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Perennial Fodder Crops as a Tool for Soil Carbon Management in Agroecosystems

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

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ABSTRACT

Carbon sequestration, typically referred to as carbon storage is defined as the "long-term storage of carbon in plants, soils, geologic formations and the ocean, which occurs both naturally and as a result of anthropogenic activities". With respect to agricultural sector, carbon sequestration is viewed as the capability of agriculture lands to absorb carbon dioxide from the atmosphere. Out of the different ways in play, cultivation of fodder crops turns out to be promising due to its high biomass production, root proliferation, mostly perennial nature, suitability for wastelands and most importantly as the feed for livestock. Restoration of degraded lands, adoption of pasture-based agroforestry systems, inclusion of grasses, sowing of improved forage species, grazing

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management, nutrient and water management are strategies that aid in improving carbon sequestration in fodder production systems. Perennial fodder grasses and fodder legumes such as alfalfa are excellent for carbon storage as they do not require replanting after each harvest which avoids soil disturbances that usually associate with annual crops. Carbon neutral methods of cultivation is greatly hoped to convert agriculture from a source of carbon to a permanent sink of carbon at a faster pace.

Keywords: Carbon dioxide; fodder crops; cropping systems; agroforestry; carbon sequestration; carbon neutrality.

1. INTRODUCTION

Carbon, the key energy currency of biological systems including agriculture; in its monoxide and dioxide versions, spurs global warming, paving way towards hastened climate change. The safe limit of atmospheric carbon dioxide (CO_2), 350 ppm was crossed in May, 1986 and has escalated to a level of 424 ppm in May, 2024 as read in the Moana Loa observatory (NOAA, 2024). The theme of World Environment Day, 2022 - '*Only One Earth*', reiterates the need for bringing out our planet from the fumes of pollution, global warming and climate change. Dependence on fossil fuels (87%), accelerating deforestation (9%) and flourishing industries (4%) opens door to CO_2, into the atmosphere. Oceans, the main sink of CO_2, absorbs and stores 60% of the total emissions, where the leftover 40% posing trouble to the planet's existence. Decelerating the escape of carbon in its dioxide form needs to be promoted by the adoption of strategies that sequesters and fix these emissions for longer periods. Agriculture, the most vulnerable sector to climate vagaries is looked upon as the most potent carbon sequester with the adoption of carbon neutral methods of cultivation. Among the multifarious approaches in attaining carbon neutrality in agricultural sector, the cultivation of fodder crops turns out to be promising due to its huge biomass production, root proliferation, mostly perennial nature, suitability for wastelands and most importantly as the feed for livestock.

The growing livestock population create higher demand for fodder cultivation, which currently accounts for only 4% of the cultivated land in India (Patil et al., 2018). In India, the total livestock population has increased by 4.8% and reached 536.76 million in the 20th livestock census in comparison with the livestock census in 2012 (FAHD, 2019). Livestock, the backbone of agriculture sector in the nation, contributes 24.7% of the annual agricultural GDP (Singh et al., 2019). But India has a deficit of dry and green fodder by 12% and 30% respectively whereas, the demand for both is expected to rise to 1012 and 631 million tonnes respectively by 2050 (IGFRI, 2020). In our country, there is a shortfall of green fodder, dry crop leftovers and concentrate feed ingredients by 35.6%, 10.5% and 44% respectively (Singh et al., 2022). In the grounds of climate change, fodder crops could be relied up on for carbon storage and subsequent attenuation of atmospheric carbon which in turn alleviates fodder shortage.

India, housing 17.7% of the world's human population and 15% of world's livestock population, experience a clear food-fodder competition for land, water, nutrients and other resources. On the other side, fodder cultivation benefits the growing human population with high milk-meat production which helps in alleviating the malnutrition-related health problems in humans (Rosegrant, 2002). Further the marginal lands and waste lands, less suitable for agricultural crops can be effectively used for cultivating climate resilient fodder crops. Raising leguminous fodder crops as intercrops improves soil fertility through biological nitrogen fixation.

