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Review

Effects of Various Herbicide Types and Doses, Tillage Systems, and Nitrogen Rates on CO_2 Emissions from Agricultural Land: A Literature Review

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Abstract: Although herbicides are essential for global agriculture and controlling weeds, they impact soil microbial communities and CO_2 emissions. However, the effects of herbicides, tillage systems, and nitrogen fertilisation on CO_2 emissions under different environmental conditions are poorly understood. This review explores how various agricultural practices and inputs affect CO_2 emissions and addresses the impact of pest-management strategies, tillage systems, and nitrogen fertiliser usage on CO_2 emissions using multiple databases. Key findings indicate that both increased and decreased tendencies in greenhouse gas (GHG) emissions were observed, depending on the herbicide type, dose, soil properties, and application methods. Several studies reported a positive correlation between CO_2 emissions and increased agricultural production. Combining herbicides with other methods effectively controls emissions with minimal chemical inputs. Conservation practices like no-tillage were more effective than conventional tillage in mitigating carbon emissions. Integrated pest management, conservation tillage, and nitrogen fertiliser rate optimisation were shown to reduce herbicide use and soil greenhouse gas emissions. Fertilisers are similarly important; depending on the dosage, they may support yield or harm the soil. Fertiliser benefits are contingent on appropriate management practices for specific soil and field conditions. This review highlights the significance of adaptable management strategies that consider local environmental conditions and can guide future studies and inform policies to promote sustainable agriculture practices worldwide.

Keywords: agricultural practices; herbicide; nitrogen fertilizer; soil; carbon dioxide emissions; tillage systems

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1. Introduction

The climate crisis driven by global warming is an urgent issue caused by the increasing release of greenhouse gases (GHGs) from natural processes and different anthropogenic activities, e.g., fossil-fuel combustion, waste treatment, and agricultural practices. CO_2 is the most prevalent GHG, and agriculture is responsible for 30% of the global CO_2 released into the atmosphere. This proportion increased by 27% from 1970 to 1990, which is concerning [1,2]. Notably, the primary source of agricultural CO_2 emissions is organic degradation by microorganisms in soil and respiration by roots. Atmospheric CO_2 levels at the start of the Industrial Revolution (circa 1860) were approximately 285 ppm, whereas current estimates are 400 ppm or above [3]. By the year 2100, these levels are projected to reach 1000 ppm [4]. Along with industrial activity, agriculture is a major source of these emissions. Since 2007 alone, agricultural activity has released nearly 3 billion tonnes of CO_2 emissions every year [5]. Therefore, agricultural practices play a central role in climate change because of their influence on GHG emissions [6]. The amount of CO_2 absorbed in soil or released into the atmosphere depends on the crop and soil management methods employed in a region [7].

Weed control in agriculture has long relied on herbicides to ensure higher yields by limiting crop competition. Previous studies analysed the variations in soil CO_2 emissions associated with different herbicides while considering different application methods, concentrations, and soil properties. In addition to herbicides, other factors such as soil temperature, soil respiration, and tillage methods influence the overall CO_2 footprint of the agriculture sector [8,9].

The impacts of pest-management strategies beyond chemical control also need to be investigated. Notably, Alskaf et al. [10] mentioned the complexity of interactions between soil conditions, climate, and specific management choices, suggesting that the benefits of integrated practices are highly dependent on the local environmental conditions. Two particularly impactful practices—tillage and nitrogen fertilisation—are garnering increasing global interest to reduce soil CO_2 emissions. Several studies worldwide have investigated the relationships among tillage intensity (from conventional ploughing to the no-tillage (NT) method), soil carbon-sequestration capability, and emission levels of CO_2 and other gases [11–13]. The direction and magnitude of the responses demonstrated a strong covariance with biophysical traits, such as soil type, moisture levels, organic matter amount, and temperature. Integrating conservation tillage with optimal pesticide application and timing has lowered soil CO_2 emissions [14].

Herbicide usage, tillage methods, and nitrogen fertilisation are integral management factors in global agriculture that impact soil CO_2 fluxes; however, their precise effects require further elucidation. In particular, the degree to which the chemical composition, applied dose, and application timing of herbicide alter soil microbial communities and decomposition rates remain active areas of investigation. Similarly, the specific intensities of mechanical soil disturbance associated with different tillage implementations (ranging from conventional ploughing to NT) shape soil carbon dynamics in complex ways, which are tied to local environmental conditions. Moreover, both the nitrogen formulation and application rate are known to influence plant growth and rhizosphere respiration, which have consequences for gaseous emissions.

This review analyses the varying effects of different herbicides and doses on soil microbiota and CO_2 emissions depending on factors such as herbicide composition, crop system, soil properties, and application methods. It highlights that both increases and decreases in emissions occur based on these factors. Tillage intensity, depth, and method (e.g., conventional ploughing vs. NT) are examined in relation to short- and long-term impacts on soil CO_2 fluxes, carbon sequestration, microbial activity, and soil properties. Reduced tillage and NT generally reduced emissions. The application rates of nitrogen fertilisers represent a critical influence on soil CO_2 emissions by impacting plant growth, rhizosphere respiration, and soil microbial activity. Both increases and decreases in emissions have been reported depending on the nitrogen source, rate, placement and soil characteristics.

GHGs emitted from agricultural practices are associated with the effects of the practices on soil microbial activity and soil carbon stocks, both of which influence the rates of respiration and GHG emissions from agricultural lands.

The sorption mechanisms of agrochemicals in soil under field conditions primarily involve the interaction of these chemicals with various soil components, such as organic matter, minerals, and biochar [15]. These interactions affect the retention, degradation, and mobility of agrochemicals in soil, which can influence the emission of GHGs such as CO_2 [15]. Moreover, biochar has been found to enhance the sorption of chemicals and reduce CO_2 emissions from the soil [16].

The desorption mechanism of agrochemicals under field conditions involves the release of previously adsorbed agrochemicals from soil particles driven by changes in soil moisture, temperature, or interactions with other chemicals [15]. The release of agrochemicals through desorption can stimulate microbial decomposition of soil organic matter, thereby increasing CO_2 emissions [17].

This work comprehensively reviewed the current scientific understanding of the relationships between standard agricultural inputs and activities and resulting soil CO_2 emissions.

The main aim and objective of this review is to comprehensively analyse the current scientific understanding of the relationships between standard agricultural inputs and activities (namely herbicide usage, tillage systems, and nitrogen fertilisation) and the resulting CO_2 emissions.

This review analysed integrated approaches' complex interactions and effects, demonstrating their potential to reduce chemical inputs and emissions [18]. The correlation between various production technologies and land-use patterns with CO_2 emissions was further explored in different regions and countries over different periods. A better understanding of these relationships can support prioritising cost-effective mitigation techniques. This review identifies gaps in the literature concerning the impacts of herbicide types and doses, tillage systems, and nitrogen rates and suggests viable mitigation techniques. Additionally, this review discusses GHG emissions, historical agricultural intensification, and implications of herbicide application across different regions to increase the sustainability of these agricultural practices. The primary aim of this review is to provide insights for agriculture sector stakeholders seeking to lower their GHG footprint through science-based practices that support productivity and global climate objectives. Examining specific crops, soil types, and climate regions may reveal interactions that are currently overlooked at broader scales. Nonetheless, further investigations are required to optimise fertilisation rates and maximise sustainable carbon storage and emission reductions.

2. Materials and Methods

The literature review data were obtained by conducting extensive searches across various bibliometric databases, including Scopus, MDPI, PubMed, Web of Science, Cambridge Journals, Taylor & Francis, Science Direct, Springer and AGRO. These databases were specifically chosen for their extensive archives of peer-reviewed academic journals in environmental science and agriculture. This approach ensured that the articles sourced were of high academic and scientific value and directly relevant to our research themes.

The analysis excluded articles published in languages other than English, popular science articles, and those describing cellular-level research findings. The review focused on research papers published between 1985 and 2023. The articles selected for the review are discussed in thematically relevant sections of the manuscript. Search terms included combinations of keywords, including "herbicides", "tillage systems", "nitrogen fertilisers", "carbon dioxide emissions", "greenhouse gases", "soil respiration", and "agriculture". This specific selection of keywords was aimed at encompassing a broad spectrum of research topics within the scope of agricultural practices and their environmental impacts.

