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Review

Plant–Soil Microbe Interactions' Effects on CO_2 Emissions, Soil Organic Carbon and Nutrients Under Different Tillage Systems

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Abstract

Soil microbes are central to carbon and nutrient cycling; however, the influence of tillage practices on plant–soil microbe interactions, particularly their contribution to carbon stabilization under increasing atmospheric CO_2, remains insufficiently understood. This systematic review evaluated 238 studies published between 2010 and 2025 from Scopus, Web of Science (WoS), and Google Scholar, of which 113 met the inclusion criteria related to carbon dynamics, agro-climatic conditions, and soil–microbial processes. Evidence indicates that conventional plowing (CP) disrupts microbial structure, habitat, and function, resulting in lower soil organic carbon (SOC) stocks and elevated CO_2 emissions. Conversely, conservation tillage promotes rhizodeposition, microbial biomass carbon (MBC) accumulation, and enhanced nitrogen (N) and phosphorus (P) availability, thereby increasing SOC sequestration and reducing CO_2 emissions. Overall, insights from this study will enhance our understanding of beneficial microbes that enhance carbon stabilization and root exudate compounds, which trigger specifically needed nutrients in the rhizosphere.

Keywords: CO_2 emissions; soil organic carbon; nutrients; plant–soil microbe interactions; tillage

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1. Introduction

Greenhouse gases (GHGs), which consist of nitrous oxide (N_2O), methane (CH_4), water vapor, Ozone (O_3), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6), nitrogen trifluoride (NF_3), and carbon dioxide (CO_2), are highly significant in the sustainability of life on Earth. The agricultural sector emits more than 10% of the total GHGs worldwide every year [1]. Moreover, approximately 10% of the atmospheric CO_2 flux is estimated to pass through agricultural soils annually due to microbial and root respiration, chemical decomposition, and soil respiration. Soil microbes regulate carbon (C) cycling through soil organic matter (SOM) decomposition, controlling CO_2 fluxes between the soil and atmosphere while acting as key drivers of biogeochemical processes in the rhizosphere [2–5]. Rhizosphere microbes, including bacteria, fungi, actinomycetes, arbuscular mycorrhizal fungi (AMF), and protozoa, regulate the balance between soil respiration and C stabilization, enhancing plant stress tolerance, nutrient availability, water retention, and soil C sequestration [6,7]. The process of C cycling process is controlled by the trade-off between photosynthesis and respiration. Autotrophic organisms are responsible for the process of C-fixation from atmospheric CO_2 to organic C materials in the soil, and they are responsible for the annual net fixation of 7×10^{16} g of C [8]. The reverse happens during decomposition of organic materials in the soil, primarily by heterotrophic organisms, which consume and utilize C substrate as an energy source for their metabolism. Thereafter, heterotrophic organisms retain a portion of C in their biomass, while the rest is released as C deposits (metabolites) into the root zone or as CO_2 into the atmosphere [4].

Conversely, plant roots release diverse exudates that act as both nutrient sources and signaling compounds, attracting beneficial microbes and facilitating symbiotic interactions that enhance nutrient uptake [9–11]. These exudate-driven microbial associations regulate rhizosphere nutrient cycling, with AMF increasing phosphorus (P) availability and nitrogen-fixing microbes enhancing nitrogen (N) acquisition in response to plant demand [12]. However, soil disturbance caused by tillage practices such as conventional plowing (CP) can disrupt these interactions by breaking microbial hyphal networks and altering soil moisture and temperature regimes [1,13], thereby limiting microbial access to C and N and impairing C and nutrient cycling in the rhizosphere [14,15]. Tillage intensity fundamentally reshapes the rhizosphere by altering the distribution of root exudates and organic residues, which creates a concentrated nutrient zone in the upper soil profile under conservation practices. Mechanical disturbance physically severs fungal hyphal networks and destroys stable microhabitats, leading to a loss of microbial diversity and a shift toward stress-tolerant bacterial taxa. These modifications directly impact ecosystem services by stabilizing soil moisture and temperature, which ultimately enhances microbial C-use efficiency and the mineralization of essential nutrients like N and P [16]. Although tillage is known to influence root exudation, microbial network structure, and soil microhabitats, how these changes collectively regulate plant–microbe interactions is not yet fully understood. This knowledge gap is driven by pronounced variability in soil properties, local climate, cropping systems, and tillage regimes, compounded by differences in experimental approaches used to characterize rhizosphere processes and microbial activity. As a result, establishing consistent mechanistic links between tillage-induced disturbance, microbial dynamics, and soil C stabilization remains challenging.