Carbon equivalent greenhouse gas (GHG) emissions and energy consumption associated with agricultural systems are steadily rising to satisfy the growing food and fodder demands of increasing human and livestock populations (Mishra et al., 2019). In this scenario, finding out the optimal fodder-based cropping systems that yield high biomass while minimizing carbon equivalent inputs is of prime importance for attaining sustainability in livestock production.

2. CARBON SEQUESTRATION

A carbon pool is a reservoir of carbon that can either store or release carbon over time. It functions as a sink for atmospheric carbon when, over a specific period, the inflow of carbon exceeds the outflow. According to Agriculture, Forestry and Other Land Use (AFOLU), the pool includes aboveground biomass, belowground biomass, litter, dead wood and soil organic carbon. Through photosynthesis, the CO_2 absorbed by trees, plants and crops get converted to carbohydrates which is stored in the biomass *viz.* foliage, branches, tree trunks and roots and also in soil (EPA, 2008).

A carbon pool that grows in size is referred to as a carbon sink. According to Gadgil (1991), the degrading green blanket of Earth, our forests have been identified as a sink for carbon and its rejuvenation as a means to diminish the adverse effects of climate change. Globally, grasslands sequester 34% of the terrestrial carbon stock, with forests and agroecosystems storing 39% and 17% respectively (WRI, 2000). Goh (2004) conferred the role of forests and stable grasslands as carbon sinks, attributing to its carbon storage ability in the flora for extended periods. Afforestation and reforestation programmes increase the carbon sequestration potential from 8.79 x 10^9 tC to 9.75 x 10^9 tC from a period of 2006-2030 (Bangroo et al., 2013).

Soil, the largest terrestrial sink of carbon, stores it mainly in the form of organic carbon which determines whether soil serves as a sink or source of carbon. Plant roots acts as the mediator for transporting atmospheric CO_2 into the soil pool primarily through root exudations, root death and root respiration (Kumar et al., 2006). Minimum soil disturbances through reduced or conservation tillage, growing deep rooted crops and cover crops helps in preserving the carbon within the sink. Jiang et al. (2006) observed that an optimum level of soil organic carbon as crucial for maintaining and improving the water retention capacity, soil quality, soil fertility, soil faunal activity and crop productivity. Lessmann et al. (2021) reported a soil organic carbon (SOC) sequestering potential of 0.1 and 2 gigatonnes of carbon per year (Gt C year^{-1}) by the croplands. Agricultural lands, including grasslands and wastelands, potentially fixes about a one-third of the net emission of GHGs i.e. 4.5-6.5 Gt C equivalent (eq.) year^{-1} (Malaviya et al., 2021).

Biomass, both aboveground and belowground plays a decisive role in the carbon sequestration potential of any vegetation (Montagu et al., 2006). The above ground biomass determines the carbon capture ability of fast-growing crops (Walker et al., 2008). According to CCI (2020), '*Agriculture is the one sector that has the ability to transform from a net emitter of carbon dioxide to a net sequester of carbon dioxide - there is no other human managed realm with this potential*'. An agricultural land's sequestering potential depends on various biotic and abiotic factors *viz*., climate, soil composition, crop or vegetation type and management strategies (Joseph et al., 2020).

3. CARBON NEUTRAL AGRICULTURE

Carbon neutral agriculture is defined as "*the scientific practice of agricultural methods that are aimed at sequestering atmospheric carbon into the soil organic carbon pool and in crop roots, wood and leaves, with the goal of creating a net loss of carbon from the atmosphere*". Multifarious approaches including manuring, nutrient management, agroforestry practices, taking up fodder cultivation in uncultivable and fallow lands, water conservation and harvesting have been entrusted for attaining net zero carbon emissions from agriculture. Sarkar et al. (2020) proposed that implementing effective land management practices, along with appropriate forage and grazing systems, can significantly enhance the storage of soil organic carbon.