Over 120 studies were initially identified and screened for relevance. A total of 98 studies met the inclusion criteria and were analysed in depth. To categorise the results systematically, studies were grouped according to the specific agricultural practice(s) investigated (herbicides, tillage, fertilisers). When possible, papers were further stratified by geographic region, soil type, climate, and crop studied, providing a comprehensive overview that reflects diverse conditions and practices across the globe.

3. Greenhouse Gas Emissions from the Agriculture Sector Released into the Atmosphere

3.1. Greenhouse Gas Emissions

The agriculture sector is experiencing severe risks associated with environmental changes; thus, urgent adjustments in agricultural practices are required. Simultaneously, farming practices release critical levels of GHGs into the atmosphere; therefore, reducing adverse farming elements is an important goal for climate change mitigation plans in numerous countries. The primary contributors of GHG emissions from the agriculture sector include crop production, livestock operations within the farm gate, and extensive carbon losses resulting from deforestation and peatland degradation [19].

Figure 1 presents the main contributors to GHG emissions. The primary GHGs are CO_2, CH_4, and N_2O [19]. It is crucial to acknowledge that agriculture also contributes to soil CO_2 emissions. According to Crop Life International [20], crop farming accounts for less than 4% of the total CO_2 emissions from the agricultural sector.

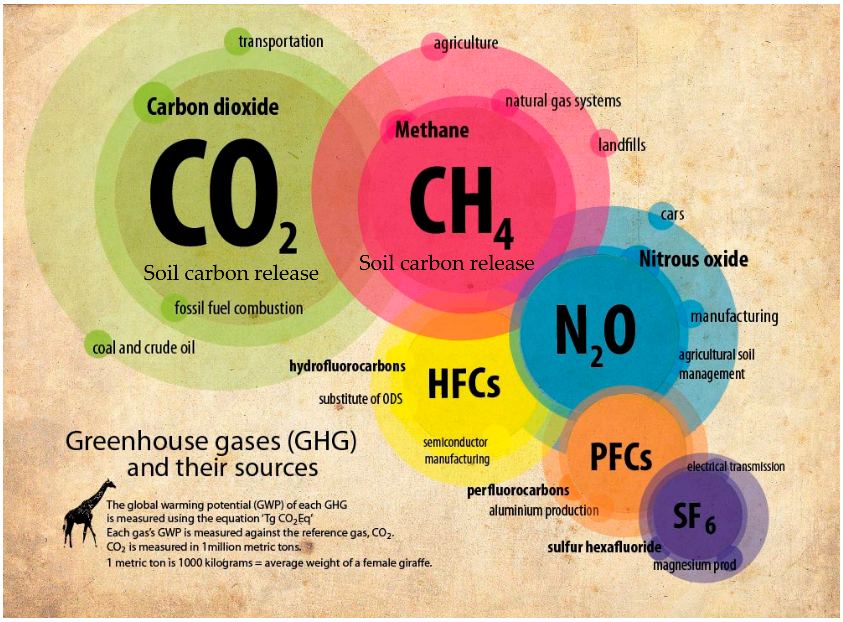

Figure 1. Major sources of greenhouse gas (GHG) emissions. Abbreviations: perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), carbon dioxide (CO_2), methane (CH_4), hydrofluorocarbons (HFCs), nitrous oxide (N_2O), ozone-depleting substance (ODS), global warming potential (GWP) [21].

3.2. Influence of Agricultural Intensification on CO_2 Emissions

According to the United Nations Food and Agriculture Organization [22], the agriculture sector contributes 14% of the world's total CO_2 emissions, and an even higher contribution is anticipated in the future. Burney et al. [23] compared historical agricultural intensification to other scenarios of vast production methods to determine the effect of each method on the climate; they indicated predominant differences in the CO_2 emissions from land-use change and that agricultural intensification decreased the overall GHG emissions due to land sparing.

The southern part of Africa has effectively embraced agricultural intensification. Herbicide use is dominant among the key intensification methods used to protect crops and improve farm yields. The use of herbicides combined with the warm and wet climate of the region increases microbial activity and organic content decomposition in soil, resulting in increased soil CO_2 emissions [24]. Soil CO_2 emissions in the region are significantly lower compared to those related to land-use changes and mechanisation in the agricultural sector.

3.3. Agriculture Sectors and Associated CO_2 Emissions

Agriculture is a key sector of the economy, and its development and growth are likely to impact CO_2 emissions. Hence, understanding the environmental implications of agricultural development is critical. According to a study by Dogan [25], the rise in CO_2 emissions associated with the growth of China's agricultural sector over four decades is important. The autoregressive distributed lag (ARDL) approach was used to assess the overall impact of agricultural growth on CO_2 emissions. Similar findings have been reported by other researchers [26–28]. According to Zhangwei et al. [26], economic growth and CO_2 emissions from agricultural activity were closely related. Xiong et al. [27] reported that the increase in CO_2 emissions outstripped the increase in agricultural growth, indicating that agricultural activity has a disproportionate effect on CO_2 emissions. Using the fully modified ordinary least squares (FMOLS-DOLS) approach, Liu et al. [28] conducted a multinational study of the agricultural sector, including the BRICS member states, and concluded that the relationship between agricultural growth and CO_2 emissions was both positive and long-term.

Certain factors influencing CO_2 emissions, such as climatic variations and crop management methods, are more dominant than others. These variables are, in turn, affected by other secondary variables, such as agricultural practice mechanisation, agricultural workforce size, livestock activity, and land-use intensity.

Although most studies specified in this section suggest that modern agricultural practices are responsible for the increase in CO_2 emissions, it is important to note that agricultural intensification, as practised in most regions today, reduces GHG emissions [23]. Furthermore, the recorded increments in CO_2 emissions that seem to correspond with agricultural growth may be attributed to the inclusion of CO_2 emissions from deforestation, biomass fires, organic soil fires, drained organic soils, and the employment of machines [29]. Agricultural emissions generally include CH_4 and N_2O, with CO_2 emissions being relatively minor.

Figure 2 illustrates the CO_2 emissions from agricultural land use and land-use changes estimated by the FAO [29]. Forest clearing was determined to be the main contributor to CO_2 emissions among all the agricultural practices. Other significant contributors were ‘drained organic soil’ and ‘organic soil fires’. It is evident from this study that crop-farming practices are responsible for the lowest CO_2 emissions.

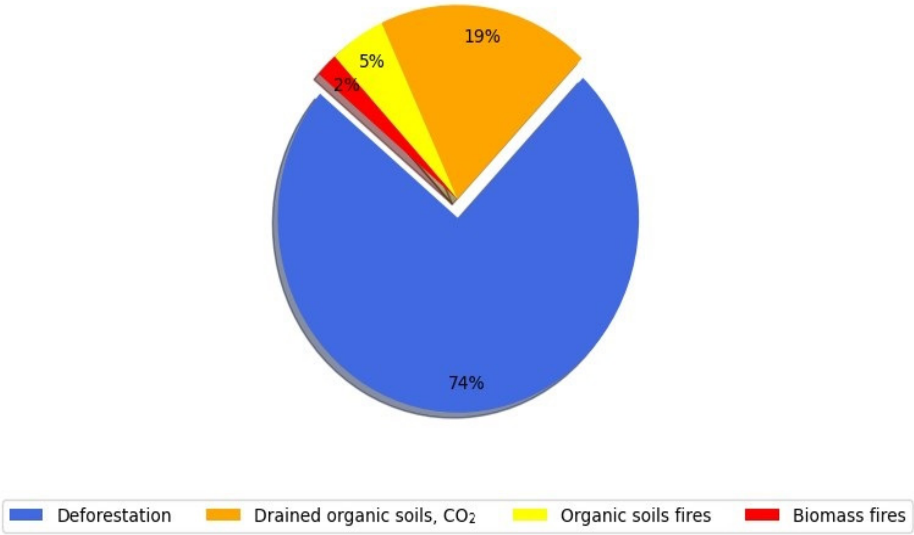

Figure 2. Contribution of different activities to the total emissions related to agricultural land use and land-use change in 2018 (3.9 Gt CO_2-eq) [30].

This review includes studies highlighting some important issues related to agricultural CO_2 emissions. Most importantly, CO_2 emissions are frequently generalised to include methane as well as emissions caused by activities that should not be included under the umbrella term of ‘agricultural CO_2 emissions’. According to Lynch et al. [31], such erroneous generalizations may lead to flawed projections about long-term CO_2 emissions and misinformed strategies. It is important to recognize the sources of agricultural CO_2 emissions, which include changes in land use, crop rotation practices, and the type of equipment used. Another misconception to avoid is confusing GHGs with CO_2 emissions.

