Carbon Footprints of Agriculture Sector

Bhavna Jaiswal and Madhoolika Agrawal

Abstract Climate change being today's major issue is concerned with the unprecedented increase in natural resource exploitation and uncontrolled population increase, reaching in an irreversible point. Greenhouse gases (GHGs) responsible for such changes are emitted by a variety of natural as well as anthropogenic sources. Agriculture sector shares a major proportion in total GHG emission. As the food demand is increasing with the rising population, the proportion of GHG emissions from agricultural sector is also increasing. The total amount of GHGs (in terms of carbon equivalent (C-eq)) emitted by the processes in agricultural sector is regarded as carbon footprint of agriculture. Various activities related to agriculture such as plowing, tilling, manuring, irrigation, variety of crops, rearing livestock, and related equipment emit a significant amount of GHGs that are categorized in three tiers of carbon footprinting, separated by hypothetical boundaries. The energy input through machinery, electricity, livestock management, and fossil fuel constitutes a major proportion of carbon emission through agriculture. Crop cultivation system mainly cereals produces higher GHGs than any other farming systems like vegetables and fruits. Beside this, land-use changes including conversion of natural ecosystem to agricultural, deforestation, and crop residue burning after harvest contribute significantly to higher carbon emission. This review article will focus on carbon footprint from agriculture including inputs for uses from energy, fertilizers, organic manure, pesticides, and processes that affect carbon emission from agriculture. The mitigation practices effective in reducing the carbon footprinting from various agricultural activities will also be reviewed. Efficient use of fossil fuel and other non-renewable energy sources in the agriculture system, diversified cropping system, enhancing soil carbon sequestration by straw return, plantation, etc., crop rotation system, and limiting deforestation will be discussed as measures which may help to reduce the GHG emissions from agriculture sector.

Keywords Greenhouse gas · Agriculture · Carbon footprint · Mitigation strategies · Farming practices

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1   Introduction

Climate change is a major concern for society, as it causing shift in weather patterns such as unpredictable precipitation, extreme temperatures, higher occurrence of flood, drought and cyclones. To prevent the extreme weather variables and spread awareness, various inventories are prepared. Among them, the term carbon footprint has become a widely discussed term as the planet has witnessed the effects of climate change. The concept of carbon footprint is taken from ecological footprint given by Rees in 1992. Ecological footprint can be defined as biologically productive land and sea area required to sustain a given human population, expressed in terms of global hectares. Likewise, Wiedmann and Minx (2008) defined carbon footprint as a certain amount of gaseous emission that is relevant to climate change and associated with human production or consumption activity. Carbon footprint is thus emission of greenhouse gases (GHGs) from all sources and processes related to a particular product or individual or system, from manufacturing to disposal. Earlier, only CO_2 is taken under consideration for carbon footprint estimation, but at present, all the major GHGs emitted such as CO_2, CH_4, and N_2O are taken under consideration in terms of CO_2 equivalent (CO_2-e). IPCC (2014) has given the definition of CO_2-e as CO_2 concentration that would cause the same radiative forcing as a given mixture of CO_2 and other forcing components.

Carbon footprint is a component of life-cycle assessment (LCA) that measures GHGs, whereas LCA assesses all the environmental impact associated with a product. Carbon footprint is calculated by dividing the whole process tier-wise, separated by hypothetical boundaries. Global warming potential (GWP) of all tiers adds to carbon footprint. Since in agriculture system, no standards are available, so boundaries are not decided. Tier 1 consists of all the direct on-site emission, such as emission from soil and machinery. Tier 2 consists of indirect farm emissions such as from electricity, and tier 3 involves all the indirect emissions related to manufacturing and transport of agriculture-based chemicals and machinery, etc. Pandey and Agrawal (2014) have given the formula to calculate carbon footprint.

GWP of tier (kg CO_2-e ha^{-1}) = emission/removal of CH_4 × 25 + emission/removal of N_2O × 298 + emission/removal of CO_2

Carbon footprint = $\sum$ (GWP of all tiers)

Carbon footprint from agriculture is calculated by the following formula (Lal 2004).

Carbon footprint

$$= \left(\sum \text{Agricultural input} * \text{GHG emission coefficients} \right) / (\text{Grain yield})$$

Agriculture is one of the major contributors in total GHG emissions. The processes related to agricultural practices from industry to farm to house, emit GHGs at every step that significantly contributes in global warming. With the increasing population demand, use of chemicals, electrical energy, and use of fossil fuels are the primary sources of emission from agriculture. The rate of natural resources exploitation in terms of fossil fuel use, minerals, and carbon utilization from soil, etc., is

much higher, than the input to the soil as carbon sequestration. Chemical fertilizers and pesticides are available at a cheap rate, and to increase the productivity, these are utilized in the farming system, on the cost of deterioration of natural resources. With due course of time, soil is losing its property to foster life due to various anthropogenic activities such as deforestation, erosion, use of chemicals, and disposal of hazardous wastes. This review focuses on aspects of carbon footprint from agriculture sector, including emission from pre-farm, on-farm, and post-farm activities. Various mitigation strategies regarding farming practices are suggested, and the models for footprint estimation are discussed.

2 Methodology

For literature survey, the World Wide Web was searched for relevant information. Google Scholar, PubMed, and ResearchGate were used for finding papers using keywords such as carbon footprint from agriculture, mitigation of greenhouse gas emission, emission from agriculture, fertilizer, machinery, electricity, livestock contribution in carbon footprint, estimation of carbon footprint, models for estimation of carbon footprint, etc., and 150 papers were finally selected. The articles published from 2010 to February 2019 were considered. Data of Food and Agricultural Organization (FAO), Intergovernmental Panel on Climate Change (IPCC), and International Federation of Organic Agriculture Movements (IFOAM) were also used.