Integration of diverse commodities *viz*. livestock, fish, poultry, with crops and adoption of crop rotation and use of organic manures contributes to boosting productivity and lowering net carbon emissions, compared to monocropping. Meera et al. (2019) reported highest net carbon sequestration and negative carbon emissions from homestead-based farming system. The more diverse the cropping system, the more biomass per unit land area and hence carbon sequestration. Incorporation of legume crops and implementation of multi-storeyed cropping system with high efficiency in utilizing the solar radiation improves carbon storage in biomass. Chethankumar et al. (2020) observed rice-rice-daincha cropping system to be twice more efficient in carbon storage than rice-rice- fallow system.

Integration of trees with different land use systems helps in an additional storage of 2.5 to 3 billion tCO_2 eq. by 2030 under the Paris Climate Agreement, which becomes an asset towards bringing down the emission and attaining India's climate change targets (Ruchika, 2019; Chavan et al., 2022). The immense ability of agroforestry in sequestering carbon in their biomass point towards the need to encourage these practices in crop lands, marginal lands and degraded lands.

4. CARBON SEQUESTRATION THROUGH FODDER CROPS

Table 1. Carbon sequestration potential of different fodder crops

Fodder crop	Carbon sequestered (t C ha^{-1})	Reference
Fodder cowpea	72.58	Sundaram et al. (2012)
Hedge lucerne	95.90	Nishanth et al. (2013)
Hybrid Napier	79.70	Rajkumar et al. (2014)
Hybrid Napier	112.23	Bama and Babu (2016)
Hybrid Napier	88.03	Kumhar et al. (2021)

Perennial fodder grasses and legumes such as alfalfa are excellent for carbon storage as they do not require replanting after each harvest which avoids soil disturbances that usually associate with annual crops. Reduced summer fallow, direct seeding of perennial forage crops, windbreaks, rotational grazing and proper straw management can be practiced for reducing CO_2 emissions and increasing soil carbon (AARD, 2000). Farm machinery and agrochemicals, less depended by the perennial fodder crops attribute to lower the usage of fossil fuel.

Wynn and Bird (2007) reported lower soil organic carbon sequestration potential for tropical C_4 grasses, as the biomass derived will cycle through the soil faster than that derived from trees. Ghosh et al. (2021) observed the rise in total organic carbon by C_4 grasses such as *Cenchrus*, *Panicum* and *Chrysopogon* (77 to 91%) and by trees like *Ficus*, *Morus*, *Acacia* and *Leucaena* (63 to 81%) as greater than fallow lands.

5. FACTORS DETERMINING CARBON SEQUESTRATION BY FODDER CROPS

5.1 Type of Fodder Crop

5.1.1 Annual and perennial grasses and legumes

Permanent grassland refers to the land utilized continuously for five years or more to grow herbaceous plants for fodder, forage or energy purposes. These crops can be established either through sowing or natural regeneration (self-seeding) and are maintained without being subject to crop rotation. Permanent grasses raise the soil organic carbon levels (Post and Kwon, 2000). Legume fodder crops improve the SOC along with protection of top soil from erosion during monsoon rains with its ground covering canopy (Ghulamhabib et al., 2011). Inclusion of legumes in the grasslands doubles or triples the carbon stored in 20 to 80 cm of soil depth (Arias et al., 2001). Gregory et al. (2016) suggested that moderate grazing, manure returns, legume cultivation, enhanced pasture diversity along with rotational grazing and reduced grazing or cutting intensity, helps prevent carbon loss, maintains preserves soil carbon levels and reduces GHG emissions.

