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**Review Paper**

# Agro-tactics for reducing carbon footprint in agricultural production systems: A review

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## ABSTRACT

Over the last half-century, global attention has focused on climate change, particularly changes in air temperature. Concerns about the sustainability of the Earth's ecosystems and other human life on the land are increasing along with population growth, rising surface temperature, and higher greenhouse gas (GHG) emissions. Agriculture is responsible for ~18% of total GHG emissions. Therefore, mitigating the effects of climate change by reducing GHG emissions is essential and can be achieved by careful evaluation of the carbon footprint (CF). The goal of this study was to gain a better understanding of the changes in CF due to agricultural management practices. Carbon footprint is a popular concept in agro-environmental sciences owing to its role in the environmental impact assessments related to alternative solutions and global climate change. The CF of agricultural products is one of the most crucial indicators to assess the effectiveness and long-term viability of agricultural products. Soil-moisture content, soil temperature, porosity, and anoxic conditions are some of the soil properties directly related to GHG emissions. The GHG emissions are also affected by different land-use changes, soil types, and agricultural management practices. Globally, better soil-management techniques can alter atmospheric GHG emissions. Therefore, the relation between photosynthesis and GHG emissions is impacted by agricultural management practices, especially focusing on soil and related systems. When maximizing crop productivity, environmental factors, land use, and agricultural practices all should be considered in CF management. The current review highlights the importance of CF and its role in maintaining the sustainability of agricultural systems.

***Key words:*** Conservation Agriculture, Carbon footprint, Crop diversification, LCA, Precision-input management

Burgeoning global population increases the unprecedented burden on the agricultural system to meet the calorie requirement (Babu *et al.,* 2022). Global food production is expected to double in the next 30 years and the global food demand will increase by 70% by 2050 (UNESCO, 2017). Even though expanding cropping areas by clearing more uncultivated lands to increase grain production is possible, this approach often comes at the expense of reducing carbon stocks in natural vegetation and soils (Babu *et al.,* 2023a). Changing forests or grasslands to farmland for improving grain production might be responsible for the rapid loss of carbon reserves on the globe, jeopardizing biodiversity, with major ecological consequences (Yadav *et al*., 2021; Babu *et al.,* 2023b). Intensified farming systems have been identified as viable means to increase grain production. However, farming intensification requires more inputs such as fertilizers, pesticides, and fuels; all of these emit greenhouse gases (GHG) and have negative environmental consequences (Yadav *et al.,* 2013; Babu *et al.,* 2023c). Thus, agriculture is an inevitable land-use change for human survival and occupies ~ 40% of land across the globe. India is an agrarian country, >58% of rural

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households in India depend on agriculture for their livelihood (FAO, 2022). Globally agriculture contributes to about 10–12% of GHG emissions (Panchasara *et al*., 2021). In India, the agriculture sector contributes 19% of the total GHG emission (Vetter *et al.,* 2017). The GHG emission from agriculture occurs mainly from enteric fermentation, rice (*Oryza sativa* L.) cultivation, soils, manure management, and from crop-residue burning. Agricultural activities like land preparation, crop-cultivation, irrigation practices, animal husbandry, fisheries, and aquaculture also have significant effects on GHG emissions. Therefore, the adoption of climate-resilient agricultural production systems is highly warranted to enhance farm productivity and reduce the GHG emission from the agriculture system. Sustainable agricultural practices have to balance environmental health and economic profitability, to promote social and economic equity (Babu *et al*., 2020a). The pursuit of sustainable development entails a strategic policy in all modern countries. Research in recent years has focused on different aspects of sustainable energy and environmental protection (Ali, 2022). One of the environmental objectives of sustainability is the reduction of negative impacts on the environment and health (Arunrat and Nathsuda, 2017). Sustainable agriculture (SA) emphasizes environmental quality, improving agronomic productivity, and minimizing negative environmental outcomes (Pigford *et al*., 2018). SA reduces the use of external energy inputs and increases the profit margin of farming systems. Sustainable agriculture can potentially improve farm productivity and meet the sustainability criteria to satisfy increasing human demands meanwhile contributing to the recovery and sustainability of landscapes, the biosphere, and the earth systems (Rockström *et al*., 2017). Greenhouse gases abatement, efficient use of renewable energy, and improved energy-use efficiency are the main pillars of sustainable development. The greenhouse gases emissions are one of the key indicators in assessing the environmental sustainability of farming systems (Babu *et al*., 2023c). Carbon footprint (CF) has become a widely used term and concept because of the recent awareness and spotlight on global climate change. The total amount of GHG emission associated with a food product or service product is known as its carbon footprint (CF) and is expressed in terms of carbon dioxide equivalent ($CO_2e$) (IPCC, 2022). The CF of a product can be quantified by assessing GHG emissions at all stages like ploughing of field, application of fertilizers and pesticides, harvesting of crop, storage, processing, packaging, transport, and finally consumption during its life-cycle (Yadav *et al*., 2021). In this review, we attempt to highlight some of the key impacts of CF on crop productivity and narrow the yield gap, concurrently lowering the environmental impacts of farming.