GHGs include methane (CH_4), which affects the environment negatively, although in different ways compared with CO_2.

Researchers such as Al Mamun et al. [32] and Luo et al. [33] have elaborated on the impact of agricultural technology on CO_2 emissions. Naturally, unsustainable agricultural practices, including intensive agricultural methods, harm CO_2 emissions [34,35]. Similarly, Qiao et al. [7] and Narasimham and Subbarao [36] stress on understanding the impact of technological factors on CO_2 emissions. These findings suggest that further investigations are required to determine the contribution of crop cultivation to the CO_2 emissions released into the atmosphere, independent of other agricultural factors.

4. Herbicide Application in Agriculture

4.1. Implications of Herbicide Usage on Crop Yield

Weeds are detrimental to crops as they compete for the same resources, negatively impacting crop yield [37,38]. Herbicides are agricultural materials used to eliminate or hinder plant invasion, and they are generally classified according to the mode of action, application mode, time, and weed targets [39]. The widespread use of herbicides was vital for boosting crop production in the 1960s. The research and development of different herbicides, such as 2,4-dichlorophenoxyacetic acid (2,4-D), enabled farmers to control weeds in cereal crops [40]. Today, farmers worldwide use herbicides to increase agricultural output per hectare and grow food on smaller land parcels. Considering the increased use, the herbicide market is estimated to increase by USD 26.23 billion between 2021 and 2025 [41].

4.2. Herbicide Usage in Different Regions

Herbicide use varies across geographical regions, reflecting the needs and challenges of local agricultural practices. The loss of production caused by weeds is estimated to be more than one-and-a-half times the sum of losses induced by animal pests, pathogens, and viruses [40]. Herbicides accounted for over 30% of the total pesticides used in the European Union (EU-27) from 2010 to 2019 [42]. Weed infestations result in significant production losses across various crops in different regions, impacting agricultural productivity [43]. In European countries such as Poland and France, maize and other crops suffer yield losses due to weed infestations, leading to economic consequences for farmers [37,44]. The European Union aims to enhance agricultural safety and resilience, emphasizing sustainable crop and weed management to minimize production losses and ensure food security [45]. Biological weed control in European crops has effectively reduced herbicide use and managed weed infestations, improving crop productivity [46,47]. Implementing Integrated Weed Management (IWM) systems with herbicide-tolerant crops is crucial for mitigating crop losses and improving European agricultural sustainability [48].

During the late 1960s in Germany, there was also a noticeable change in the composition of the agricultural labour force as an increasing number of individuals began migrating to urban areas in search of work. The need for increased agricultural output during that time resulted in the heavy utilisation of herbicides [49]. Herbicide usage has increased to unprecedented levels in countries such as Australia, Pakistan, and the Philippines. Herbicides generate the highest agricultural sales value among all the pesticide categories in Australia, amounting to over AUD 1.5 billion.

Among agricultural pesticides, herbicides have the highest sale values in Australia, followed by insecticides and fungicides [50]. The increased use of herbicides has improved yields and correspondingly increased soil CO_2 emissions in the country.

The use of herbicides has increased considerably in the Philippines. Common herbicides used in rice plantations in the Philippines include butachlor, propanil, pretilachlor, tetrachlorfeno, bispyribac-sodio, and cyhalofop-butyl. The amount of herbicides imported into the country has remained consistent over the years [51]. Weed infestation is a considerable challenge for agricultural productivity in the Philippines and other countries, such as Pakistan. A study in Pakistan indicated that weeds can cause yield losses of up to 11.5% [52], while in India, the economic impact is estimated to be approximately USD 11 billion [53]. To further explain the effects of weeds on productivity, Table 1 presents the financial implications of weeds for different crops in Pakistan. Findings from a study by Shrestha et al. [54] indicate that wheat farmers experience the highest losses due to weight, at PKR 881.8 billion, followed by sugarcane and rice farmers, with losses of USD 2.624 and USD 2.588 billion, respectively. Notably, maize, cotton, lentil, and gram farmers also experience significant losses due to weeds. An increase in the import of herbicides into Pakistan is, therefore, instrumental in reducing weed-induced losses for farmers.

Table 1. Crop-wise monetary losses due to weeds in Pakistan [1 USD = ~160 Pakistani Rupees (PKR)] [54].

Crop	Production (Million Tons)	Production Losses in Million Tons (10%)	Local Market (PKR/ton)	Loss Due to Weeds (Billion Rupees; 10%)
Cotton	1.67637	0.167637	87,500	14.67
Sugarcane	67.174	6.7174	6250	41.98
Rice	7.202	0.7202	57,500	41.41
Maize	6.309	0.6309	30,000	18.93
Wheat	25.195	2.5195	35,000	88.18
Gram	0.107	0.0107	100,000	1.07
Lentil	0.117	0.0117	100,000	1.17
		Total		207.41

4.3. Use of Herbicides in Sustainable Agricultural Practices and Crop Yield Management

Chemical weed control holds promise for the effective, timely, and economical suppression of weeds [55]. Weeds compete with crops for sunlight, water, and nutrients, reducing crop yield. If left unchecked, this may result in 100% crop failure. On a global scale, weeds reduce total grain production by 10% [56]. The current literature indicates that herbicide utilisation is often considered a primary method for maintaining high crop yield and that it promotes sustainable farming. However, herbicides may be replaced by other weed-managing techniques in the future to ensure high or better yields and reduced environmental effects [56].

Effective weed management is critical in achieving high crop yield and fostering sustainable farming practices worldwide. Pakistan is a major wheat-producing country that has experienced a substantial rise in herbicide usage. Therefore, it is used as an ideal case study for understanding herbicide usage in different agricultural settings. Herbicide application on wheat in Pakistan exhibited significant growth from 1985 to 2010, covering 35% of the agricultural area and playing a crucial role in establishing the country as a top producer of wheat crops [54]. Table 2 compares the herbicide usage in Pakistan in 1986 and 2010. Considering all the major crops grown in the country, its usage was considerably increased from 1986 to 2010. The use of herbicides in Pakistan has greatly increased in wheat, rice, cotton, and maize plantations (in that order) [54].

Table 2. Crop-wise comparison of the area treated with herbicides in 1986 and 2010 in Pakistan [54].

Crop	1986		2010	
	Cropped Area (ha)	Area Treated (%)	Cropped Area (ha)	Area Treated (%)
Wheat	7258	0.74	9042	35
Rice	2000	0.39	2883	26
Sugarcane	903	1.35	943	19
Maize	808	0.06	1052	7
Cotton	2242	0.13	3106	25

Changes in environmental guidelines and concerns about herbicide usage affect the application of herbicides worldwide. Farmers may change their herbicide use to conform to guidelines or address issues such as herbicide-safe weeds. Colbach et al. [57] discovered that: (1) without effective alternative agricultural techniques, decreasing the amount of herbicide can exacerbate weed infestation, emphasising the potential danger of reducing the herbicide amount without considering a suitable alternative strategy; (2) if farmers use alternative methods, reduced herbicide usage does not necessarily increase crop-yield losses, suggesting that proper management strategies can mitigate the associated negative impacts; and (3) to fully understand these dynamics, comprehensive examinations are required to depict the influence of weeds on agricultural production, which requires explicitly involving weeds and disentangling the impacts of herbicides from other practices.

Weed infestations are estimated to cause a 37% reduction in global maize production [58]. According to Ayana [59], applying various herbicides to maize plots may significantly and consistently increase grain yield. Furthermore, herbicides provide a primary method of weed control for crops, which is otherwise relatively expensive for farmers. For instance, over 92% of midwestern maize and 98% of soybean production in 2018 relied on herbicide usage [60].

Despite several studies affirming the advantages of herbicide usage, Colbach et al. [57] argued that reducing herbicide usage may not restrict agricultural productivity, with adopting effective agronomic methods being the caveat. While herbicides are the safest and most effective weed-control methods, their use can lead to the development of herbicide-resistant weeds, along with increased costs and reduced crop yields. Additionally, there are concerns about potential environmental impacts, e.g., resource contamination and potential harm to non-target plants and animals. Colbach et al. [57] proposed that adopting effective agronomic practices to minimise herbicide usage may be a viable option that may not compromise agricultural productivity.