3 Components of Agriculture and Their Contribution in Carbon Footprint

Emission from total agricultural sector has increased since records (FAOSTAT 2019). Agriculture sector along with land-use change accounts for one-fourth of total anthropogenic GHG emission (IPCC 2014). World population has increased by 36%, and the agricultural land has increased by 42.5% since 1990 to 2014, but emission from agriculture, forestry, and land use has increased by 1.1% (FAO 2015). Emission from India has increased by 11.8% from agriculture, forestry, and land use, whereas the increase in population and harvested area was increased by 45.8 and 50.8%, respectively (FAO 2015). Asia has a major share in total emission from agriculture that is 44%, followed by America, Africa, Europe, and Oceania (FAO 2014). Various factors responsible for carbon footprint in different tiers are shown in Fig. 1.

Total energy: Yuosefi et al. (2017) calculated the carbon footprint of sunflower cultivation in Iran. It was reported that sunflower cultivation requires 70.31% direct energy that involves human labor, diesel, water for irrigation and electricity, and 29.69% indirect energy that involves seeds, fertilizers, pesticides, and machinery. In terms of renewable energy, 20.97% include human labor, seeds, and water for
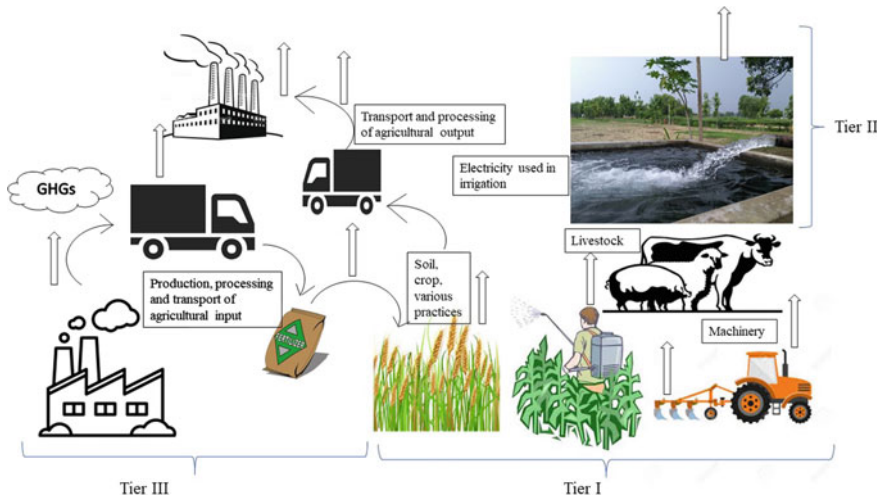
Fig. 1 Emission sources from agriculture sector under different tiers

irrigation and 79.03% of non-renewable energy includes diesel, pesticides, fertilizers, electricity, and machinery (Yousefi et al. 2017). Energy from fossil fuel that is utilized in agriculture contributes maximally in GHG emissions (Yadav et al. 2018). From the utilization of energy in agriculture using fossil fuel, 785 million tons of CO_2-e was emitted globally in the year 2010 (FAO 2014). Crop residue removal after harvest utilizes energy and thus increases the carbon footprint by 6% per hectare (Goglio et al. 2014).

Fossil fuel utilization in agriculture emits GHGs, and the production and transport of fossil fuel also add to the emission of GHGs. From livestock sector, energy uses contributed 20% of the total emission from livestock sector (Gerber et al. 2013). Input of energy contributed only 8% in semiarid areas compared to other agricultural inputs such as fertilizers and pesticides which contributed 82 and 9%, respectively (Devakumar et al. 2018). Pre-farm processes such as production of fertilizers, pesticides, diesel, and electricity in cotton production in Australia contributed 25.3%, whereas post-farm processes such as cottonseed drying utilizing LPG, gin machinery utilizing electricity, bale packaging, gin trash treatment, and transportation accounted for 26.2% (Hedayati et al. 2019). Rest 48.4% were emitted during on-farm processes.

Electricity used in agriculture contributed the most in carbon footprinting (Yousefi et al. 2017). Yousefi et al. (2017) reported that the contribution of electricity is 78.7% of carbon footprinting. Electricity used for irrigation in rice farming in China contributed 4% of total carbon footprinting, whereas for wheat and maize farming contributed 37 and 18%, respectively (Zhang et al. 2017). Sah and Devakumar (2018) reported 3% emission from the use of electricity from India for the period of 2000–2010. In soybean oil production in Thailand, electricity share was 6% of total carbon footprint (Patthanaissaranukool and Polprasert 2016).

Irrigation contribution is small in GHG emission that is 1–13%, except for wheat and rice in India (Rao et al. 2019). Carbon footprint of rainfed agriculture is lower than the irrigated areas as the emission related to irrigation is reduced and the areas are smaller, so the practices are done manually (Devakumar et al. 2018). Irrigation of cotton cropping contributed 13.9% of the total on-farm carbon footprint (108 kg CO_2e t^{-1} lint) (Hedayati et al. 2019).

Lal (2004) reported land-use change from natural to agricultural land causes the reduction in SOC by 60–75%. Low SOC not only reduces the productivity of plants, but also reduces the nutrient use efficiency of the plants as well as sequestration of atmospheric carbon (Lal 2011). SOC also decides the N status of the soil (Nath et al. 2017). Deforestation causes the emission of 0.81 Pg C year^{-1} during 2000–2005 that contributed 7–14% of total emission during that time period (Harris et al. 2012). Conversion of forest land to agricultural land or pastures accounted 6–17% in total global GHG emission (IFOAM 2016).