Soil organic carbon stocks (t ha^{-1}) can be computed using the equation formulated by Pearson et al*.* (2007):

$$C\ (t\ ha^{-1}) = (\text{soil bulk density} \times \text{soil depth} \times \%\ C) \times 100$$

The total carbon stocks (both aboveground and belowground) in herbs and shrubs, can be worked out using the equation given by Woomer (1999). It can be obtained by adding the above and belowground carbon stocks.

$$\text{Carbon stock}\ (t\ ha^{-1}) = \text{total forage crop biomass}\ (t\ ha^{-1}) \times 0.45$$

Carbon dioxide sequestration potential can be computed using the following formula given by Rajput (2010):

$$\text{Carbon sequestered} = \text{Carbon stock}\ (t\ ha^{-1}) \times 3.67$$

Rajkumar et al. (2014) reported better carbon sequestration abilities of the perennial fodder crops *viz*. Hybrid Napier (0.92 to 1.24%) and hedge lucerne (0.90 to 1.17%) compared to annual fodder crops *viz*. fodder cowpea and fodder maize in the Southern districts of Tamil Nadu suggesting the adaptation of these perennials as an effective step towards the aim of attaining carbon neutrality. Carbon fixation potential of Hybrid Napier was observed to be more efficient in the black soils than in red soils (Sivakumar et al., 2014).

In the semi-arid region of Karnataka, monocropping of Hybrid Napier, lucerne, desmanthus and sesbania, as well as their legume intercropping systems, excelled the annual fodder cereal monocropping and its legume intercropping systems in biomass production, carbon output and energy yield (Manoj et al., 2022).

Kumhar et al. (2021) observed Hybrid Napier in paired rows + rice bean - Egyptian clover, to possess higher total carbon stock of 57.96 Mg ha^{-1}, total carbon sequestration of 212.70 Mg ha^{-1} accounting to a carbon credit of ₹ 49264 ha^{-1} yr^{-1} over the sole crop of guinea grass. Usha et al. (2021) reported that grass legume mixture of Hybrid Napier in paired rows + fodder cowpea sequestered 20.69 tC ha^{-1}, which was 4.8% higher than Hybrid Napier in paired rows + *Agati*; with a green and dry fodder yield of 208.27 t ha^{-1} and 48.87 t ha^{-1} respectively.

Halli et al. (2022) reported higher sustainable yield and carbon sustainability indices from guinea grass (0.9 and 89.29) and perennial tussock grass (0.89 and 71.61) with minimal inputs along with considerable improvement in soil properties making these fodder grasses a sound strategy for carbon sequestration in the semi-arid region of central India.

5.2 Crop Growth Stage

Shehzadi et al. (2021) reported that Napier or mott grass produced the highest forage yield (3.88 t ha^{-1}) and carbon stock (3.56 t ha^{-1}) in 60 days compared to 21 and 45 days. Thus, Napier grass (*Pennisetum purpureum*), possessing high biomass production potential makes a viable option in washing out the carbon burden from environment.

5.3 Nutrient Supply

Nutrients in adequate quantities determine the production of biomass and accumulation of soil organic carbon. Organic manure applied together with synthetic fertilizers helps in realizing higher yields. Judicious nutrient management plays a vital role in carbon sequestration by tropical soils (Bhattacharyya et al., 2008). Global potential of agricultural soils to store carbon is estimated at approximately 0.3 t C ha^{-1} yr^{-1} in croplands and 0.5 to 0.7 t C ha^{-1} yr^{-1} in grasslands (IPCC, 2014).

Fodder maize *var*. African tall exhibited better green fodder production and carbon storage potential of 41.63 t ha^{-1} and 4.15 t ha^{-1}, respectively with the application of improved farmyard manure (mixture of dung, feed refuse and urine, composted and turned at fortnightly intervals), compared to inorganic fertilizer (40.20 t ha^{-1} and 3.72 t ha^{-1} of green fodder and sequestered carbon respectively) according to the findings of Thennarasu et al. (2014).