The utilisation of mechanical weed-removal strategies is garnering increasing interest. The emphasis on quality outweighs the environmental considerations and pressures in decision-making processes. Human errors and inaccuracies during mechanical weed-removal processes are significantly minimised by modern technology. Farm equipment automation and real-time data sharing between farm equipment and detection technologies augment the efficacy of these practices. Several sensors are used in weed-removal devices, e.g., cameras, global positional systems (GPS), lasers, and ultrasound, which enhance the accuracy of the processes [61]. Although this approach may protect humans and animals from the adverse effects of herbicides while ensuring high yields, it undoubtedly contributes to CO_2 emissions into the atmosphere. It is, therefore, vital to develop a weed-control approach that will not harm humans and animals or increase CO_2 emissions. A balanced understanding of the overall effects of herbicides can lead to more sustainable agricultural practices about the frequency and intensity of herbicide use.

Different types of herbicides have varying impacts depending on the crop they are applied to. Some herbicides have short-term effects, while others have more enduring effects. Dinelli et al. [62] argued that triasulfuron has relatively short-term effects on soil activity, and soil respiration and dehydrogenase activity returned to normal after 38 days. A study by Zheng et al. [63] showed that the level of CO_2 emissions was not impacted when glyphosate was applied to citrus plants. Moreover, butachlor was shown to lower CO_2 emissions when applied in woodland areas but had a negligible impact on citrus crops, thus showing that the same herbicide can have different outcomes on CO_2 emissions depending on the crop [64]. Another study by Shi et al. [65] showed that butachlor, in general, leads to higher CO_2 emissions compared with the lack of herbicide treatment. However, not all herbicides have the same effect on soil emissions. Sandor et al. [2] investigated the impact of different herbicides on soil emissions. By comparing the effects of Andengo, Capreno, and Figaro, these researchers found that only the application of Figaro resulted in a conclusive reduction in CO_2 emissions, whereas the other two herbicides produced inconclusive results. These differences highlight the need to understand the composition and effects of specific herbicides on soil emissions. Zabaloy and Marisa [66] revealed that low doses of glyphosate and 2,4-D temporarily inhibited soil CO_2 emissions, while metsulfuron methyl did not significantly affect soil CO_2 emissions or microbial respiration.

To enhance our current understanding of herbicides' effects on CO_2 emissions, Safa and Samarasinghe [67] examined the correlation between CO_2 emissions and various agricultural inputs used in wheat production (Table 3).

Table 3. Carbon dioxide (CO_2) emissions from agricultural inputs in wheat production (kg CO_2/tonne) [67].

	Fertiliser	Crop-Protection Product	Power	Machinery	Fossil Fuel	Aggregate
Total amount	539 (52%)	55 (5%)	86 (8%)	149 (14%)	203 (20%)	1032
Irrigated farmland	516 (45%)	63 (5%)	137 (12%)	198 (17%)	228 (20%)	1142
Dry farmland	579 (68%)	41 (5%)	0	65 (8%)	162 (19%)	847

Safa and Samarasinghe [67] analysed 35,000 hectares of wheat fields. The most commonly used pesticides on wheat farms in the region were the herbicides Roundup 360 SL (glyphosate as the active ingredient), Reglone 200 SL (diquat dibromide as the active ingredient), Glean, and Cougar; fungicide Caramba 60 SL (metconazole as the active ingredient); and adjuvant Spodnam 555 SC (di-1-P-menten as the active ingredient). The study revealed that herbicides accounted for 5% of the overall emissions, equating to 55 kgs of CO_2 per hectare.

4.4. Different Doses and Types of Herbicides Used in Corn, Wheat, and Barley and Their Impacts on Soil Carbon Dioxide (CO_2) Emissions

Herbicides such as atrazine and 2,4-D may be applied before or after emergence to chemically suppress weeds in maize plantations. Several novel formulations have been introduced to enhance their effectiveness, and they may have a lower herbicidal dosage than the original formulation. This review assessed the effectiveness of a new atrazine formulation for controlling maize weeds. A similar trend was noted in different studies, including an increase in weed dry matter with decreasing atrazine dosage, indicating reduced decomposition rates and, thus, reduced CO_2 emissions into the atmosphere. Smaller doses of atrazine in the soil demonstrated little effect on the soil pH, texture, and moisture content, thereby supporting normal decomposition rates of microbial communities. This ensures minimal disruption of the carbon cycle [68]. Higher doses of atrazine may cause mutations in soil microbial organisms, resulting in higher rates of decomposition and CO_2 emissions. In other cases, higher doses of atrazine may reduce microorganism activity in the soil, slowing the decomposition rate and disrupting the carbon cycle [68].

2,4-D is a herbicide commonly used in wheat and barley plantations. When applied directly to the soil surface in low concentrations, 2,4-D affects soil microbial movement and CO_2 emissions. Low doses of 2,4-D tend to reduce the soil CO_2 emissions for a short period due to the resulting disruption in microbial activity. However, high doses or repeated applications can upset soil microbial networks and possibly influence the soil carbon elements, thereby guaranteeing higher CO_2 emissions in the long run [69,70]. Notably, for most herbicides, smaller doses reduce soil CO_2 emissions. In contrast, higher doses tend to disrupt the carbon cycle, guaranteeing high CO_2 emissions in the long term. According to Zabaloy and Gómez [66], low doses of glyphosate and 2,4-D can temporarily inhibit soil CO_2 emissions but disrupt the carbon cycle. Higher doses typically result in higher soil CO_2 emissions over time.

4.5. Impact of Herbicides on Methane, Nitrous Oxide, and Carbon Dioxide Emissions from the Soil

Applying herbicides to wheat fields in winter does not alter the seasonal rhythm of N_2O emissions, but it does reduce the emissions of other GHGs; this change is particularly noticeable after 10 days of treatment. This suggests that while the seasonal pattern of emissions remains consistent, specific reductions in emissions may be observed following the application of herbicides. Applying a combination of herbicides during the wheat season may reduce the greenhouse gas intensity (GHGI) by approximately 41%. Similarly, using specific herbicides throughout the rice season may result in a 22% decrease in the GHGI. This decrease, however, is not statistically significant [71]. Applying the herbicide prosulfuron for brief periods generally reduces N_2O emissions [72]. The herbicide butachlor reduced soil CH_4 emissions by 20% in a directly sown flooded rice field. Butachlor additionally prevents the oxidation and formation of CH_4, even in inadequate quantities [73].

Kinney et al., 2004 [72] indicated that prosulfuron increased N_2O emissions and CH_4 consumption in fertilised grassland soils in Colorado by up to 1600% and 1300%, respectively. While comparing NT and tilled plots where herbicides had been applied with those without any such application, they found varying levels of trace gas fluxes. Furthermore, the levels of CH_4 increased universally when prosulfuron was applied. Moreover, the application of metolachlor did not significantly impact CO_2 emissions, with crops that received the application exhibiting similar results to those that did not receive the application. On the other hand, the levels of N_2O emissions were different following the application of prosulfuron in plots with and without tillage. The use of herbicides in combination affects emission levels differently. A study by Das et al. [74] showed that a combination of pretilachlor and bensulfuron-methyl increased methane and N_2O levels. In contrast, the separate application of the two herbicides decreased the emission levels.

Apart from the use of herbicides in isolation or combination, other factors affect the levels of CO_2 emissions. It is important to understand this complex relationship by identifying the relevant contextual or environmental factors. Climate differences, soil composition, and agricultural practices vary from one region to another and invariably affect emission levels [71,75–77]. Another area of concern identified in the research is the tendency to generalise findings from one region or crop to others without considering the similarities and differences in contextual factors [73,78]. Kyaw and Toyota [79] explain how the same herbicide can produce different outcomes depending on its application. Therefore, complete awareness of how herbicides interact with soil chemistry, the environment, and other herbicides being applied in combination is vital for understanding their impact on CO_2 emissions.

Safa and Samarasinghe [67] assessed the association of CO_2 emissions with various agricultural inputs commonly used for wheat production. The factors assessed in the study included fertilisers, crop-protection products, electricity, machinery, and fuel used in irrigated and dry farmlands. Notably, crop protection products, including herbicides, resulted in the lowest CO_2 emissions into the atmosphere [20].