Machinery: For the growing demand of population, the use of machinery is increasing and the energy provided to machinery is fulfilled by fossil fuel that is responsible for GHG emission. For production, transportation, and application, the fossil fuels are used extensively. In sunflower production, machinery contributed 67.176 kg CO_2-e ha^{-1} out of 2042.091 kg CO_2-e ha^{-1} total CO_2-e (3.29%) emissions (Yousefi et al. 2017). Rice contribution in total carbon footprint was reported to be 13% from machinery using fossil fuels in China (Zhang et al. 2017). Zhang et al. (2017) reported 25 and 20% emission from fuel utilization by machinery in wheat and maize cropping, respectively. For production of cotton in Australia, Hedayati et al. (2019) calculated carbon footprint of machinery and found it to account for almost 7% (125.5 kg CO_2e t^{-1} lint) in total carbon footprint including pre-farm, on-farm, and post-farm processes. Among the three processes, the contribution of on-farm emission was 16% from machinery. Farag et al. (2013) estimated the carbon footprint of rice production in Egypt and found the lowest contribution of machinery in total emission.

Diesel: Diesel consumption occurs in transport of fertilizers, pesticides, seeds, and other farm equipment, and major emissions occur during tillage process. The consumption of diesel is dependent upon the size of tractor, tillage depth, frequency, and type of tillage. Yousefi et al. (2017) reported that the diesel consumption contributes to 12.24% carbon footprint during sunflower production. In conventional tillage and no-tillage system in rice–mustard cropping, diesel contributed 19 and 6%, respectively, in total carbon footprint (Yadav et al. 2018). From India, for the period of 2000–2010, contribution of diesel in carbon footprint was estimated less than 1% by Sah and Devakumar (2018). Patthanaissaranukool and Polprasert (2016) reported 38% contribution of diesel in soybean oil production from Thailand that accounts for 270 kg CO_2-e ton^{-1} soybean oil and 17% contribution was recorded from heavy oil.

Chemicals: Fertilizer production, transport, and application contribute significantly in total GHG emission (Rao et al. 2019). Synthetic fertilizers account for 13% in total agricultural emission of GHGs (FAO 2014). In production process, major GHG that is emitted is CO_2 and in the field emission of N_2O is the major contributor

(Rao et al. 2019). Chemical fertilizers in sunflower farming contributed 5.77% of the total carbon footprint (Yousefi et al. 2017). Nitrogenous fertilizer contributed 14% in rice production, while higher contribution is reported under wheat (28%) and maize (39%) in China (Zhang et al. 2017). Again, in rice–mustard cropping system, conventional tillage with residual incorporation and no-tillage with residue retention emitted 33 and 37%, respectively, under fertilizer application (Yadav et al. 2018). Gan et al. (2011) reported about 57–65% share of production and use of nitrogenous fertilizer in total emission in Canadian prairies. Devakumar et al. (2018) also reported that the contribution of inorganic nitrogenous fertilizers is approximately 72 and 9% from phosphorus and potassium fertilizers in semiarid areas of India. Contribution of Asia is highest in emission from fertilizers, followed by America and Europe during 2000–2010 (Tubiello et al. 2013). Fertilizers use in cotton production led to 442 kg CO_2-e t^{-1} lint, accounting approximately 57% from on-farm emission, whereas production of fertilizers led to 267.7 kg CO_2-e t^{-1} lint, contributing 16.7% in total carbon footprint in Australia (Hedayati et al. 2019). Yue et al. (2017) observed 37–88% contribution of fertilizers in agriculture footprint of different crops. Farag et al. (2013) reported that the contribution of N fertilizers accounts for 10% in rice cultivation in Egypt. For wheat, maize, and soybean crops, the major contribution in carbon footprint is due to use of fertilizers that is more than 75% (Cheng et al. 2015). N fertilizers contributed 89% of carbon footprint, whereas phosphorus (4%) and potassium (2%) contribution were very small in India during 2000–2010 (Sah and devakumar 2018). During the same time period, pesticides accounted for 2% of the total carbon footprint (Sah and devakumar 2018).

Crop: Carbon footprint of different crops varied according to the demand of nutrients and management practices. Emission from crops largely depends on the amount of fertilizer used (Gan et al. 2011). Rice is the most energy demanding crop and thus also contributes most in GHG emissions (Rao et al. 2019). Zhang et al. (2017) reported rice as having the highest carbon footprint of 1.60 kg CO_2-e per unit yield due to emission of CH_4 that contributes 45% of total carbon footprint. Wheat had a lower carbon footprint than rice but higher than maize. The carbon footprint of maize was estimated as 0.48 kg CO_2-e per unit yield and for wheat 0.75 kg CO_2-e per unit yield in China (Zhang et al. 2017). FAO (2017) report suggested that rice cultivation produces 523 million tons of CO_2-e per year that contributed 8.8–10% in 2012 of total agricultural emission globally. In 2015, rice cultivation emitted 2917 Gg CO_2-e and wheat emitted 1537 Gg CO_2-e which contributed, respectively, 60 and 31% of total cropland emission, in which rice covered 37.7% and wheat covered 44.5% of total cropland area in Punjab, India (Benbi 2018). Rice cropping in India contributed 21% of total agricultural emission (INCCA, Indian Network for Climate Change Assessment 2010). Devakumar et al. (2018) analyzed different crop groups and concluded that oilseeds and commercial crops have a highest carbon footprint of 30 and 29%, respectively, followed by cereals and pulses that contributed around 25 and 16%, respectively. Thus, leguminous crops have the highest sustainability index (Devakumar et al. 2018). Oilseed cropping emits higher GHGs than cereals as they have high N content (Liu et al. 2016). In contrast, Sah and Devakumar (2018) reported highest carbon footprint of cereals followed by oilseeds and then pulses.