In the alluvial soils of Gwalior, Madhya Pradesh, intercropping fodder oats with maize resulted in superior growth characteristics, including plant height, tiller count and yields of green and dry fodder. It also achieved the highest carbon accumulation and CO_2 sequestration when treated with 25 g urea, 38.125 g SSP and 7.5 kg vermicompost, followed closely by the application of 25 g urea, 37.5 g SSP and 7.5 kg FYM. At harvest, maximum carbon of 31.35%, 17.10%, 12.35% and 9.82% was observed in oats, berseem, lathyrus and makhan grass respectively. High carbon uptake in oat may be due to high biomass yield as compared to other crops (Sharma, 2020).

5.4 Fodder Trees and Agroforestry

Agroforestry's key role in regulating CO_2 levels and boosting carbon sink potential, has gained significant attention, particularly following the Kyoto Protocol under the United Nations Framework Convention on Climate Change (UNFCCC). Agroforestry mitigates the impacts of climate change by moderating microclimates and conserving natural resources in the short term, while promoting carbon sequestration over the long term, more efficiently compared to crop and grass systems (Dhyani et al., 2016). Agroforestry is powerful weapon against climate change due to its efficacy in holding higher levels of atmospheric carbon in its plant parts and soil compared to conventional farming (Yadav and Singh, 2022).

Biomass production and the storage rate of carbon in this vegetation plays a crucial role in assessing the system output and enumerating the CO_2 sequestration rates for mitigating climate change (Chaturvedi et al., 2016). Silvopasture, one among the agroforestry systems turns out to be a very promising land-use system in terms of carbon sequestration in biomass and in soil. Varsha (2016) points out the carbon storage in tree biomass and pasture lands as important attributes of silvopasture system for lessening the CO_2 emissions.

Table 2. The carbon sequestration potentials of different silvopasture systems

Silvopasture system	Carbon sequestered (t C ha^{-1})	Reference
Acacia mangium + *Arachis pinctoi*	173	Amézquita et al. (2008)
Coradia alliodora + *Guazuma ulmifolia* + *Brachiaria brizantha*	132	Nair et al. (2009)
Pinus elliottii + *Paspalum notatum*	6.9-24.2	Haile et al. (2009)
Teak + Hybrid Napier	165.74	Kumari (2019)
Hybrid Napier + Mulberry (2:1)	147.67	Varsha et al. (2019)
Chinaberry + *Stylosanthes hamata*	140.315	Ahmad (2023)

According to Ghosh and Mahanta (2014), by 2040 the carbon sequestration potential of 630 M ha of degraded grasslands and croplands improves to 5,90,000 tC $year^{-1}$ with the introduction of trees and an additional storage of 12,000 t C $year^{-1}$ from the existing agroforestry system by practicing improved management practices.

Kaur et al. (2002) reported that the silvopastoral system with *Leucaena leucocephala*, *Cenchrus ciliaris* and *Stylosanthes hamata* as the components, increased the organic carbon by 1.7 to 2.3 times compared to control. A study conducted at NRCAF (2007) for comparing the biomass production of natural grassland and silvopastoral system with woody perennials such as *Leucaena leucocephala, Dichrostachys cinerea* and *Albizia amara*; grass species *viz*., *Chrysopogan fulvus* and fodder legumes *viz*., *Stylosanthes scabra* and *Stylosanthes hamata*. The results showed that over eight years, the carbon storage rate by the biomass of silvopastoral system as 6.72 tC $ha^{-1}yr^{-1}$, which was double that of the natural grassland i.e. 3.14 tC $ha^{-1}yr^{-1}$.

Amézquita et al. (2008) observed that the silvopastural system consisting of *Brachiaria brizantha* + *Arachis pinctoi*, *Ischaemum ciliare* and *Acacia mangium* + *Arachis pinctoi* possess higher soil carbon stocks compared to the native forests. Prasad et al. (2012) provided valuable insights into the potential of tree fodder-based agroforestry or farm forestry systems for carbon sequestration. Their research highlighted the efficacy of *Leucaena*-based systems in mitigating climate change due to their ability to sequester CO_2 rapidly.