4.6. Effect of Biochar Modification and Pyrolysis

Chen et al. [80] created a new type of biochar called iron-modified base-activated biochar (FeBBC) by treating sugarcane bagasse with iron and a base. They then tested this FeBBC for its ability to remove the insecticide imidacloprid (IMI) from water. Testing of FeBBC showed it contained more carbon and less oxygen than regular biochar without iron added. Microscopic analysis of FeBBC confirmed that it contained iron particles. Experiments where FeBBC was mixed with water containing IMI revealed that it could remove up to 92% of the IMI. Testing suggested the maximum amount of IMI that FeBBC could hold was approximately 10 mg per g. The amount of IMI removed depended on factors such as FeBBC use, initial IMI concentration, and water pH. Both physical and chemical bonding of IMI to FeBBC were involved. Kinetic studies indicated that both surface adsorption and absorption occurred, with the rate being limited by how fast the IMI could enter the inner pores of the FeBBC particles. Characterisation pointed to IMI binding mainly through hydrophobic interactions, with some ionic binding and pore filling also playing a role [80].

According to Hassan et al. [81], the pyrolysis temperature and biomass type used to make biochar significantly impact its properties. As the temperature increases, the carbon content, pH, ash content, surface area, and stability generally increase, while the hydrogen content, oxygen content, H/C ratio, and O/C ratio usually decrease. Different biomass sources react differently to pyrolysis conditions due to variations in cellulose, hemicellulose, lignin, and mineral composition. Biochar from manure and grass tends to have more oxygen-containing functional groups than wood sources.

Hardwood biochar typically has the largest surface area, followed by softwood, grass, and manure biochar. Manure biochar also tends to have the highest ash content [81]. Biochar produced at lower temperatures (<300 °C) is better suited for removing ionic contaminants because of the stronger electrostatic forces, ion exchange, and more oxygen functional groups. Biochar produced at higher temperatures (>500 °C) is more appropriate for organic contaminants due to the increased hydrophobicity, pore space, and aromatic carbon structure [81].

Mineral components in biochar also affect its properties and ability to adsorb contaminants. For example, silicon-rich biochar can incorporate silicon into stable crystal structures that help bind and precipitate contaminants. Metals such as iron may provide catalytic or magnetic attributes. No single biomass source or pyrolysis setting is optimal; thus, the properties must match the target contaminant. Research has provided relationships to help choose a suitable biochar configuration for different remediation applications [81].

In conclusion, herbicides have improved agricultural yields and supported the global food supply. However, overreliance on herbicides also brings risks, such as herbicide-resistant weeds and environmental contamination. Sustainable agriculture requires balanced weed management strategies. Minimising herbicide use through alternative practices like mechanical removal or precision application can reduce environmental impacts while maintaining productivity.

Herbicide use has complex and varying impacts on carbon dioxide and greenhouse gas emissions. While some herbicides have been shown to reduce short-term CO_2 emissions from soils, others can disrupt microbial activity and soil carbon cycling in a way that increases long-term emissions. The type of herbicide, application rate, crop type, and local environmental conditions all influence the emission outcomes. Low to moderate herbicide doses tend to have more temporary and negligible effects, but high doses risk permanently altering soil biology (Table 4).

Table 4. Impact of Various Herbicides on CO_2 and CH_4 Emissions.

Herbicide	CO_2 Impact	CH_4 Impact	Reference
Glyphosate	Temporarily inhibits soil CO_2 emissions at low doses.	No significant impact on CO_2 or CH_4 emissions from citrus plants.	[66]
Butachlor	Increases soil CO_2 emissions.	Reduced CH_4 emissions by 20% in flooded rice fields.	[65]
24-D	Reduces CO_2 emissions temporarily at low doses but increases long-term emissions at high doses.	-	[66]
Atrazine	Lower doses reduce CO_2 emissions by supporting normal microbial decomposition rates.	-	[68]
Prosulfuron	No effect on CO_2 emissions.	Increases CH_4 consumption by 1300% in fertilised grasslands. Increases N_2O emissions by up to 1600%.	[72]
Pretilachlor and Bensulfuron-Methyl	Increased both CH_4 and N_2O emissions when applied together.	Increased CH_4 emissions when combined. Increased N_2O emissions.	[74]
Figaro	Reduced soil CO_2 emissions.	-	[2]
Roundup 360 SL	Contributing 5% of total CO_2 emissions from agricultural inputs.	-	[67]

5. Influence of Tillage Systems on Carbon Dioxide Emissions

Several studies have explored the effects of different tillage methods on soil CO_2 emissions. Amami et al. [82] explored the effects of different tillage depths in a semiarid region of Tunisia (Africa) while considering the NT area and shallow (9 cm), medium (14 cm), and deep (25 cm) tillage depths. CO_2 emissions increased rapidly within 24 h of tillage application based on the intensity of tillage, which ranged from NT to deep tillage. Conversely, the bulk density demonstrated an inverse relationship with the tillage depth, with the highest densities noted for NT. A strong negative correlation was observed between CO_2 emissions and bulk density. Accordingly, the NT area exhibited decreased CO_2 emissions and elevated bulk density compared to the areas with deep tillage, indicating its potential as a mitigation strategy against CO_2 release in semi-arid environmental conditions.

In another study, Mozammel et al. [83] evaluated the effects of conventional tillage (CT) and strip tillage on GHG emissions and soil organic carbon levels in a rice-mustard-rice cropping system in Bangladesh. Strip tillage resulted in a 24% increase in soil-based CO_2 respiration compared with CT and increased absorption of net ecosystem CO_2 by 8%. Moreover, although strip tillage yielded higher soil CO_2 output, it decreased other GHG emissions, with methane emission factors reduced by 24–47% and methane fluxes lowered by 20–32% compared to those observed for CT. For the mustard crop alone, relative to CT, strip tillage demonstrated more pronounced effects and reduced the GHGI by 55–61% and global warming potential (GWP) by 52–58%. Therefore, while strip tillage slightly elevated the release of soil CO_2, it mitigated additional GHGs and enhanced the net carbon sequestration in the ecosystem. These findings confirm that despite increasing the CO_2 respiration in the soil, strip tillage can promote net carbon sequestration, especially in mustard plantations.

Reicosky and Lindstrom [84] discovered notable differences in short-term CO_2 release between various fall-tillage methods based on experiments with four methods using standard tillage equipment after a wheat crop harvest: mouldboard plough, mouldboard plough with a disk harrow twice, disk harrow, and chisel plough. The mouldboard plough-only method exhibited the greatest CO_2 loss, approximately 55–60% higher than the other methods. Furthermore, the CO_2 release rates peaked within the first 24 h of tillage, indicating that the most significant immediate impact on soil CO_2 release occurred immediately after tillage. Similarly, Scala et al. [85] reported that CT performed with a mouldboard plough offset disk harrow and chisel ploughing resulted in the highest soil CO_2 emissions during the majority of the study period, excluding the period immediately after tillage, with the reduced tillage producing the largest emissions. This study highlights the fact that the impact of tillage on soil CO_2 emissions varies over time, with soil moisture playing a significant role in controlling emissions. Tillage depth also plays a crucial role in determining the amount of CO_2 emitted from the soil. The deeper the mouldboard ploughing, the greater the CO_2 loss from the soil [86].

A long-term field study conducted by Wang et al. [9] from 2007 to 2019 compared NT, subsoil tillage, and mouldboard ploughing in a farming system wherein crop residues were returned to the soil and measured the CO_2 fluxes in the soils that received different tillage treatments. Based on the principal findings regarding CO_2 emissions, NT and subsoil tillage demonstrated smaller fluxes than mouldboard ploughing (over a two-year average). Notably, NT reduced the average CO_2 flux by 14.5% compared to the CO_2 flux after mouldboard ploughing. Subsoil tillage reduced the average flux by 8.5% compared to the CO_2 flux after mouldboard ploughing.

Mühlbachová et al. [87] recently conducted a field study in the Czech Republic to investigate the effects of different soil-preparation methods on the soil temperature, moisture, and CO_2 levels. Four different treatments were administered in the study. The treatments were implemented between 2020 and 2021 after harvesting wheat and barley. The four treatments included chiselling to 10–12 cm (depth), shallow chiselling to 5–6 cm and leaving straw mulch and straw+stubble residues on the surface. In 2020, chiselling to 10–12 cm resulted in significantly higher temperatures at up to 20 °C greater than that observed after other treatments. This treatment also resulted in significantly lower moisture content. The CO_2 emissions were approximately twice as high as those noted after other treatments. In 2021, the temperature differences among all treatments were minor due to lower air temperatures and more rain, with only the moisture level differing significantly between the deeply chiselled and other treatments. The CO_2 emissions did not vary significantly and remained low because of the cooler soil and high moisture from rainfall. The study concluded that the tillage depth and amount of straw residue left behind directly influenced soil CO_2 emissions. Deeper tillage and less straw residue contributed to higher temperatures, lower moisture levels, and more significant CO_2 emissions. This effect was particularly pronounced in warmer and drier conditions.