Gan et al. (2011) reported highest carbon footprint of canola, followed by mustard, flaxseed, spring wheat, chickpea, dry pea, and then lentil. While comparing carbon footprint of various crops in three soil types, viz. brown, dark brown, and black soil in semiarid regions, higher carbon footprint of crops was recorded in humid black soil. Carbon footprint of different crop plant studied is given in Table 1. Leguminous crops have 65% less emission than canola and wheat (Gan et al. 2011). Kharif cropping has a higher carbon footprint than rabi as the rabi cropping is confined to the areas where irrigation can be done easily (Devakumar et al. 2018). According to Yue et al. (2017), vegetables, among the grains, oilseeds, fruits, etc., have the lowest carbon footprint of 0.15 kg CO_2-e kg^{-1}. Yadav et al. (2018) reported that carbon footprint due to contribution of N_2O emitted from fertilizer application, mulching, and roots is highest and contributed 41 and 36% for no-tillage and conventional tillage, respectively, in rice–mustard cropping system.

The studies concluded by Rao et al. (2019), Zhang et al. (2017), Benbi (2018), and Cheng et al. (2015) in different regions of the world showed that the highest carbon footprint is recorded by rice due to large-scale emission of CH_4. Rao et al. (2019) compared carbon footprint of rice, wheat, sorghum, maize, pearl millet, and finger millet, in all states of India, and found that rice crop has higher energy demand, especially for irrigation. Although for crops, other than rice and wheat, requirement of energy for irrigation is very low and carbon footprint is mainly due to fertilizers and machinery. Millets have the lowest carbon footprint as the crop water requirement is too less. The part of North India shows higher carbon footprint as rice and wheat are there as major crops. Carbon footprint also depends upon water pump efficiency. The efficiency of water pump in India is quite lower (40–50%), whereas internationally, it is 70–90% efficient. Crop cultivation in India is mainly based on water availability and climate conditions of that region. Carbon footprint of different crops in rainfed areas reduces overall carbon footprint due to low carbon footprint from irrigation.

Pandey et al. (2013) studied the effect of tillage on carbon footprint of rice–wheat system, in India. In the study, the comparison of four treatments, tillage before both crops, tillage before rice only, tillage before wheat only, and no-tillage, was done. Tillage before both rice and wheat cropping increased CO_2 and N_2O emission but CH_4 emission was significantly declined. Therefore, the overall carbon footprint of this treatment was found to be negative. In no-tillage condition, the yield response was better, but carbon footprint was also high. Tillage before rice transplantation and no-tillage before wheat sowing showed highest carbon footprint among all treatments.

Cheng et al. (2015) analyzed the national statistical data of major crops such as rice, wheat, maize, and soybean for carbon footprint calculation of China in the year 2011. The highest carbon footprint was found for rice (0.37 kg CO_2-e kg^{-1}), followed by wheat (0.14 kg CO_2-e kg^{-1}) and maize (0.12 kg CO_2-e kg^{-1}), and lowest was recorded for soybean (0.10 kg CO_2-e kg^{-1}). Reduced carbon footprint of soybean may be attributed to the reduced use of N fertilizer. Carbon footprint of these crops was positively correlated with N fertilization rate in production with r^2 value of about 0.91, whereas for rice cropping, carbon footprint was correlated with CH_4 emission with r^2 value of 0.85 (Cheng et al. 2015). Variation in carbon footprint for the same

Table 1 Carbon footprint of selected crops

S. No.	Crops	Carbon footprint (kg CO_2-e kg^{-1})	Comments	References
1	Canola	0.913	Pre- and on-farm CF (carbon footprint) of crops grown in brown soil of Canadian prairie	Gan et al. (2011)
	Mustard	0.601		
	Flaxseed	0.456		
	Chickpea	0.254		
	Dry pea	0.189		
	Lentil	0.164		
	Spring wheat	0.383		
2	Cotton	1.600	Pre-, on-, and post-farm CF in Australia	Hidayati et al. (2019)
3	Rice	0.37	Pre- and on-farm CF in China	Cheng et al. (2015)
	Wheat	0.14		
	Maize	0.12		
	Soybean	0.10		
4	Rice	1.90	On-farm CF in Egypt	Farag et al. (2013)
5	Maize	0.21–0.24	On-farm CF in India	Jat et al. (2019)
6	Tomato	0.11	On-farm CF in China	Yue et al. (2017)
	Cucumber	0.14		
	Eggplant	0.18		
	Green pepper	0.33		
7	Rice	1.60	Pre- and on-farm CF in China	Zhang et al. (2017)
	Wheat	0.75		
	Maize	0.48		
8	Sunflower	0.875	On-farm CF in Iran	Yousefi et al. (2017)
9	Rice	0.80	On-farm CF in China	Yan et al. (2015)
	Wheat	0.66		
	Maize	0.33		
10	Wheat	1.061	On-farm CF in India in no-tillage condition	Pandey et al. (2013)

crop was also recorded for different regions in China due to different N application rate and irrigation.