Soil microbes obtain different forms of C from their environment solely to fulfil their key mandate, which is survival through reproduction [4]. The labile organic compounds, which are readily available substrates for microbes, have a high turnover rate due to the plant–soil microbe interactions [17]. Another study indicated that plant debris on the soil surface contains unstable organic C, which is readily available for microbial decomposition and utilization [18]. However, soil–atmosphere C cycling is strongly influenced by agroclimatic factors, including climate, soil type, temperature, pH, soil organic matter (SOM), and nutrient availability. The second factor consists of distal drivers, which are caused by human activities such as land use, land cover, organic amendments, and the use of fertilizers [1]. Studies show that soils under different tillage practices experience significant variations of organic C in the form of CO_2 emissions as a result of soil microbial activity interference and exposure to harsh environmental conditions. A study done by Buragienė et al. [19] indicated that deep tillage significantly increased CO_2 emissions up to seven times higher than the emissions under no-tillage. Contrary to these findings, Jia et al. [2] found no significant difference in the rates of soil CO_2 efflux between tillage practices, but the average annual CO_2 efflux under CP was 7.8% higher than in no-tillage ($p > 0.05$), with no significant difference between CP and ridge tillage. Lower

CO_2 efflux during the growing season under no-tillage and ridge tillage was associated with enhanced microbial respiration and microbial biomass carbon (MBC) accumulation in the upper soil layer under ridge tillage, suggesting potential benefits for increased soil organic carbon (SOC) stocks. Overall, these contrasting results highlight the complexity of soil CO_2 fluxes and the lack of a clear mechanistic explanation linking tillage practices to emission responses.

The function of soil as both a C source and sink depends entirely on land use changes, environmental factors, and management practices. Tradeoffs between C losses from autotrophic and heterotrophic respiration [17] and C gains through the addition of organic matter have led to changes in SOC. One of agriculture's main GHGs mitigation strategies is soil C sequestration, wherein crops remove CO_2 from the atmosphere during photosynthesis, and non-harvested residues and roots are converted to soil organic matter [20].

Environmental factors such as temperature and soil moisture play an important role in soil behavior [21], and the microbial activities influence CO_2 emissions and nutrient availability to a large extent [22]. However, these abiotic factors can be easily manipulated by anthropogenic activities to accelerate or reduce microbial activities, which influences nutrient availability and organic C from microbial biomass, rhizo-deposits, and litter in the soil [23], especially through appropriate tillage and soil amendment practices.

Plant–soil associated microbes, ranging from diverse taxa including bacteria, fungi, protozoa, actinomycetes, algae, and AMF, play pivotal roles in enhancing plant growth and development, nutrient uptake and cycling, plant tolerance against abiotic stresses, and reduction of CO_2 emissions [24]. However, their functions differ because fungal and bacterial communities respond differently to variations in abiotic changes. For instance, bacteria tend to be more sensitive to fluctuations in soil abiotic factors like moisture and temperature than the fungal community. The fungal community tends to lag due to its massive structure [25], which makes it better able to adapt than bacteria. In this regard, tillage practices that alter soil moisture content and temperature may have the capacity to change and interfere with microbial communities and habitats in the soil, thus affecting plant–soil microbe interactions within the rhizosphere. These changes in moisture and temperature as a result of tillage tend to have a crucial influence on both the nutrient and C cycling processes in the soil ecosystem.