### *Carbon footprint and factors contributing to CF in agricultural production systems*

The CF of agricultural products is one of the main measures for monitoring the efficiency and sustainability of agricultural production systems (Yadav *et al.,* 2021). Hence comprehensive assessment of CF of the various management practices involved in agricultural production systems is imperative to formulate specific mitigation and adaptive strategies. The term CF can be defined in 2 metrics (Liu *et al*., 2016)-the total amount of greenhouse gas emissions per unit of farmland quantifying the total amount of emissions in crop production that focuses more on environmental health, and total GHG emissions associated with per kilogram of grain produced - emphasizing both emissions during the production of a crop as well as the products (i.e., grain yield) associated with per unit of emission. The latter focuses on increasing crop yield while reducing GHG emissions. These are the most commonly used terminology in the full 'Life-Cycle-Assessment' (i.e., LCA) analysis for quantifying the impact of farming activity on the environment. It links up with a product, producing process, or activity during its life-cycle from raw material extraction or production to the final disposal. Recently, this methodology has begun to concentrate on agriculture and its affected environmental impacts, such as climate change, eutrophication, acidification, nutrients, fertilizers, and crops (Pergola *et al*., 2017).

Environmental LCA is a significant method for presenting environmental improvements, given that it quantifies sources of impacts throughout a product's life-cycle for various environmental impacts, thereby allowing environmental improvements to be determined and ranked; this method has been confirmed to be useful (Renouf *et al*., 2018). The concept of circular economy is changing our awareness of waste. The LCA is a method to assess environmental impacts by recycling from cradle to narrow the generation of waste (Oldfield *et al*., 2018). The full LCA analysis includes $CO_2$ emissions from off-farm manufacture, transportation, and delivery of various input products to the farm gate as well as those emissions during the cultivation of a crop (Fig. 1).

The food-production sector contributes one-third of the world's anthropogenic GHG emissions, about 16.5 $GtCO_2e$ per annum from a total of 54 $GtCO_2e$ of annual production with both pre-and post-production phases, representing a high and increasing share of total emissions (FAO, 2022). The total emission included direct and indirect emissions through volatilization of $NH_3$ and NOx, leaching of nitrate from the application of N fertilizers on farm fields (27% of the total emissions), and emissions associated with the production, transportation, storage, and delivery of N fertilizers to the farm gate (Menegat *et al*., 2022). The greatest