Narain (2008) noted that the introduction of trees and grasses in degraded arid lands raised the carbon stock in soil from 24.3 Gt to 34.9 Gt. Additionally, various experiments at IGFRI in Jhansi demonstrated that intercropping fodder grasses with fodder trees resulted in higher fodder yields compared to monocropping of fodder Lok et al. (2013) noted the silvopastoral system including *Leucaena leucocephala* and *Panicum maximum* (guinea grass) as superior in carbon storage (54.4 to 65.3 tC ha^{-1}) compared to monocropping of guinea grass.

Shamsudheen et al. (2014) reported the superiority of *Acacia tortilis* + Anjan grass (*Cenchrus ciliaris*) system in carbon sequestration (6.82 Mg C ha^{-1}), compared to tree alone (6.02 Mg C ha^{-1}) and grass alone (4.26 Mg C ha^{-1}) situations. It was also observed that this silvopasture system raised the soil organic carbon stock by from 36.3% to 60% and from 27.1% to 70.8% compared to sole tree and sole grass systems respectively. Toppo and Raj (2018) observed silvopasture as more efficient in carbon sequestration (31.71 tC ha^{-1}) than agrisilviculture (13.37 tC ha^{-1}) and agrihorticulture (12.28 tC ha^{-1}).

Kumar et al. (2019) found that the total carbon stock ranged from 112.53 to 181.51 Mg ha^{-1} in the *Salvadora persica* combined with a mixed-grass system, while it ranged from 102.81 to 138.23 Mg ha^{-1} in the *Acacia nilotica* and *Cenchrus ciliaris* silvopastoral systems. Toppo et al. (2021) suggested the silvopasture system combining teak with Hybrid Napier (88.64 tC ha^{-1}) as superior over the gamhar and Hybrid Napier system (84.72 tC ha^{-1}), the teak and Sudan grass system (77.68 tC ha^{-1}) and the gamhar and Sudan grass system (77.42 tC ha^{-1}) in terms of carbon sequestration potential, which was 64 to 66% more than that in the native grassland system.

Varsha (2016) reported the fodder production efficiency and carbon storage capacity of 2- tier Hybrid Napier + densely planted mulberry hedges (11111 trees ha^{-1}) system to be the most promising and suitable silvopastural system for quality fodder production and carbon sequestration in the humid tropics of Kerala. Raveendra et al. (2017) reported that coconut +

glyricidia intercropping system as superior in terms of carbon sequestration with a total ecosystem carbon stock of 138 Mg ha^{-1} as compared to 60 Mg ha^{-1} from coconut monoculture. Calliandra (*Calliandra calothyrsus*), intercropped in coconut garden at a density of 27,777 plants ha^{-1} with forage harvests scheduled at 12 weeks interval captured 90.46 Mg ha^{-1} more carbon than the coconut monoculture system, of which 63% stored in soil and 9% in woody stump and root accounted for 72% of permanent carbon (Joy et al., 2019).

5.5 Grazing

Grazing is the practice of allowing livestock to move freely and feed on the wild vegetation such as grasses, legumes, etc in a pasture or grassland. Controlled grazing stimulates the growth of aboveground and belowground biomass along with the addition of dung and urine of livestock which improves the production from grasslands. In tropical soils, pasture improvement and management confer to better carbon sequestration (Conant et al., 2001).

Voisin's Rational Grazing (VRG) is an agroecological pasture management system that combines practices aimed at enhancing and preserving soil organic matter by promoting increased biocenosis (Voisin, 1961). In VRG, the entire area is sub-divided into plots, with fodder crops allocated based on the growth patterns of the forage and the requirements of the animals. The paddocks or enclosures should be small enough to prevent animals from grazing on plant regrowth before it has had adequate time to recover. This recovery period should be long enough for the plants to gather sufficient reserves in their roots before the next grazing session.