According to Halvorson and Del Grosso [88], the plant species within the rotation in northeastern Colorado affect the soil CO_2 emissions in the region. Barley (maize-barley rotation) emits a higher annual cumulative CO_2 flux than maize (continuous maize) and dry beans (maize-dry bean rotation). The quantity and quality of the decaying residues from the preceding crops accounted for the variations in the cumulative CO_2 flux.

Similarly, Nyambo et al. [89] examined the effects of tillage, crop rotation, and residue handling on the soil CO_2 flux. Tilling increased the flux by 26.3% compared with that observed in the case of NT, whereas residue removal resulted in lower fluxes than those noted after straw retention or biochar addition. The CO_2 fluxes were higher in summer than in winter. Therefore, NT and residue removal were considered the most effective methods for reducing soil CO_2 emissions.

The findings of another study by Cillis et al. [14] indicated that conservation tillage methods, such as minimum tillage and NT, can reduce GHG emissions more effectively than traditional methods. The System Approach to Land Use Sustainability (SALUS) simulation model demonstrated that minimum tillage could reduce soil organic-carbon loss by 17%, and NT can reduce the loss by 63% (over 15 years). Conservation tillage techniques, especially in combination with precision agriculture strategies, can decrease the carbon emissions from farming tasks and reduce the total CO_2 emissions by 56% compared with CT.

Bilandžija et al. [90] observed reduced soil CO_2 emissions when conservation tillage practices were employed compared with that after conventional methods. These findings were supported by Bilandžija et al. [91] in their evaluation of the impact of tillage systems on short-term soil CO_2 emissions and microclimate. Similarly, in a study on the Loess Plateau, Lu et al. [92] noted significantly higher soil CO_2 emissions after CT than after NT. De Araújo Santos et al. [93] observed that long-term NT systems with various crop sequences demonstrated varying impacts on soil CO_2 emissions. The study also revealed that the primary determinants of soil CO_2 emissions are soil temperature, moisture content, and organic matter concentration.

The effect of variations in local climate and tillage techniques on CO_2 emissions has been investigated by various researchers. In an earlier study, Al-Kaisi and Yin [94] argued that NT practices increased the capacity of the soil to store carbon, thereby reducing the levels of CO_2 that were released into the atmosphere. Supporting these findings, Ussiri and Lal [95] concluded that reduced CO_2 emissions were produced in soils that were not subjected to tillage. Additionally, these soils also had higher organic matter content. These findings were verified in later studies. For example, Kristof et al. [96] linked CO_2 emissions directly with the intensity of tillage practices, with NT producing the lowest emissions. A study by Mohammed et al. [97] showed that NT resulted in the greatest reduction in CO_2 emissions when compared with conventional methods. However, the study was conducted only with maize-growing soils. Another study conducted in sugarcane soils indicated that the levels of CO_2 emissions were invariably linked with the tillage techniques employed [98]. In a related study, minimal tillage was found to be associated with higher soil organic content [99].

Tillage practices alone are not the sole determinant of CO_2 emissions, and a host of other variables influence this relationship. Several studies have elaborated on the impact of soil properties, precipitation and temperature as mediating factors. An earlier study suggested that CO_2 emission levels are greatly affected by the organic content of the soil, with NT systems yielding fewer organic matter stocks than CT systems [100]. As a mediating factor, humidity levels, through their impact on nitrogen fertilisation, affect the outcomes of NT practices. Incorporating these factors into determining tillage practices is necessary to reduce CO_2 emissions significantly and sustainably [101]. A matter of concern has been whether pursuing lower CO_2 emissions through minimal tillage can negatively impact crop yields. However, a study by Shakoor et al. [102] demonstrated that these concerns were baseless. Their findings show NT practices do not result in lower crop yields despite significantly reducing CO_2 emissions. In contrast, lower soil moisture levels and high temperatures can diminish the positive impact of NT methods [103]. Other factors that are known to affect NT outcomes on CO_2 emissions include air pressure, groundwater levels, and soil chemistry [104,105]. Due to these multiple factors, NT practices might result in higher CO_2 emissions or less impressive reductions than expected. Therefore, all these factors should be considered when modifying tillage techniques. Muhlbachova et al. [106] suggested that the same methods could yield different results over time due to climatic changes from one year to the next under NT and reduced-tillage systems.

Investigations on soil CO_2 emissions under different tillage treatments produced widely varying results based on geography, soil type, and conditions. Considering these factors, Abdalla et al. [107] conducted a meta-analysis of 42 studies conducted across different regions and soil types and found that tilled soils emitted 21% more CO_2 than untilled soils. This difference increased to 29% in sandy soils in dry climates in areas with low organic-carbon contents and soil moisture levels but exhibited no impact on the CO_2 emissions in clayey soils with high organic-carbon content.

The findings of the above studies suggest the positive effects of tillage techniques on lowering soil CO_2 emissions and helping to slow down climate change effects in the long run. Specific techniques recommended in these studies, including minimum tillage to NT, may lead to higher emissions than CT. Factors such as reduced soil organic carbon content and diminished accumulation of organic matter in the soil could be a common reason for this.

Several climatic factors and other geographical differences influence the effectiveness of tillage systems in reducing CO_2 emissions. However, reliable data linking these variables to tillage effects is lacking, which increases the difficulty of providing universal agricultural recommendations. The long-term effects of different tillage methods on soil organic matter and carbon storage are not fully understood.

In conclusion, this section highlighted the complex relationships among tillage systems, soil properties, and CO_2 emissions. The depth and intensity of tillage generally correlate with higher short-term CO_2 fluxes, as seen with conventional ploughing compared to reduced tillage or NT. However, soil texture, organic matter, temperature, moisture, and crop residues also significantly influence emissions. Additionally, the effects of tillage may differ over both the short and long term. While reduced tillage and NT often reduce short-term fluxes, CT can increase soil carbon stocks with continued use. More research is still needed to understand these relationships under varying climates and farming systems fully. Overall, conservation tillage practices that minimise soil disturbance while maintaining crop residues appear promising for mitigating agriculture's contribution to climate change through decreased CO_2 emissions. However, local soil and climatic conditions must also be considered to develop sustainable and effective tillage management plans (Table 5).

Table 5. Effects of Different Tillage Methods on Greenhouse Gas Emissions.

Tillage Methods	Effect on CO_2 Emissions	Effect on Other GHGs	Reference
NT, shallow, medium, and deep tillage	CO_2 emissions increased with tillage depth. NT had lower emissions.		[82]
CT vs. Strip tillage	Strip tillage increased soil CO_2 by 24%.	Reduced methane emissions by 24–47% and methane flux by 20–32%.	[83]
Mouldboard plough, chisel plough, disk harrow	Mouldboard plough had the highest CO_2 loss (55–60% higher).		[84]
NT, subsoiling, mouldboard plough	NT reduced CO_2 flux by 14.5%, subsoiling by 8.5%, compared to plough.		[9]
Chiselling (deep, shallow), straw residues	Deep chiselling doubled CO_2 emissions compared to other treatments.		[87]
Maize-barley vs. maise-dry bean rotations	Barley rotation emitted higher cumulative CO_2 flux than maise.		[88]
Tillage, crop rotation, residue handling	Tilling increased CO_2 flux by 26.3%.		[89]
Conservation tillage (NT, minimum tillage)	NT reduced CO_2 emissions by 63%; minimum tillage reduced by 17%.		[14]

CT, conventional tillage; NT, no tillage.