Yousefi et al. (2017) estimated the carbon footprint of sunflower agroecosystem in Iran. Data collection was done from 70 sunflower agroecosystems in 2012, and mean carbon footprint was found to be 0.875 kg CO_2-e kg^{-1}. The output energy of sunflower was higher than the input energy. Major share in input energy was of electricity that was used to power water pump. Sunflower grows in Iran during summer, so water loss due to evapotranspiration is high. Sah and Devakumar (2018) also reported sunflower as having higher carbon footprint.

Zhang et al. (2017) assessed carbon footprints of rice, wheat, and maize in different regions of China through a survey that started in 2014. The study showed similar results as of Rao et al. (2018) and Cheng et al. (2015). Rice was found to have the highest carbon footprint, i.e., 2.10 kg CO_2-e kg^{-1}, followed by wheat (CF-1.26 kg CO_2-e kg^{-1}) and then maize (CF-0.95 kg CO_2-e kg^{-1}). The farm emission, manufacturing, processing and transport of fertilizer, electricity, chemicals, and machinery were also included in total carbon footprint. The study showed a higher contribution of later processes rather than the on-farm emission. For wheat cropping, the share of upstream input is 86% and is highest; among the studied crops, followed by maize, the contribution is 63% and then rice, for which the contribution of upstream inputs is 50%. Differences in carbon footprint of the same crop in different regions are due to regional differences, nutrient requirements, irrigation, and farming practices.

Straw burning increases the carbon footprint of crops significantly. Powlson et al. (2016) reported a great loss of C due to burning of straw in field and also as the fuel. The carbon stored in residues is lost in atmosphere totally as CO_2. Farag et al. (2013) estimated 35.8% share of rice straw burning in total crop production emission in Egypt during 2008–2011. Burning of crop residues not only emits GHGs but also emits many harmful gases that create negative effects on human as well as the environment. Sahai et al. (2011) reported 80–85% of GHGs due to field burning of rice, wheat, and sugarcane residues. In India, 488 million tons of crop residues was generated in 2017 and 24% of it get burnt, which emitted 211 Tg CO_2-e GHGs, along with other gaseous air pollutants (Ravindra et al. 2019). The major contribution is of CO_2, followed by CH_4 and N_2O (Ravindra et al. 2019).

Livestock: Livestock sector emits GHGs majorly via enteric fermentation, feed production, transport, and manure application. Carbon footprint from livestock is more than doubled compared to the crops. Globally, CH_4 is the dominant GHG emitted from livestock sector, which contributed about 44% of total, whereas N_2O and CO_2 account for approximately similar contribution, i.e., 29 and 27%, respectively (Gerber et al. 2013). Globally, livestock contributed about 66% of total agricultural GHG emissions, in which enteric fermentation accounts for 40%, manure left in pastures accounts for 16%, and manure management share is 7% (FAOSTAT 2014) (Fig. 2). Gerber et al. (2013) reported that livestock contributed 14.5% of total anthropogenic emission globally. From India, Chhabra et al. (2013) reported 99.8% CH_4 and 0.2% N_2O emission from livestock. From livestock sector, feed production and transport contributed 45% and the second largest share is by enteric fermentation which is approximately 40% of the total livestock sector (Gerber et al. 2013).
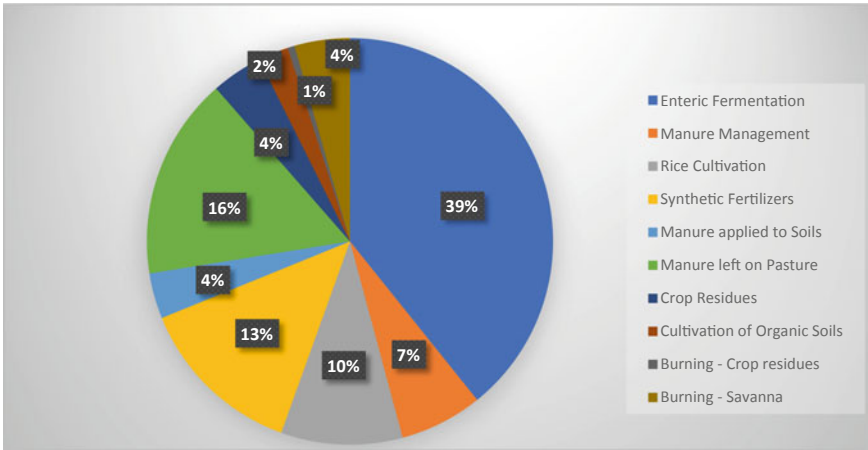
Fig. 2 Global emission of GHG from agriculture sector (FAOSTAT 2014)

Also, the contribution of beef and dairy cattle is more in carbon footprint than other ruminants or animals (Gerber et al. 2013; Chhabra et al. 2013). Cattles sharing the major contributions in GHG emissions are from the production of milk and meat. From pork and poultry, the emission is mainly from fed production, processing, and manure processing. The variations in carbon footprint of different livestock are also due to variations in management practices, environmental conditions, as well as on processing and marketing. By manure management, major share is of N_2O and CH_4, whereas CO_2 and N_2O are emitted from feed processing and CO_2 and CH_4 from energy consumption and enteric fermentation, respectively. Enteric fermentation and manure management in India account for 91 and 9%, respectively, of the total CH_4 emission (Chhabra et al. 2013). Manure contains organic matter and N that lead to CH_4 emission by decomposition of organic matter and N_2O emission indirectly by NH_3 emission. Chhabra et al. (2013) reported that the livestock footprint of India in 2003 was 247.2 Mt CO_2-e and CH_4 emission from livestock was 74.4 kg ha^{-1}. INCCA (2010) report suggests that enteric fermentation is responsible for 63% of total emission from agriculture sector, whereas manure management contributed 0.73%, during 2007. Gerber et al. (2013) reported lower emission from buffalo, whereas higher emission from buffalo due to high demand of meat and milk in India was reported by Chhabra et al. (2013). Yue et al. (2017) reported livestock-based products have higher carbon footprint than crop-based products. The carbon footprints of meat, poultry egg, and milk were reported as 6.21, 4.09, and 1.47 kg CO_2-e kg^{-1}, respectively, which were higher than the crops, vegetables, oilseeds, soybeans, and fruits, having the carbon footprint of less than 1 kg CO_2-e kg^{-1}. The higher carbon footprint of animal-based products is due to higher carbon footprint of animal feed.