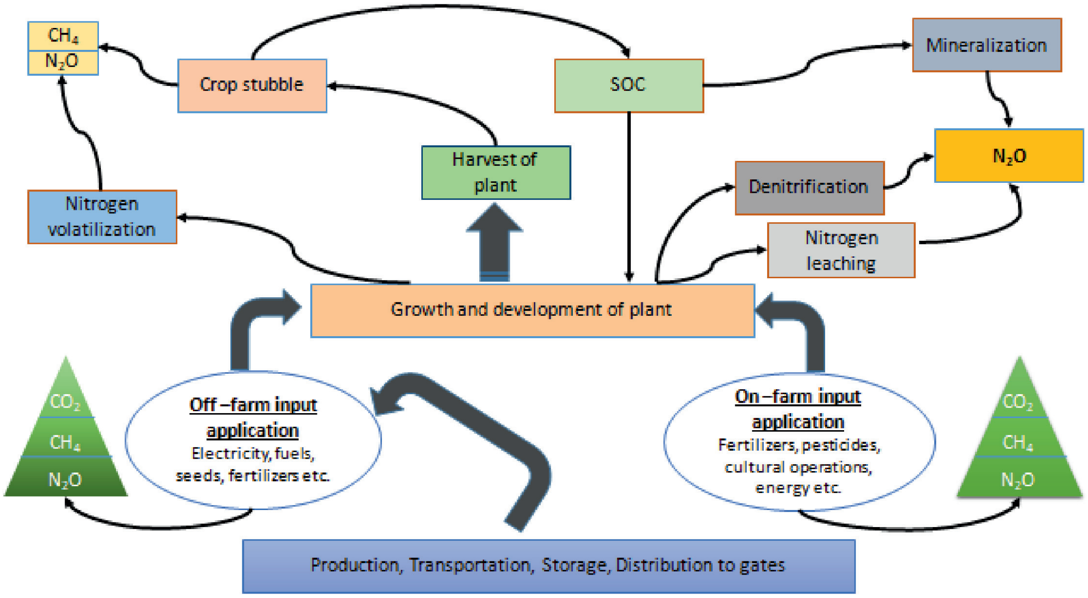

**Fig. 1.** Major contributors to greenhouse gas (GHG) emissions in crop production

sources of indirect emissions of $N_2O$ come from agricultural $NO_3^-$ leaching and runoff, accounting for approximately 30% of the nitrogen lost from agricultural soils (Ramzan *et al.,* 2020), whereas denitrification and nitrification through microbes entail the direct emissions pathway of $N_2O$. Under aerobic circumstances, the changes of $NH_4^+$ to $NO_3^-$ occur, i.e. nitrification, while the denitrification event occurs with the conversion of $NO_3^-$ to $N_2$, while $N_2O$ acts as an intermediate product (He *et al.,* 2020). The production and use of fertilizers make the most significant contribution to the CF of all crops. For wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), soybean [*Glycine max* (L.) Merr.], and cotton (*Gossypium* spp.), the majority of this impact is attributable to the production of fertilizers; for rice, the impact is largely attributable to high methane emissions associated with flooded paddy field rice cultivation as well as anaerobic degradation of organic material. Energy consumption also makes a significant contribution to the CF of crop cultivation. However, new fertilizer regulations were introduced in various countries like European unions, which obligate farmers to reduce nitrate, ammonia, and phosphate losses by specified fertilizer planning, calculation, and application techniques. While the main goal of these regulations is to avoid excess nutrient releases into the environment, especially into water-bodies, they will also contribute to reducing agricultural GHG emissions.

Modern agriculture largely owes its successes to an abundant supply of fossil fuels, which are essential for synthetic fertilizer production, transportation, storage, and delivery to the farm gate, as well as for various farm operations including seeding, fertilizer and pesticide applications, and crop harvesting. Energy consumption also makes a significant contribution to the CF of crop cultivation. In general, the emissions from the industrial processes of synthesizing N fertilizers using fossil fuel before on-farm use far surpass the emissions from pesticide production and application to field crops (Liu *et al*., 2014). Crop straw is normally left on the soil surface under no-till management or is incorporated into the soil through tillage after a field crop is harvested for grain or feed. The crop residue serves as an important N source in the soil for nitrification and denitrification, contributing directly and indirectly to $N_2O$ emissions. The net productivity of the crop, N concentrations in the plant matter, soil temperature and moisture content, etc. are all related factors affecting the net emission of $N_2O$ from the decomposition of straw and roots (Liu *et al.,* 2016). The burning of rice residues in the field was the main factor determining GHG emissions in the atmosphere. An effective way to reduce GHG emissions and contribute to sustainable rice production for food security with low GHG emissions and high productivity is by avoiding the burning of rice residues.

Herbicides remain the most commonly used weed-management practice in majority of the agricultural production systems (Raj *et al*., 2022). Similarly, fungicides and insecticides are used to minimize diseases and insect problems in agricultural systems. Each chemical has different emission strength; nevertheless, at the current moment, emissions for each pesticide used in crop production are not easily available. Researchers frequently presume that the emission factors are alike among products within a similar category, but there is a great dissimilarity between plant types in the quantity of pesticide used during a given crop season. For example, in intensive apple (*Malus domestica*

Porkh.) production, GHG emissions associated with pesticide production and application accounted for 51% of total GHG emissions, in viticulture 37%, and in sugar beets *Beta vulgaris* subsp. *vulgaris* 12%. The GHG emissions due to pesticide production and application can be significant, especially for pesticide-intensive crops (Cech *et al.,* 2022).