6. Implications of Nitrogen Fertiliser Usage on Carbon Dioxide Emissions

The impact of fertiliser use on CO_2 emissions from soil and agricultural productivity has been analysed by various researchers. Wang et al. [108] investigated the effects of various fertilisers on soil CO_2 emissions in semi-arid fields in China based on the results of a nine-year investigation. All fertiliser treatments included equal amounts of nitrogen (200 kg/ha), and two types of nitrogen fertilisers were used: chemical (urea) (with 46% nitrogen content) and organic (cow manure) (with 3.3% nitrogen, 1.0% phosphorus, and 0.7% potassium). Maise straw was used as a fertiliser (with 0.7% nitrogen, 0.4% phosphorus, and 0.5% potassium). The findings indicated that all fertiliser treatments significantly increased CO_2 emissions from the soil compared with the control group. Among all the treatments, those that incorporated maize straw demonstrated the highest increase in emissions. Akhtar et al. [109] conducted a study in the arid and semi-arid regions of northern China with a focus on the use of straw mulching (4500 and 9000 kg/ha) combined with inorganic nitrogen fertiliser (192 and 240 kg/ha). They concluded that this combination reduced the soil CO_2 emissions and improved the wheat yield. The positive outcomes were attributed to the conservation of soil moisture and the enhancement of microbial activities in the soil. However, Zhai et al. [110] explored the long-term effects of mineral fertilisers and organic manure on the soil N_2O and CO_2 emissions for a maize-wheat rotation in China. Urea and manure were used as nitrogen fertilisers (300 kg N/ha), superphosphate was used as a phosphorus fertiliser (53 kg P/ha), and potassium chloride (KCl) was used as a potassium fertiliser (100 kg K/ha). The manure had a nitrogen content of 16.7 g/kg (dry weight). The findings demonstrated that using mineral fertilisers had a negligible impact on soil CO_2 emissions compared to the control group, which had no treatment. The study suggested that mineral fertilisers and high organic-manure input had a limited influence on the soil CO_2 emissions in the cropping system.

Shao et al. [111] conducted a two-year field experiment to examine the effects of various nitrogen fertiliser application rates on soil CO_2 emissions in a winter wheat field. Different nitrogen fertilisers were applied as urea $CO\ (NH_2)_2$ at 0, 90, 180, and 360 kg N/ha. The findings demonstrated that high rates of nitrogen-based fertilisers were associated with higher CO_2 emissions. In a corn-soybean rotation system, Al-Kaisi [112] examined the short-term effects of various rates of nitrogen fertilizer application (0, 90, 180, and 225 kg/ha) using ammonium nitrate (NH_4NO_3). The findings revealed that the intense application of nitrogen-based fertilisers leads to increased microbial activity and higher CO_2 emissions during the growing season due to improved plant growth and root biomass. Sainju et al. [113] investigated the effects of different cropping systems and nitrogen fertilisation rates on soil carbon content and CO_2 emissions. The study findings suggested that soil CO_2 emissions may be affected by varying nitrogen application rates, which can impact plant growth and soil microbial activity.

Cheng-Fang et al. [114] conducted a study in central China to investigate the impacts of tillage and nitrogen fertilisers on the soil CH_4 and CO_2 emissions and soil organic content (SOC) levels in paddy fields. The study used two levels of nitrogen (0 and 210 kg/ha) in urea, with a nitrogen content of 46%. The results demonstrated a significant increase in the CH_4 and CO_2 emissions and a decrease in the SOC content after nitrogen fertilisation, which led to increased microbial activity and organic matter decomposition. Similarly, Jiang et al. [115] demonstrated that using fertilisers with different nitrogen compositions, ranging from 0 kg N/ha to 375 kg N/ha, in the form of urea (46.0% N) on rice production's carbon footprint and sequestration potential. The study revealed a significant relationship between the nitrogen application rate and soil CO_2 emissions, with higher nitrogen levels leading to increased CO_2 emissions and reduced carbon sequestration. Zhang et al. [116] examined the effects of different fertiliser regimes on the soil CO_2 and N_2O emissions in the upland red-soil region of southern China. All fertiliser treatments were administered with an equal dose of nitrogen (300 kg/ha/yr) as urea. They reported that excessive nitrogen application invariably resulted in higher CO_2 emission rates. In a recent study, Saeed et al. [117] investigated the effects of increased nitrogen input on the GHG emissions and carbon footprints of cropping systems in Northwest China. The fertilisers used included urea, single superphosphate, potassium sulfate (46% N), single superphosphate (12–16% P_2O_5), and potassium sulfate (50% K_2O). Several studies indicate that increasing the nitrogen input leads to higher total GHG emissions and an increased carbon footprint. This emphasises the critical role of nitrogen management in maintaining environmental sustainability.

Wilson et al. [118] suggested that an optimal level of nitrogen fertilisation should be applied to other supportive practices, such as crop rotation, to maintain CO_2 fluxes more sustainably. The study evaluated the effects of three various rates of N fertilizer application—0, 135, and 270 kg N/ha—on plant growth and soil respiration. The results ensured that nitrogen fertilisers promoted plant growth and increased soil microbial biomass, enhancing soil respiration and more CO_2 emissions.

A study by Sosulski et al. [119] differentiated between administering NH_4NO_3 to the soil via deep placement and topdressing. In the absence of a crop cover, when ammonium nitrate was applied to the soil with the 1 g N per pot dose, which is equal to 263.158 kg/ha, a significant increase in N_2O emissions was reported. Between the two fertiliser management approaches, topdressing caused higher CO_2 emissions compared with deep placement. However, factors such as moisture content, temperature, and deep placement resulted in higher emissions of CO_2 from the soil than topdressing.

Based on current data, the use of synthetic fertilisers is a significant source of GHG emissions. As seen in Table 6, different regions experience varying GHG emissions levels, depending on their use of synthetic fertilisers. These figures reveal the urgent need for developing sustainable approaches to soil fertilisation without harming the environment.

Table 6. Consumption of nitrogen through synthetic fertilisers and the greenhouse gas (GHG) emissions from synthetic fertilisers [120].

Region	**Nitrogen Consumption (Mt N)**	**Industry Emissions from Synthetic Nitrogen Fertiliser Production**		**Emissions from the Application of Synthetic Nitrogen in Agriculture**				**Total Emissions from Synthetic Nitrogen Fertilisers (Industry + Agriculture)**	
		Manufacturing (Mt CO_2)	**Transport (Mt CO_2)**	**Urea Application to Soils (Mt CO_2)**	**Direct N_2O Soil Emissions (in Mt CO_2-eq)**	**Indirect N_2O Soil Emissions from Volatilisation and Redeposition (in Mt CO_2-eq)**	**Indirect N_2O Emissions from Leaching (in Mt CO_2-eq)**	**Total Emissions (Mt CO_2-eq)**	**Share of Global Emissions (%)**
World	107.7	438.5 ± 37.1	29.8 ± 4.0	86.0 ± 39.1	379.9 ± 160.5	66.3 ± 11.3	130.1 ± 31.4	1129.1 ± 171.1	100
China	28.1	161.3 ± 30.1	11.1 ± 3.8	14.1 ± 6.4	73.3 ± 106.8	18.2 ± 8.8	38.1 ± 24.5	316.1 ± 113.3	28.0
India	17.6	52.8 ± 7.9	2.4 ± 0.7	23.5 ± 10.7	51.7 ± 53.3	11.5 ± 5.6	23.7 ± 15.6	165.5 ± 57.4	14.7
USA	11.6	40.2 ± 3.9	2.9 ± 0.7	7.5 ± 3.4	42.0 ± 51.6	7.5 ± 3.4	15.4 ± 10.0	115.5 ± 52.9	10.2
EU28	11.1	37.5 ± 3.4	1.6 ± 0.1	5.1 ± 2.3	35.9 ± 17.5	7.2 ± 1.1	14.9 ± 3.0	102.4 ± 17.6	9.1
Brazil	4.6	17.4 ± 1.2	2.2 ± 0.6	4.4 ± 2.0	33.2 ± 50.9	3.0 ± 1.5	6.1 ± 3.9	66.3 ± 51.2	5.9
Canada	2.8	8.5 ± 0.8	0.7 ± 0.2	2.7 ± 1.2	15.3 ± 54.5	1.8 ± 0.9	3.7 ± 2.4	32.8 ± 54.5	2.9
Pakistan	3.4	10.6 ± 1.6	0.5 ± 0.2	4.7 ± 2.1	10.4 ± 11.8	1.1 ± 0.9	0	27.0 ± 11.1	2.4
Mexico	1.3	4.3 ± 0.3	0.6 ± 0.1	1.1 ± 0.5	13.5 ± 20.9	0.9 ± 0.4	1.8 ± 1.2	21.8 ± 17.5	1.9
Indonesia	3.2	11.5 ± 1.7	0.8 ± 0.2	3.8 ± 1.7	15.8 ± 39.4	2.1 ± 1.0	4.4 ± 2.8	21.8 ± 17.5	1.9
France	2.2	7.2 ± 0.8	0.3 ± 0.1	1.4 ± 0.6	7.2 ± 7.2	1.5 ± 0.7	3.0 ± 1.9	20.5 ± 7.6	1.8

United States of America (USA); European Union (EU28).