4 Mitigation Strategies

Under the current scenario of adverse effects of climate change, it is very important to reduce the carbon footprint of agricultural products. Awareness of carbon footprint of the products is important in local people, so the choice of preferences would help to reduce the emission. Figure 3 shows the practices that can be utilized to reduce GHG emissions.

Crop diversification: Carbon footprint of agricultural products varies with species to species and various agricultural practices. Diversified cropping system increases the productivity as well as lowers the carbon footprint (Gan et al. 2011; Liu et al. 2016). Leguminous crops have lower carbon footprint by sequestering carbon and nitrogen (Gan et al. 2011; Liu et al. 2016). Nitrogenous fertilizers during crop cultivation are one of the major sources of agricultural emission of GHGs. The crops grown after leguminous crops require less N fertilization, so total carbon footprint is lowered. Even the requirement of energy for manufacture and transportation of fertilizers is reduced, leading to low GHG emissions. Hedayati et al. (2019) reported reduction in total GHG emission by 13.2% by using optimum rate of N fertilizers. Lentil wheat rotation has the same yield as of continuous wheat cropping but with low N addition and thus improves the N use efficiency. Lentil and wheat system was reported to have lowest carbon footprint compared to continuous wheat, fallow flax wheat, and fallow wheat systems as carbon footprint was reduced by 150% compared to wheat monoculture (Gan et al. 2014).Cropping sequence in a crop rotation system also accounted immensely in the carbon footprint (Gan et al. 2011; Liu et al. 2016). Gan et al. (2011) reported wheat crop when planted after leguminous crops emitted 20% lower GHGs compared to when cultivated after cereals. Similarly, when grown after oilseed, the emission of GHGs from wheat cropping reduced by 11% as compared to cereals. Crop biomass and N content of the crop are also the responsible factors that decide the carbon footprint.

Summer fallowing: Summer fallowing system reduces the carbon footprint of agriculture as it increases the N availability and thus reduces the amount of N fertilizer
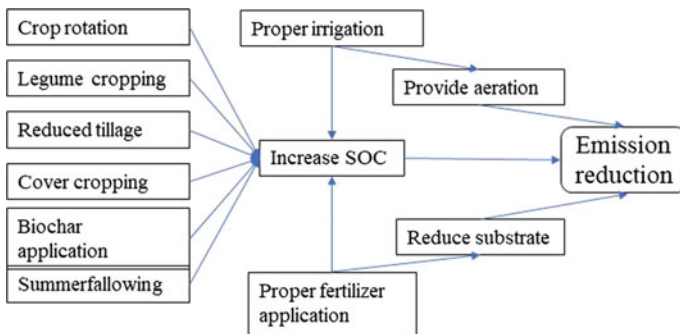

Fig. 3 Mitigation measures to reduce carbon footprint from agriculture

required. Summer fallowing also enhances the productivity (Liu et al. 2016). In contrast, Gan et al. (2014) reported reduced frequency of summer fallowing for reducing the carbon footprint. Instead of summer fallowing, cropping of legumes reduced the carbon footprint to more extent. Residue removal although reported to emit higher CO_2 and also causes the loss of SOC, it reduces the emission of N_2O (Liska et al. 2014).

Increasing SOC: Soil acts as a sink for organic matter and practices that directly releases terrestrial carbon to atmosphere, such as burning of straw and fossil fuel, leading to loss of SOC and increase the GHG concentration. For increasing the SOC, conservation tillage, integrated nutrient management, mulching, cover cropping, diverse cropping system, and biochar application are recommended (Lal 2011). Deficit irrigation helps to increase SOC and thus can be used to reduce carbon footprint as the allocation of biomass is more toward below ground in order to access more water (Pawlowski et al. 2017). Pressurized irrigation systems can help in lessen the total carbon footprint from agriculture (Hedayati et al. 2019). Powlson et al. (2016) concluded that conservation agriculture enhances the SOC through reduced tillage, incorporation of crop residues, and diversification of crops through a meta-analysis in Indo-Gangetic plain and Sub-Saharan Africa.

Mitigation during rice cultivation: Weller et al. (2015) reported that flooded rice emits 90% higher CH_4 than the aerobic rice, but N_2O emission from flooded rice system was lower insignificantly. Emission of CH_4 from rice fields can be lowered by rotation of rice with aerobic rice or maize in dry season and with rice in wet season although N_2O emission was reported to be enhanced (Janz et al. 2019). Proper anaerobic condition is not maintained in aerobic rice as flooding of rice is not done as well as drying of soil occurs in between irrigations. So, during aeration of soil, methanogens are unable to produce CH_4 and methanotrophs are encouraged for CH_4 oxidation (Janz et al. 2019). Rotation with maize reduced the emission as maize cropping acted as weak sink for CH_4 (Janz et al. 2019; Linquist et al. 2012). From rice–aerobic rice and rice–maize rotation, although N_2O emission was higher from straw application, GWP of these rotations was 33% and 48%, respectively, lower than rice–rice rotation (Janz et al. 2019). Rice maize rotation also reduces the irrigation water requirement, so overall carbon footprint is greatly reduced (Janz et al. 2019). Yao et al. (2017) suggested the production of rice in ground cover rice production system, where rice crop is covered with a thin plastic sheet, so that the moisture level is maintained and thus direct emission from flooding as well as carbon footprint of irrigation will be reduced. This method reduces the total carbon footprint along with increasing the yield.