### *Carbon footprint estimation in agricultural production systems*

The CF of agricultural products is one of the main measures for monitoring the efficiency and sustainability of agricultural production systems (Marini *et al*., 2020). It is a potential tool for assessing and comparing GHG performances of different agricultural products along with the identification of points to improve environmental efficiencies (Holka *et al.,* 2022). Determination of the CF of agricultural products requires a detailed analysis of energy consumption in the various processes used for crop production. Total input energy in agricultural production is the sum of all the components of the energy used in the different production processes. Conversion of one form to another form of energy in CF analysis under agricultural production system is imperative and accounted for in recent studies (Yadav *et al.,* 2020; Yadav *et al.,* 2021).

Several activities and inputs involved in crop cultivation influence CF (Fig.2). The CF can be calculated by the following formula Cheng *et al*., (2011).

CF = Agricultural input × Emission factor

where the emission factor is the carbon equivalent of individual input. Thus, the estimation of total CFt in crop production can be estimated by summing all the individual carbon costs from all the inputs used as:

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

where CFF, CFN, CFP, CFIR and CFD represent the individual carbon footprint from fertilizers, direct $N_2O$ from N fertilizer application, pesticides, irrigation and mechanical operations involved in crop production respectively.

The calculation of the CF is also carried out for agricultural products using the Life Cycle Assessment (LCA) methodology (Zomer *et al.,* 2017). The LCA is one of the most widely recognized approaches to the environmental assessment of products and processes (Chaudhary *et al*., 2022). Quantification of the carbon balance compares the carbon cost of inputs and practices with the benefits of displacing carbon released by burning fossil fuel (Babu *et al*., 2020a).

### *Carbon footprint and sustainable agriculture*

Technological progress has made it possible to achieve remarkable improvements in land productivity, increasing per-capita food availability, despite a decline in per-capita agricultural land area in India. An increase in population leads to a decrease in farm size on one hand and a reduction in per capita arable land area on the other. In India, the increase in food production will have to come from increased production per unit area from the existing land, because there is the least possibility to bring newer areas under cultivation. The adoption of more intensified cropping systems has shown to increase crop yields compared with traditional fallow or monoculture systems (Singh