Nitrogen-based fertilisers also change the soil chemistry. A study by Yu et al. [121] showed that these fertilisers reduce soil pH and thus increase soil acidity. Over time, this can negatively affect the productivity of the soil. At the same time, the level of CO_2 emissions increases, with more severe cases in soils where carbon levels are already depleted. The change in pH was less severe in carbon-rich soils, and the CO_2 emission rate was also slower than that in carbon-poor soils. This shows that the impact of nitrogen-based fertilisers differed according to the soil composition. Another study by Hangs et al. [122] showed that the effect was temporary rather than long-term. The researchers showed that different nitrogen application rates (0–120 kg N/ha) and two types of nitrogen granules, namely urea (46% N) and NH_4 phosphate (11% N), led to significant CO_2 emissions in the short term but insignificant changes in after 30 days. Enhanced-efficiency nitrogen fertilisers (EENFs) have been developed in response to these concerns. Yang et al. [123] reported that these fertilisers have positive effects and showed that overall GHG emissions changed with applying EENFs. The study focused on improving management practices to minimise environmental impacts while enhancing nutrient utilisation.

Specific conditions result in more positive outcomes for nitrogen-fertilised soils. A study conducted in eastern Canada by Gagnon et al. [124] used laboratory incubation and field experiments to assess the impact of nitrogen fertilisation on soil CO_2 emissions. The study examined the effects of adding either KNO_3 or $(NH_4)_2SO_4$ at a rate of 150 kg N/ha to nine different soil types. The results demonstrated that nitrogen-fertilised soils produced lower levels of CO_2 emissions under certain conditions. Notably, applying KNO_3 resulted in an average decrease in CO_2 emissions of 22% compared with that of $(NH_4)_2SO_4$. However, when examining clay soil, the field experiments demonstrated significantly higher cumulative seasonal CO_2 emissions in the control plots than those noted in the plots treated with nitrogen. This suggests that nitrogen sources and rates should be optimised to mitigate soil CO_2 emissions while maintaining crop productivity. According to another study by Kong et al. [125], not applying any fertiliser had the most negative effect compared to traditional fertilisers. They investigated the influence of different nitrogen-fertiliser management practices on soil CO_2 emissions in north-central China. Three different nitrogen fertiliser treatments were tested in their study: a traditionally used rate of 300 kg/ha, an optimised rate of 0.8 kg/ha, and no fertiliser. The results demonstrated that the highest levels of CO_2 emissions were observed when no fertilisers were applied, whereas lower levels were observed when 300 kg/ha of nitrogen-based fertilisers were applied. However, the best outcome was reported with the application of 0.8 kg/ha of fertiliser treatment, which resulted in the lowest levels of CO_2 emissions. Therefore, a moderate approach to using nitrogen-based fertilisers can have the optimum results in lowering CO_2 emissions from the soil.

Using nitrogen fertilisers in combination has different impacts on soil CO_2 emissions. The impact can be positive or negative depending on different factors, such as the amount of fertiliser used, type of nitrogen, type of soil, crop being grown, timing of application, and duration of the study.

The results presented in this section demonstrated that nitrogen fertiliser use can both increase and decrease soil CO_2 emissions depending on the application rate, source, timing, placement, crop conditions, and soil characteristics. Generally, higher nitrogen application rates tend to increase short-term emissions by boosting microbial activity and organic matter decomposition. However, moderate optimised rates that meet crop needs without excess application can help reduce emissions versus no fertilisation. Moreover, deep placement rather than surface application and pairing fertilisers with practices such as straw mulching and crop rotation can also help lower emissions. Soil conditions such as texture, pH, and carbon levels influence the fertiliser effects. Overall, judicious nitrogen management through optimised rates, efficient sources, and placement and integrated soil health practices provide an opportunity to minimise agriculture's carbon footprint while maintaining productivity (Table 7).

Table 7. Carbon and Greenhouse Gas Dynamics in Response to Different Fertilizers and Application Rates.

Fertiliser Type and Rate	Key Findings for CO_2 Emissions	Impact on Other GHGs (e.g., N_2O, CH_4)	Reference
Urea (46% N), Cow Manure (200 kg/ha)	All treatments increased CO_2 emissions, with maise straw causing the highest increase.		[108]
Straw Mulching + Inorganic N (192–240 kg/ha)	Reduced soil CO_2 emissions due to improved soil moisture and microbial activity.		[109]
Urea + Manure (300 kg N/ha)	Mineral fertilisers have a negligible impact on CO_2 emissions.	Increased N_2O emissions in the cropping system.	[110]
Urea (0–360 kg N/ha)	Higher nitrogen rates resulted in increased CO_2 emissions.		[111]
Urea (0–210 kg N/ha)	Significant increase in CO_2 and CH_4 emissions, reduced soil organic carbon (SOC).	Significant increase in CH_4 emissions.	[114]
Urea (0–375 kg N/ha)	Higher nitrogen rates led to increased CO_2 emissions and reduced carbon sequestration.		[115]
Urea + Superphosphate + Potassium Sulfate	Increased nitrogen input led to higher total GHG emissions and carbon footprint.	Increased total GHG emissions (including N_2O and CH_4).	[117]
Ammonium Nitrate (263 kg N/ha)	Topdressing caused higher CO_2 emissions than deep placement.	Increased N_2O emissions from ammonium nitrate application.	[119]
KNO_3 (150 kg N/ha)	KNO_3 application reduced CO_2 emissions by 22% compared to $(NH_4)_2SO_4$.		[124]
Optimised Nitrogen Rate (0.8 kg N/ha)	Lowest CO_2 emissions observed with optimised nitrogen usage.		[125]

7. Conclusions

This review deepens our current understanding of how various agricultural practices, particularly herbicide usage, tillage systems, and nitrogen fertilisation, influence soil CO_2 emissions. Furthermore, the correlation between land management (concerning soil moisture, temperature, and the type of crop residue) and soil CO_2 emissions highlights the significant impact of these factors on CO_2 emissions from agricultural systems. The detailed analysis of various herbicides and different tillage practices on CO_2 emissions demonstrates that the soil response varied significantly while repeatedly crossing the threshold for soil CO_2 mitigation, indicating an inconsistent rate of CO_2 emission reduction.

Herbicides influence soil microbiota and CO_2 differently depending on their type, dose, and crop system. This emphasises the importance of herbicide application strategies that consider the effectiveness of weed management and the environmental benefits of minimising CO_2 production. Similarly, tillage affects the soil, impacts carbon dynamics, and often increases CO_2 emissions. However, a few studies demonstrated contradictory results regarding soil CO_2 emissions under NT, which exhibited increased CO_2 emissions in the soil under specific climate conditions. Fertilisers present similar dynamics and may promote crop growth or cause harm depending on the application rate and soil type.

Although several studies have analysed the effect of herbicides on CH_4 and N_2O emissions, the same cannot be said about their impact on soil CO_2 emissions. Therefore, comprehensive studies must be performed to provide a complete understanding of all the GHGs emitted into the atmosphere due to herbicide usage to support sustainable agricultural practices with minimal or no implications for the climate.

The relationship between soil CO_2 emissions and tillage techniques is multifaceted and complex. Further studies on the impact of various tillage techniques on CO_2 emissions need to be conducted to understand better how these practices impact microbial activity and carbon levels. Bridging these knowledge gaps may develop more sustainable agricultural practices.

Further investigations are required to compare deep fertiliser placement with surface application, which leads to higher emissions. The impact of nitrogen fertilisers on soil CO_2 emissions varies depending on different factors, such as the fertiliser type and amount, soil type, crop growth, application timing, and study duration. More extensive data are required to understand the impact of nitrogen fertilisation on soil CO_2 emissions in different regions and cropping systems.

These observations highlight the broader impact of agricultural practices on environmental sustainability and climate change mitigation. Embracing integrated pest-management approaches, optimising nitrogen fertilisation, and adopting sustainable tillage practices are crucial for reducing agricultural CO_2 output. These strategies can reduce GHG emissions and improve the overall sustainability of agricultural practices worldwide. Further studies must analyse specific interactions between crops, soil systems, herbicides, and climate regions to develop tailored management practices that reduce GHG emissions and maximise agricultural output while refining and improving mitigation strategies.

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