Generally, the interaction between microbes and plants in soil has a great influence on carbon cycling. However, the emission and sequestration of CO_2 in the soil rely on both tillage practices and nutrient availability. The biotic and abiotic interactions within the root zone are very complex and dynamic, and this review highlights key elements towards understanding how the microbial interactions in the soil affect CO_2 emissions, SOC stocks, and nutrient availability under conventional (plowing) and conservational tillage practices. The output of this review would provide vital information for evaluating the significance of microbial interactions on C and nutrient cycling in the soil for agricultural sustainability and climate adaptation.

2. Materials and Methods

Data Collection and Synthesis

The literature of this review was collected from Scopus, Web of Science (WoS), and Google Scholar databases published between the years 2010 and 2025, and literature older than 2009 was excluded (Figure 1). The peer-reviewed publications were searched on 19th September 2025 using the following queries: "soil microbial interactions" OR "CO_2 emissions" OR "Carbon cycling" OR "tillage practices" OR "nutrient interactions and availability" OR "soil organic carbon" OR "root exudates". A total of 238 publications were retrieved, including reviews, articles, conference papers, and book chapters. The publications spanned multiple subject areas, with a primary focus on climate change mitigation, conservation agriculture, soil science, particularly soil health and biology. The 238 publication records were subjected to screening using predefined inclusion and exclusion criteria (Table 1). The studies were retained only if they explicitly analyzed (i) microbial-mediated CO_2 pathways, (ii) interactions between soil microbes and C dynamics, and/or (iii) the effects of tillage practices on CO_2 emissions, nutrient availability, and microbial processes in the soil. Publications not meeting these analytical criteria, as well as non-English language studies, were excluded. Following screening, 113 publications were selected for synthesis. The selected publications were thematically analyzed to find patterns and research gaps in sustainable soil management practices.