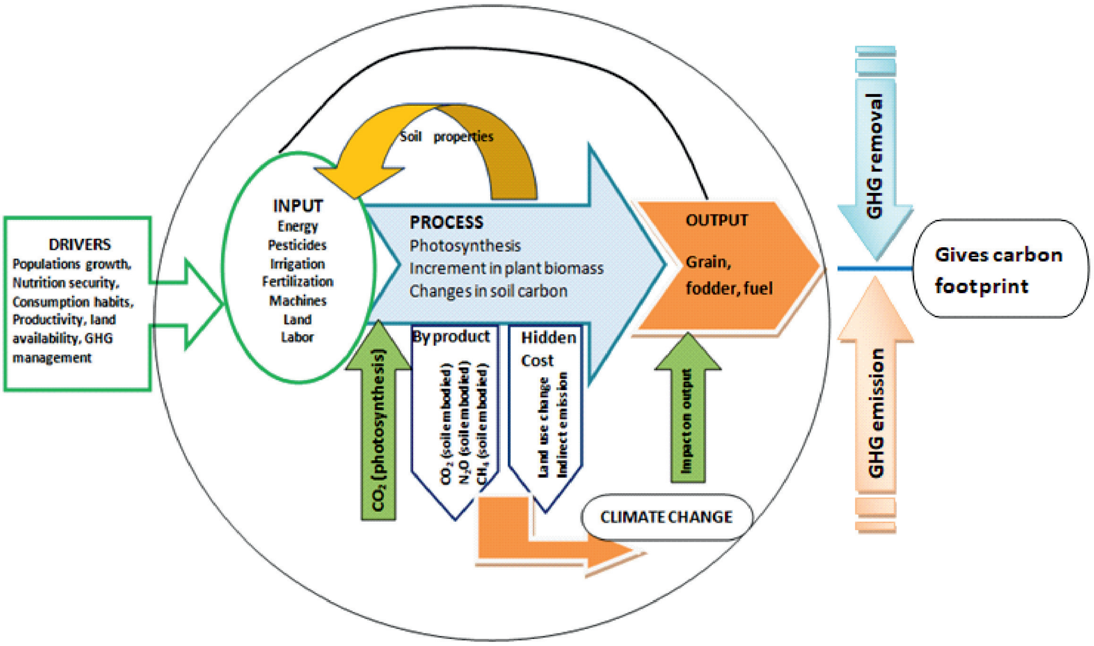

**Fig. 2.** Various activities and inputs associated with carbon footprint in crop production

*et al*., 2021). However, the increased use of inorganic fertilizers and pesticides in high-yielding systems increases greenhouse gas emissions (FAO, 2022). Also, there is growing evidence of yield plateaus or abrupt decreases in the rate of yield gain over the years (Zhao *et al*., 2020). In some areas, crop yields have either stagnated or even decreased in recent years. This evidence indicates that, high-yielding systems can also have negative climate consequences. Along with fossil fuel combustion, agricultural practices have a major impact on the global C cycle (GCC), leading to an increase in the global temperature during the 20th Century by 0.6 ± 0.2°C on an average rate of increase of 0.17 °C per decade since 1950 (Lal, 2022). Crop production, food processing, and marketing of produce cause GHG emission contribution to global climate change.

### *Strategies for reducing the carbon footprint*

*Efficient nutrient management:* The application of chemical fertilizers not only contributes to $N_2O$ emissions but may also have an impact on $CO_2$ and $CH_4$ emissions contributing to enhanced global warming (Menegat *et al*., 2022). Hence improved fertilizer application techniques such as green seeker, chlorophyll meter, and LCC are needed to reduce GHG emissions and enhance crop yield (LCC, 2022). Site-specific nutrient-management in rice is more efficient than the conventional methods in reducing nutrient losses and improving nutrient-use efficiency (Sapkota *et al.,* 2021). Including $N_2$-fixing pulse crops in a crop rotation can significantly decrease greenhouse gas emissions and the carbon footprint (Yadav *et al.,* 2017; Babu *et al.,* 2020b). The emissions from the application of N fertilizer averaged 251 kg $CO_2$ eq/ha for durum wheat (*Triticum durum*) produced in cereal-durum or oilseed-durum, whereas the durum wheat produced in the pulse-durum system emitted 162 $CO_2$ eq/ha or 37% lower than the durum wheat produced in the cereal- or oilseed- durum system (Hiya *et al*., 2020). Since, application of nano fertilizers reduces the GHG emission compared to the conventional fertilizers, these can be promoted on a larger scale to reduce the CFP from the agricultural production systems (Babu *et al.,* 2022). One of the common practices to reduce applications of chemical fertilizers and also maintain crop yield is the incorporation of organic manure or green-manure in the crop field. Both, the use of organic as well as green-manures not only improves the soil fertility but also enhances microbial activity, which can affect the internal cycling of C and N affecting the release of $N_2O$ (Lv *et al.,* 2020). Some reports are available which highlighted that the application of green-manure in place of chemical fertilizers that the application on $N_2O$ emission in crop fields (Zhang *et al.,* 2020). On the other hand, compared to chemical fertilizer application alone, a meta-analysis revealed that the application of organic manure and chemical fertilizer could enhance $N_2O$ emissions (Zhou *et al.,* 2017). Organic manure application not only reduce the the inputs of chemical fertilizers but also maintain yield and reduced the cumulative $N_2O$ emissions in citrus orchards (Zhou *et al.,* 2022) and $CH_4$ release in paddy fields (Toma *et al.,* 2019).