Biochar application: Biochar helps to sequester carbon in soil (Gan et al. 2011; Lal 2011; IPCC 2014; Zhang et al. 2012). Zhang et al. (2012) found a reduction in emission after biochar addition, in China. However, different concentrations of biochar did not have any significant effect on GHG emissions, applied different concentrations of biochar to the soil in rice field in China. Biochar application reduced the GHG emission and also enhanced the crop yield (Xiao et al. 2019). Sun et al. (2019) also reported reduced emission after biochar application in rice field. Biochar application in soil causes alteration of soil biota and improves soil characteristics that

lead to lower emission of CH_4 and N_2O. Sun et al. (2019) speculated that applied biochar enhanced the methanotrophic community or decreased the population of methanogens, enhanced N immobilization, decreased denitrification, and increased soil pH, leading to reduced CH_4 and CO_2 emission. Xiao et al. (2019) suggested reduction in CH_4 and N_2O emission by applying biochar in rice field under controlled irrigation.

Organic farming: In organic farming system, energy use is greatly reduced due to no use of fertilizers and pesticides. Carbon sequestration is high in organic farming. Organic farming helps in reducing the total carbon footprint of agriculture (Meier et al. 2015; Adewale et al. 2018; Skinner et al. 2019; Hedayati et al. 2019). Manure composting done in organic farming can reduce N_2O emission by 50% and CH_4 emission by 70% (IFOAM 2016). Skinner et al. (2019) reported that organic farming reduces the N_2O emission by 40.2%. Proper management of manure also helps in lessen the carbon footprint. IFOAM (2016) report suggested that turning and aeration of manure heaps, keeping manure in closed space, solid and slurry separation and addition of substances that reduce the emission and biogas production by biodigesters from manure, can be used to lower the emission from manure management. N content in animal feed in the form of crude protein is also responsible for emission. Concentrates in diet lead to higher CH_4 emission (Meier et al. 2015). This is because it increases the undigested part in the manure and degradation of the undigested matter emits CH_4.

Biofuel: Use of biofuels in place of fossil fuels is also reported to reduce the carbon footprint of agriculture (Pawlowski et al. 2017). Crop residues containing lignin can be burnt to produce biofuel that reduces the overall emission from electricity used (Liska et al. 2014). Solar powered irrigation pumps reduced the total agricultural carbon footprint by 8.1% by substituting the electrical energy and also the use of biofuel-based machinery instead of diesel-based reduced the emission by 3.9% in cotton cultivation (Hedayati et al. 2019). Unblended biodiesel can also be used that is generated from wastes. Pawlowski et al. (2017) reported sugarcane and napier grass grown in place of arable crops, reduced the carbon footprint, when grown with conservation farming practices. It also helped in increasing SOC. Napier grass cultivation has more environmental benefits in terms of reduced GHG emissions, increase in SOC and biofuel production.

Tillage: Tillage causes the disturbances in soil thus carbon stabilization in soil gets disturbed, organic matters are unveiled for the oxidation and thus loss of SOC occurs. Mulching of crop residue with no-tillage significantly enhanced the soil carbon and also stabilizes the new aggregates. Reduced tillage causes increment in total and recalcitrant C pool in rice–wheat system (Pandey et al. 2014). Crop residues left under no-tillage condition add organic carbon to the soil (Pandey et al. 2014; Powlson et al. 2016; Nath et al. 2017; Yadav et al. 2018), and also, the rate of oxidation of organic molecules is greatly reduced due to soil cover (Lal 2004). Carbon sequestration rate was found highest under continuous no-tillage condition by Pandey et al. (2014). No-tillage reduces the CH_4 and N_2O emission but enhances CO_2 emission, but the GWP is reduced (Pandey et al. 2012). Similarly, Nath et al. (2017) found that during no-tillage condition, soil moisture content and soil temperature

are higher, thus making the conditions for denitrification more favorable. In contrast, Powlson et al. (2016) observed that no-tillage may increase the C sequestration, when the decomposition rate is slow and input C is also stabilized. Pandey et al. (2013) also reported lowest carbon footprint under tillage in rice–wheat cropping system. The potential of no-tillage to enhance the SOC depends upon the region and soil condition.

N fertilizer: By the proper application of N-based fertilizer, mitigation of emission can be done (Yue et al. 2017). By the limited use of fertilizers, emission from soil as well as emission from production and transportation may also be reduced. Even a small change in applied N fertilizers can lead to a big difference in emission pattern. Various techniques are developed to apply only the required amount of fertilizers such as GreenSeeker and leaf color chart-based urea application. Nath et al. (2017) reported lower emission of N_2O by the use of GreenSeeker by 11–13% in wheat cropping. International Rice Research Institute developed a more efficient technique to reduce the excessive use of N fertilizer that is based on the color of leaf. Urea is applied by comparing a chart provided, to the color of leaf, and is called leaf color chart (LCC)-based urea application (Bhatia et al. 2012). This LCC-based urea application method can be used to reduce the fertilizer-based emission, and it also enhances the N use efficiency as well as yield of the crop (Bhatia et al. 2012). Bhatia et al. (2012) reported 10.5% reduction in GWP of rice–wheat system through using LCC-based urea application. Jat et al. (2019) suggested the use of neem-coated urea. Jat et al. (2019) compared neem-coated and sulfur-coated urea from prilled urea in maize cropping system in conservation agriculture and concluded that coated urea not only lowered the carbon footprint of maize cropping, but also enhanced the yield. Although carbon footprint was recorded lowest when no N fertilizer was used, but significant yield loss occurred. Deep placement of urea rather than surface application is reported to reduce the GHG emission by 41% under ground cover rice production system (Yao et al. 2017). For the deep placement of urea, it is placed in 10–15-cm deep holes made near each rice hills. To reduce the carbon footprint, different methods can be applied to fields that will prevent excess use of fertilizers and also improve the soil quality.