The VRG pastures are perennial and feature high species diversity, consisting of one to five legume species such as *Medicago sativa*, *Trifolium pratense*, *Trifolium repens* and *Lotus corniculatus* during the winter, along with *Desmodium* species and *Arachis pintoi* that remain consistent throughout the growing cycle. They also include five to nine grass species, including *Axonopus compressus*, *Axonopus catharinensis*, *Avena sativa*, *Cynodon* species such as *Cynodon nlemfuensis*, *Pennisetum purpureum*, *Lolium multiflorum*, *Brachiaria plantaginea*, *Hemarthria altissima*, *Sorghum sudanense*, *Digitaria decumbens* and *Pennisetum clandestinum*. Tilman et al. (2001) observed 2.7 times more biomass production in diversified pastures compared to monocultures. Mueller et al. (2013) noted that diverse communities exhibited deeper root distribution due to the flexibility in root biomass allocation. Interaction between legumes and grasses stabilizes soil carbon along with nutrient recycling for plant growth (Redin et al., 2014).

In VRG system, the carbon stored in the soil, aerial plant parts and roots were 95%, 1% and 4% respectively. Seó et al. (2017) reported the capacity of VRG pastures (115.0 Mg C ha^{-1}) to stock more carbon in the soil compared to the no-till fields (92.5 Mg C ha^{-1}).

5.6 Management Practices

Fodder-centric livestock production is essential for reducing poverty and ensuring food security, yet it significantly contributes to agricultural GHG emissions. Enhancing fodder production through improved management techniques is crucial for addressing the growing levels of carbon dioxide in the atmosphere. Restoration of degraded lands, adoption of pasture-based agroforestry systems, inclusion of grasses, sowing of improved forage species, grazing management, nutrient and water management are strategies that aid in improving carbon sequestration in fodder production systems.

Management practices for augmenting carbon storage offer numerous additional advantages, including higher productivity, decreased erosion, enhanced soil quality, improved efficiency in nutrient and water use, resource conservation, lower expenses, increased soil carbon stocks and socio-cultural benefits. Management systems play a decisive role in determining an ecosystem's fate to become a source or sink of CO_2 (Prasad et al., 2018). Kumar et al. (2021) investigated the impact of three techniques for resource conservation *viz*., rainfed systems, lifesaving irrigation, and in-situ conservation of moisture on the carbon sequestration potential of fodder crops. The study revealed that the combination of Tri-Specific Hybrid fodder, CS5 with *Desmanthus virgatus*, sorghum, cowpea and chickpea) demonstrated the highest carbon sequestration potential, achieving values of 12.25 g kg^{-1} for total carbon, 41.5 mg kg^{-1} for hot water-soluble carbon, 3.5 g kg^{-1} for particulate organic carbon, 289.5 mg kg^{-1} for labile carbon, 424.8 µg g^{-1} for soil microbial biomass carbon, along with 54.69% and 39.31% for humic acid carbon and fulvic acid carbon, respectively.

6. CONCLUSION

To meet India's ambitious Intended Nationally Determined Contributions (INDCs) outlined in the Paris Agreement, it is essential that our future development initiatives pursue a "Carbon-Neutral" path. Agriculture not only significantly contributes to climate change but is also one of its major victims and has the potential to play a crucial role in addressing this issue. Given the commitment India made at the Conference of Parties meeting in Glasgow, England (CoP-26) in December 2021 to achieve net zero by 2070, dedicated efforts must be undertaken within the agricultural sector to lower greenhouse gas emissions by implementing suitable practices.

The cultivation of fodder crops plays a vital role in achieving carbon neutrality by enhancing carbon sequestration, improving soil health and promoting sustainable agricultural practices. By integrating diverse and well-managed fodder systems, farmers can effectively reduce greenhouse gas emissions while increasing productivity and resource efficiency. As countries, including India, strive for ambitious climate targets, prioritizing the development and adoption of sustainable fodder crops will not only contribute to climate change mitigation but also support food security and rural livelihoods. Ultimately, fostering a carbon-neutral agricultural landscape through the strategic use of fodder crops is essential for a sustainable and resilient future.

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.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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