### *Efficient crop-residue management*

Returning crop residues (CR) to the farmland is extensively practiced, owing to its benefits in escalating agricultural productivity and soil fertility (Memon *et al.,* 2018). Rice-residue management compared to other crops is a tedious task and cannot be used as animal feed due to its high silica content. Moreover, CR return also influences $N_2O$ emissions by regulating the microbial activities, and C and N availability. Burning of crop residue causes the emission of GHGs like $CO_2$ (70%) and $N_2O$ (2.09%) which can alter the radiation balance of the atmosphere (Jain *et al*., 2014). Residue incorporation in the soil is the easiest and most successful method to improve water productivity, retain soil moisture, suppress weeds, and regulate soil temperature. Presently, Happy seeder-based crop production is keeping pace in residue management by following conservation agricultural practices. This technology was introduced as an alternative in the north-western regions of India to effectively manage the paddy straw burning issue for the timely sowing of wheat. This technology has demonstrated tremendous potential to mitigate environmental pollution, as it could reduce GHG emissions by more than 78% while enhancing remuneration by up to 20% in rice–wheat cropping regions (CIMMYT, 2019). Despite its immense calibre, the large-scale adoption of Happy Seeder by farmers is hindered by several reasons, including a lack of knowledge of profitable no-burn solutions and impacts of burning, uncertainty about new technologies, and initial high cost (Jat and Sidhu, 2021; Singh *et al*., 2021). Valorization of crop residue into another usable form can also be an effective alternative to minimize residue-related GHG emissions from the agricultural sector (Singh *et al.,* 2021 and Babu *et al.,* 2022). In the 11 years of continuous rice–wheat rotation, the application of farmyard manure (FYM) and incorporation of rice straw before seeding wheat improved soil organic carbon (SOC) content by 34%, and the addition of rice residue with N fertilizer increased SOC by 84% (Benbi *et al*., 2012). Increasing SOC sequestration is one of the most important strategies in reducing atmospheric $CO_2$ concentrations and mitigating the greenhouse effect, with a significant potential to mitigating climate change (Cotrufo *et al*., 2019). Wang *et al*., (2020) observed that, residue retention could significantly increase SOC storage by 10.1, 8.7, and 8.0% ($P < 0.05$) when residues were returned once in a single cropping system (OSCS), in a double cropping system (ODCS) and twice in a double cropping system (TDCS) when compared to residue removal respectively ($P < 0.05$). Lu *et al*., (2018) found that, residue retention had a higher SOC sequestration rate in single-cropping than in double cropping fields. Chethan *et al*., (2020) reported that, in current farmers' practice (FP) crop residue was burned, but it was utilized as mulch in conservation agriculture (CA) and conservation agriculture with improved weed management (CAW), thus, emission of 34,400kg $CO_2$e was avoided and energy potential of 100.1 × $10^4$ MJ was created. Conversely, Nan *et al.,* (2016) argued that, the production of $CH_4$ is generally low under soil mulch as compared to no-soil mulch for maize. Liu *et al*., (2014) also reported that, soil mulching encouraged the absorption of $N_2$ by crops thereby decreasing the content of inorganic nitrogen and restraining $N_2O$ emissions. The soil-mulching technique efficiently enhanced productivity by 21.8% while it also increased the $CO_2$ (21.6%) and $N_2O$ (1.73%) emissions except for a significant reduction in $CH_4$ by 43.08% (Guo and Liu, 2022)