5   Models to Estimate Carbon Footprint

To mitigate the emission from agriculture in future, various models are developed and used. As the climate change is very diverse and carbon footprint of agriculture sector is complex, so the developed models help to assess the impact and mitigation strategies for agricultural system. Emission factor methods are also used for carbon footprint estimation of variety of crops such as wheat, canola, maize, and sunflower. Emission factor is simpler models, and it uses IPCC tier I methodology. Limitations with emission factor methodology are: (1) It is region specific; (2) less interaction of soil, climate, and crop management. Again, some models are simple that use only biomass or yield or soil carbon or other properties of soil or manure input, etc.,

Table 2 Models for assessing soil C dynamics influencing carbon footprints and their required inputs

Models	Inputs
Roth C	Soil temperature, soil water, clay content
C-TOOL	Mean monthly air temperature, clay content, C/N ratio, C in organic inputs
ICBM	Crop type, soil temperature, rainfall, soil characteristic, tillage frequency
DayCent	Daily min/max temperature and precipitation, soil texture, vegetation type, amount and timing of nutrient amendment
DNDC	Site and climate, crop, tillage, fertilizer and manure amendment, plastic film use, flooding, irrigation, grazing, and cutting
CERES-EGC	Weather, soil properties, crop management, soil organic matter
Info-RCT	Precipitation, manure/residue application, SOC, human labor, animal labor, machine, seed

Abbreviations *Roth C* Rothamsted Carbon, *ICBM* Introductory Carbon balanced model, *DayCent* the daily time step version of CENTURY, *DNDC* DeNitrification DeComposition, *CERES-EG*C Crop Environment REsource Synthesis Environnement et Grandes cultures, *Info-RC*T Information on Use of Resource Conservation Technologies

and some complex models are dynamic crop–climate–soil models. Roth C (Rothamsted Carbon, Coleman and Jenkinson 1996), ICBM (Introductory Carbon Balanced Model, Andrèn and Kätterer 1997) and C-TOOL (Hamelin et al. 2012) are few of the simple C models. In these models, soil characteristics are included as input such as soil temperature, water content and clay content, and crop type (Table 2). These models give soil C change, along a time series. Roth C uses monthly time step, and C-TOOL uses both daily and annual time steps. These models are simple and easy to use. Although these models have some drawbacks as they are not applicable globally, they did not take into account other determinants and all the soil borne emissions are not included.

The more complex and mathematical models are dynamic crop–climate–soil models. The output of these models is shown as soil C and N, crop growth, and GHG emission. CERES-EGC (Crop Environment REsource Synthesis Environnement et Grandes cultures, Gabrielle and Gagnaire 2008), DNDC (DeNitrification DeComposition), CropSyst (Cropping Systems Simulation Model, Zaher et al. 2013), and DayCent (the daily time step version of CENTURY, Kim and Dale 2009) models estimate change in SOC stock as well as GHG emission. These models can be used for agricultural fields, grassland, and forests and require large statistical data. Saharawat et al. (2012) used Info-RCT (Information on Use of Resource Conservation Technologies) model that predicted crop yield, N budget, and GHG emission in South Asian region, developed by Pathak et al. (2011). The models to be used are selected depending upon the objective and data availability. Goglio et al. (2015) suggested that for small-scale site-specific management, dynamic crop–climate–soil model should be preferred then simple models. Similar is with large-scale assessment, so dynamic crop–climate–soil model is better and can be used in all cases, but it is cumbersome.

6   Conclusion

Agriculture shares a major proportion in impacting the climate change scenario via a higher carbon footprint. Processes related to agriculture from the production of agricultural input to the processing of agricultural output and emission of GHGs are inevitable. From the studies, it can be concluded that carbon footprint of pre-farm activities such as manufacture and transportation of fertilizers, pesticides, and the machineries is significant. Emission from field is largely dependent on crop type and their water and fertilizer requirements. Rice crops have the highest carbon footprint due to CH_4 emission and irrigation demand, among all the studied crops. Carbon footprint of livestock sector is quite higher due to manure management, feed production, and enteric fermentation. The interrelation of the processes decides the carbon footprint, and thus, mitigation of emission can be done by using some improved agricultural practices. For mitigation, appropriate use of fertilizer, crop rotation, irrigation management, biochar application, reduced tillage frequency, organic farming, etc., are some suggested measures. Farming practices that enhance SOC are the best mitigation strategies for lowering the carbon footprint. Carbon footprint of N fertilizer is observed highest among all, so various techniques are developed such as GreenSeeker, LCC-based urea application, neem, and sulfur-coated urea to reduce the carbon footprint of N fertilizers. Various models are developed to estimate carbon footprint that take some physicochemical properties of soil, crop data, and agricultural input data to provide SOC dynamics and GHG emission. Models should not be used only for carbon footprint calculation, but also as a tool to foresee the positive effects of management practices.

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