meaning of carbon farming, and they lack detailed information about the pros and cons of carbon farming. The situation was further exaggerated by high input costs and apprehensions regarding the effect of carbon farming on yield and farm productivity.

CFI's other significant barriers are lack of approved methods and procedures, higher administrative expenses, and difficulty in getting certification as a qualified carbon offset provider [152,153]. In addition, the capital investment required, unsuitability of carbon farming with existing farm management practices, and the probable impacts on the ability of farmers to obtain financial assistance from banks or other sources have been identified as significant challenges to carbon farming [150,154]. Some other barriers that need specific mention here include: instability in carbon prices [155]; uncertainty regarding benefits from carbon farming [156]; difficulty in monitoring the progress of such initiatives [157]; uncertainty regarding carbon market selling practices [158]; and the financial consequences of participation [159]. Farmers also stated that the sale of products from tree plantations is difficult, indicating their reluctance to implement carbon farming as they consider it to be dissenting with other objectives [151,153]. Moreover, some farmers believe that the carbon farming policy rewards them with an antiquity of improper land management, preventing their involvement [160,161]. This suggests that farmer's interests or sentiments may offer a participation barrier to CFI along with the other barriers mentioned above. In such a scenario, encouragement through financial incentives for increased participation in CFI does not seem to be sufficient to tackle the barriers that farmers generally face.

10. Discussion

Carbon farming involves, as discussed in this review, the management of carbon content in soils. Carbon farming presents an opportunity to maintain biodiversity, economic and social co-benefits along with terrestrial carbon abatements (Figure 3). The review emphasizes some of the important factors that must be considered to implement carbon farming and other reforestation policies. However, its effective implementation primarily relies on appropriate institutional provisions and sufficient information dissemination. Landholders are required to be provided with clear information about the relative outcomes and benefits of adopting carbon farming, including precise information on carbon abatement, expected financial returns in the carbon market, variations in carbon yields depending upon soil type, possible impacts on property value, and farm productivity [162]. Evans et al. highlighted the possibility of carbon farming to be adopted as a feasible land use practice in agricultural lands of north-eastern Australia. The research, in particular, illustrated the potential of carbon farming as a cost-effective alternative for agrarian production capable of sequestering carbon and restoring biodiversity simultaneously [154].

Further, changes in land-use pattern remain, arguably, the most compelling threat to biodiversity conservation which requires utmost attention. Therefore, we have presented an approach to enumerating the impacts of carbon farming across various ecosystem components and exploring synergies to minimize the adverse effects through careful implementation. Generally, the mechanisms involved in carbon farming help restore the lost functions of the ecosystem and strengthen ecosystem services delivery. This mainly includes soil health and water quality (services significant for environmental well-being), in addition to improved farm productivity [163].

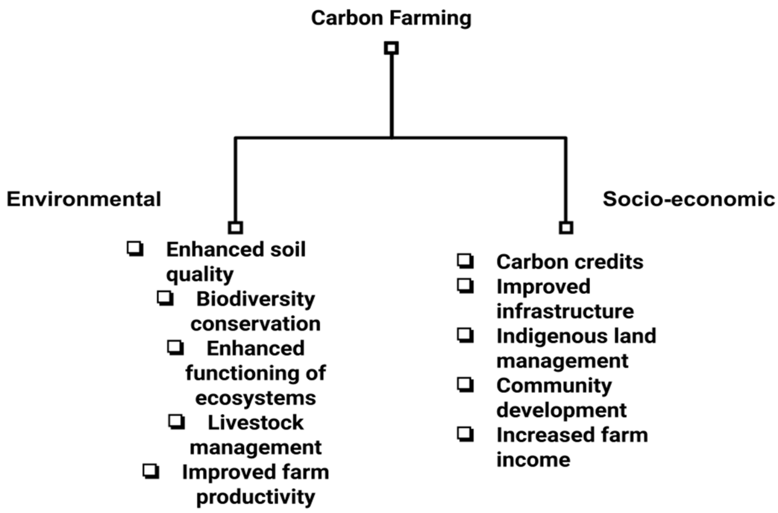

Figure 3. Environmental and socio-economic advantages of carbon farming [164].

11. Conclusions

Given the increasing human demands and subsequent effects on the environment, sustainable practices of agricultural production are being encouraged. The dependence of the agricultural output on climatic change can be stabilized by using less-intensive and judiciously organized farming methods. The agro-environmental parameters must be considered thoroughly to discover farming systems that can control the delicate balance between climatic change and agricultural productions. Carbon farming, in this context, offers an all-inclusive and sustainable land-use management method, beneficial for both environment and the society. The combination of forest vegetation with crop farming and livestock production through agroforestry improves net agricultural production and food security. It is also known for reduced GHG emissions and carbon sequestration which depend mainly upon climate conditions, soil characteristics, vegetation, and land-use practices. Agroforestry ecosystems might be estimated with various environmental indicators depending on energy use, the yield and productivity, and production processes. However, the silvopastoral system is generally found to be more effective in relation to carbon sequestration and GHG emissions reduction than the agroforestry system. Besides, carbon farming systems are highly efficient at retaining organic carbon stocks in the soil. These systems are capable of accumulating more significant amounts of SOC as compared to mono-cropping, thereby improving soil quality. However, in spite of so many advantages, carbon farming is not well-appreciated by farmers due to a number of reasons. Therefore, well-informed advisory services are required to encourage farmers to adopt CFI for agricultural production and soil management and reduce the unsustainable farming practices.

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