### *Conservation effective irrigation*

Non-puddled transplanting of rice saves 35% of the net life-cycle greenhouse gases (GHGs) compared with the conventional practice by a combination of decreasing greenhouse gases emissions from soil and increasing soil organic carbon (SOC) while puddling in transplanted rice consumes up to 30% of the total rice-water requirement (Alam *et al.,* 2020). In direct-seeded rice (DSR), seeds are directly sown in soil and do not require puddling hence this technology is reported to reduce $CH_4$ emission (10–90%) and save labour and water (Chaudhary *et al*., 2022). The DSR could reduce methane emissions as fields are not continuously submerged in water. A study conducted in Karnal, Haryana, showed that, yield of transplanted rice was 10–12% higher than DSR but practicing DSR caused labour and cost savings of 97% and 80% (Laura *et al*., 2022). Intermittent wetting and drying (IWD) of soil in rice also saves irrigation water and reduces $CH_4$ emissions (Baye *et al*., 2020). Among different technologies studied, resource-conservation technologies (RCTs) like DSR, and SRI had lower GWP (up to 40%) than conventional practices (Bowles *et al*., 2020). Irrigation practices have a significant effect on greenhouse gas (GHG) emissions, as it controls the soil microbial activity as well as the substrate supply. Both aerobic and anaerobic organic carbon respiration are major causative mechanisms leading to $CO_2$ emission from soils generally related to processes, such as microbial, root, and faunal respiration which are highly manipulated by moisture availability within the rhizosphere (Sapkota *et al*., 2020). Soil moisture has a great influence on soil redox potential and *p*H, both of which determine the thermodynamics favourability of biotic and abiotic reactions in soils. An increase in soil moisture reduces the soil redox potential, thereby altering the probability and rate of GHGs such as $N_2O$ emission (Sapkota *et al.,* 2021). Reduced irrigation (drip line, sprinkler etc.) can reduce GHG emissions by improving the nitrogen and carbon cycle in soil, therefore, shifting towards reduced irrigation strategies can decrease GHG emissions from cropland (Maris *et al.,* 2015). The $CO_2$ emission was found to be reduced by 40% with intermittent irrigation, and $CH_4$ emissions were reduced by up to 350 kg $CH_4$/ha in loam soil with sprinkler irrigation as compared to continuous flooding (Wang *et al.,* 2018). Drip-line irrigation system has the highest and traveling boom has the lowest global warming potential (Guiso *et al.*, 2015). The high impact of drip-line systems is owed to their short lifetime, as they have to be changed yearly whereas the hose reel equipped with boom appears to be the most sustainable system, in terms of GWP/$m^3$ of distributed water, because of its long lifetime as well as low working pressure.

### *Tillage management*

Tillage disturbance is the dominant factor reducing soil-carbon stabilization within micro aggregates in the clayey soil, whereas conservation practices increase soil organic carbon contents. Reduced tillage along with cover crops significantly improved the organic carbon content of soil and reduces the CF (Yadav *et al*., 2021). Repeated tillage breaks the soil aggregates, increasing the oxygen supply which promotes the decomposition of organic matter and the evolution of more $CO_2$ from tilled soil than undisturbed soil (Yadav *et al.,* 2019). Zero-tilled wheat (ZTW) is an option that allows earlier planting of the crop, helps in controlling weeds, reduces $CO_2$ emission, saves water and fuel, and enhances soil carbon stock (Baye *et al.,* 2019). Conservation agriculture (CA)-based conservation-tillage systems (CTS) led to enhancement in yield, productivity, and C sustainability improves household income, enhances adaptation and resilience, and reduces GHG emissions from agriculture (Thierfelder *et al*., 2017). Zero tillage reduces the oxidation of soil organic matter to $CO_2$ and this may help in mitigating soil emissions and increase soil organic carbon (Lan *et al.,* 2020; Babu *et al.,* 2020b).

The greatest reductions in $CO_2$ emission are associated with those tillage systems having less soil disturbance, such as the double no-tillage systems (Feizienë *et al*., 2010). Reducing tillage intensity and increasing crop residue on the soil surface reduces soil $CO_2$ emission to the atmosphere. The cumulative $CO_2$ emission from no-tillage without residue is 23% lower than that with moldboard plough, but 24% greater than the $CO_2$ emission from no-tillage with residue over the 20 days (Reda, 2016). Reduced tillage intensity in corn–soybean cropland contributed to SOC accumulation at 1.0 Tg C/year (1.6 g C/$m^2$/year) from 1998 to 2008 (Yang *et al*., 2018). Benefits from adopting conservation tillage and no-till are evident, including the potential for protecting soil from erosion, reducing SOC decomposition in top soils, reducing GHG emissions, and curtailing fossil-fuel consumption (Lal, 2022). The soil $CO_2$ fluxes in CT was 1.2 times those in NT and 3.1 times those in the unconverted conservational field (Lu *et al*., 2018).

### *Crop diversification*

Crop diversification (crop rotation, cover cropping and intercropping) has become increasingly important in many parts of the world as a means to control problem weeds, suppress plant diseases, increase production sustainability, and enhance economics (Zhao *et al.,* 2020). Crop diversification helps reduce weed density by negatively impacting weed seed germination and weed growth (Rathore *et al.,* 2022). Moreover, crop diversification has been considered a key cropping practice for improving agro-ecosystem productivity (Babu *et al.,* 2023a) and reducing the dependency of agricultural systems on synthetic inputs and limiting their environmental impacts by promoting the expression of ecosystem services thus lowering the negative environmental impacts such as CF of crops. Diversifying crop rotations is key in optimizing resource-use efficiency (Wang *et al*., 2018). Additionally, these systems can contribute to increasing the stability and resilience of production in the face of climate change (Marini *et al*., 2020), while helping to mitigate its effects through increased carbon storage in soils and/or mitigation of greenhouse gas emissions. In South Africa, cereal production accounted for 68% of GHG emissions while legumes and oilseeds 11% and vegetables 7% (Saet *et al*., 2017). With the use of RCTs such as the system of rice intensification (SRI), direct-seeded rice (DSR), and zero tillage wheat (ZTW), there was a lowering in GWP than conventional puddled transplanted rice and tilled wheat, therefore, the site-specific intervention of RCTs may be recommended to reduce the emission of GHG in the rice–wheat cropping system (Gupta *et al*., 2015).

### *Increasing carbon sequestration in soil*

The function of soil organic carbon in global carbon cycles is getting greater notice both as a significantly large and uncertain source of $CO_2$ emissions in response to predicted global temperature increase, and as a natural sink for carbon able to decrease atmospheric $CO_2$. It is estimated that, the capacity of soil carbon sequestration is potentially massive; however soil may reach its saturation limit. At this condition, the soil will stop acting as a sink and can either become a $CO_2$ source or reach a steady state wherein it draws in as much carbon as it emits yearly (Pandey and Agrawal, 2014). Soil carbon plays an important role in the estimate of the carbon footprint of a cropping system because per unit of farmland greenhouse gas emission represents the balance between carbon-equivalent emissions and carbon sequestration in the production of a field crop. Therefore, soil-carbon measurement will have a significant impact on the determination of soil CF. The inclusion or exclusion of soil-carbon measurements can make a huge difference in the estimation of the CF. Many crop/land-management practices can be used to increase the amount of organic matter in the topsoil and/or decrease decomposition rates, help maintain soil structure and physical-chemical protection of soil organic carbon, improve soil carbon sequestration, and mitigate emissions to the atmosphere. For instance, no-till management, and inclusion of legumes in crop rotation enhanced the soil C in the soil (Laura *et al.,* 2022). However, soil organic carbon can be gained or lost depending on soil type and land-use practices. Soil disturbance affects the quantity and quality of plant residues entering the soil, their seasonal and spatial distribution, and the ratio between above- and below-ground inputs (Prost *et al*., 2017). Agroforestry combines agriculture and forestry practices, and has the potential to mitigate GHG emissions by sequestering carbon in soil and biomass, decreasing fossil-fuel usage by reduced equipment runs in fields, enhancing energy conservation around farm buildings, and enhancing the efficiency of nitrogen fertilizer use hence, reduce carbon footprints (Milne *et al*., 2015). Agroforestry systems sequester more C than other agricultural systems. However, below- and above-ground vegetation C sequestration is highly variable as the amounts of biomass and SOC addition vary with tree species, soil type, rainfall, and environmental conditions (Lal, 2022). Carbon sequestration and CF have an inverse relationship (Babu *et al*., 2020b). Every human activity that releases carbon dioxide into the atmosphere contributes to a carbon footprint. Therefore, managing ecosystems for carbon sequestration can play a vital role in mitigating the impact of human activities on the environment and in reducing our carbon footprint. The promotion of sustainable land-use practices, including agroforestry, can significantly enhance carbon sequestration, leading to the reduction of carbon footprints (Vetter *et al*., 2017).

Sustainable agricultural practices are crucial to produce high-quality and affordable food in sufficient quantity to meet the calorie demand of growing global population without jeopardizing the environmental quality. It is imperative to increase the efficiency of applied inputs to reduce the CF of the agricultural sector. Healthy soil plays an important role in minimizing the CF, as fertile and productive soil is stable and resistant to erosion, easily workable and good habitat for soil micro-organisms, and ultimately a good C sink. Conservation tillage, mulching, crop diversification including agroforestry and integrated farming systems, precision fertilization and irrigation management are the recommendable option for reducing the CF without compromising the farm productivity and profitability. On the other hand, practices like deforestation, conventional tilling, mono-cropping, residue burning and controlled irrigation etc must be discouraged to make the agricultural production system carbon neutral and/or negative.

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