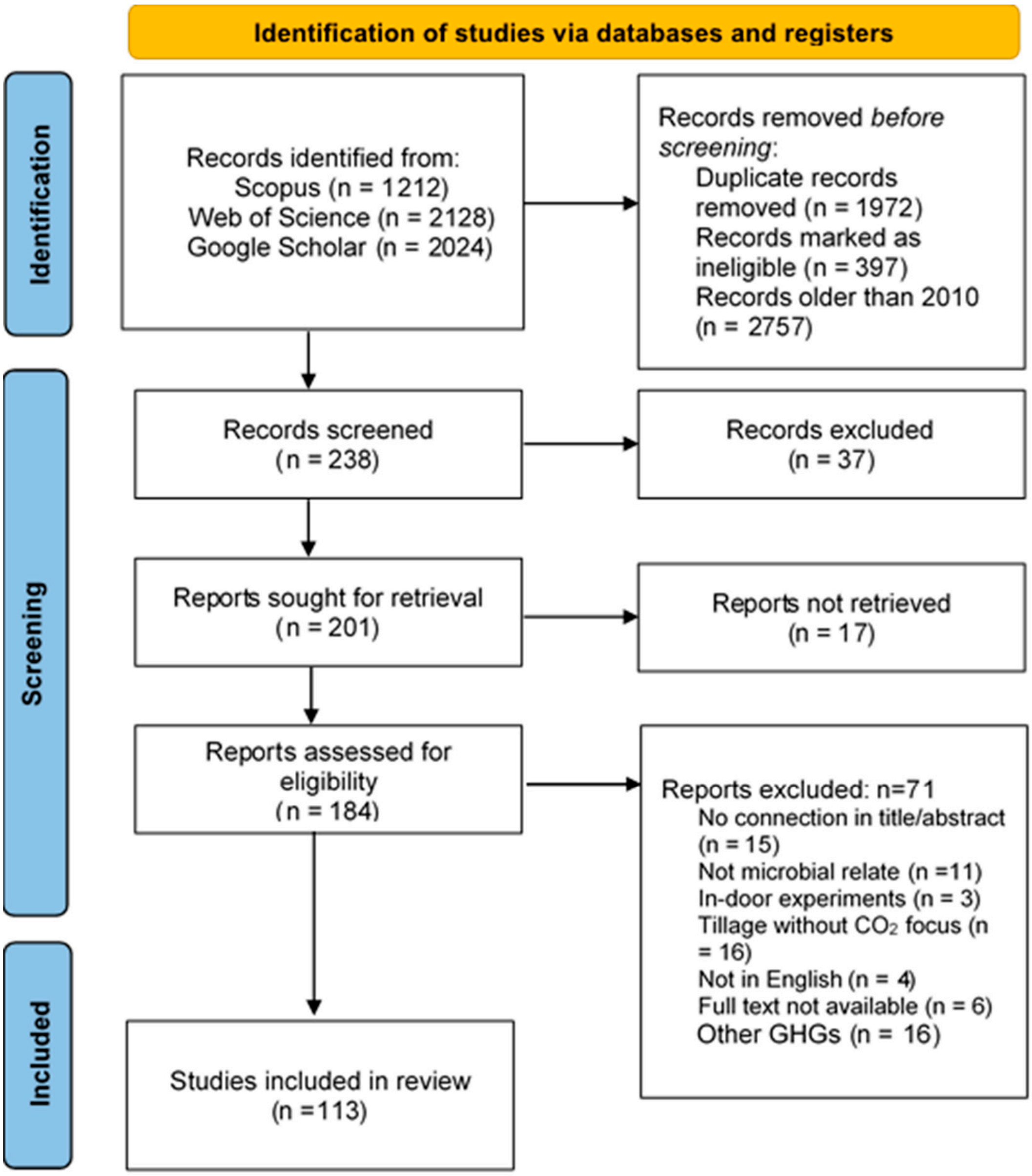

Figure 1. Flowchart summarizing literature screening and selection.

Table 1. Literature selection on inclusion and exclusion criteria.

Inclusion Criterion	Description	Exclusion Criterion	Description	No. of Excluded Studies
Analytical Scope of Microbial CO_2 Interactions	Explicit quantitative or qualitative analysis of soil microbial interactions (bacterial and/or fungal) directly linked to CO_2 emissions, C fluxes, or nutrient availability.	Not microbial interaction-focused	Studies that emphasize gas measurement methods, crop yield simulations, or agronomic performance metrics, but exclude microbial community profiling or functional analyses.	(n = 11)
Field-Scale Management Context	Field-based studies evaluating and comparing two or more tillage practices (e.g., no-tillage, reduced tillage, ridge tillage, and CP) within crop production systems.	Different practices	Small pot experiments, greenhouse production, or one type of tillage rather than the different tillage practices.	(n = 3)
Content evaluation	Analyzes soil microbial interactions influencing CO_2 emissions or C pathways in different tillage practices, nutrient regimes, and the agro-climatic factor conditions.	Irrelevant interactions and systems	Focuses on chemical fertilizations, vertical farming, pot experiments, or soil-less cultures.	(n = 15)
		General tillage practices	About soil tillage practices, land use, or tillage on bare soils without a focus on CO_2 emission.	(n = 16)
		Broader sustainability/ climate focus	About climate change adaptation, socio-economic adoption barriers, or trends, without a direct analysis of soil moisture and temperature under different tillage practices.	(n = 6)
		Other GHGs	Studies primarily address ammonium oxide or nitrous oxide rather than CO_2.	(n = 16)
		Non-English	Publications written in languages other than English.	(n = 4)

3. Plant-Microbe Interaction in the Rhizosphere

3.1. Mechanisms of Plant-Microbial Communications

Plants, animals, and microbes continuously respire, contributing to the atmospheric CO_2 emissions. While some C is stabilized as SOC, enhancing soil structure and fertility, much of it cycles rapidly through these biological processes (Figure 2), which are impacted by tillage to a considerable level. SOC is primarily sourced from plants, which influence the soil C turnover through photosynthesis [3]. The involvement of microbes in plant–soil activities offers significant benefits to soil C cycling through mineral formation, detritus food chain, and stabilization of C and soil structure.

Approximately 20–30% of total photosynthetically fixed C through root exudates is metabolized and incorporated by microorganisms. Studies have confirmed that the increasing rate of atmospheric CO_2 concentration leads to an increased rate of photosynthetic assimilation through the AM hyphae extension networks in the soil [3]. A symbiotic relationship exists where plant roots create a C sink in the soil as the host plant provides carbohydrates for the AMF, as plants lose approximately 4–20% of the C.

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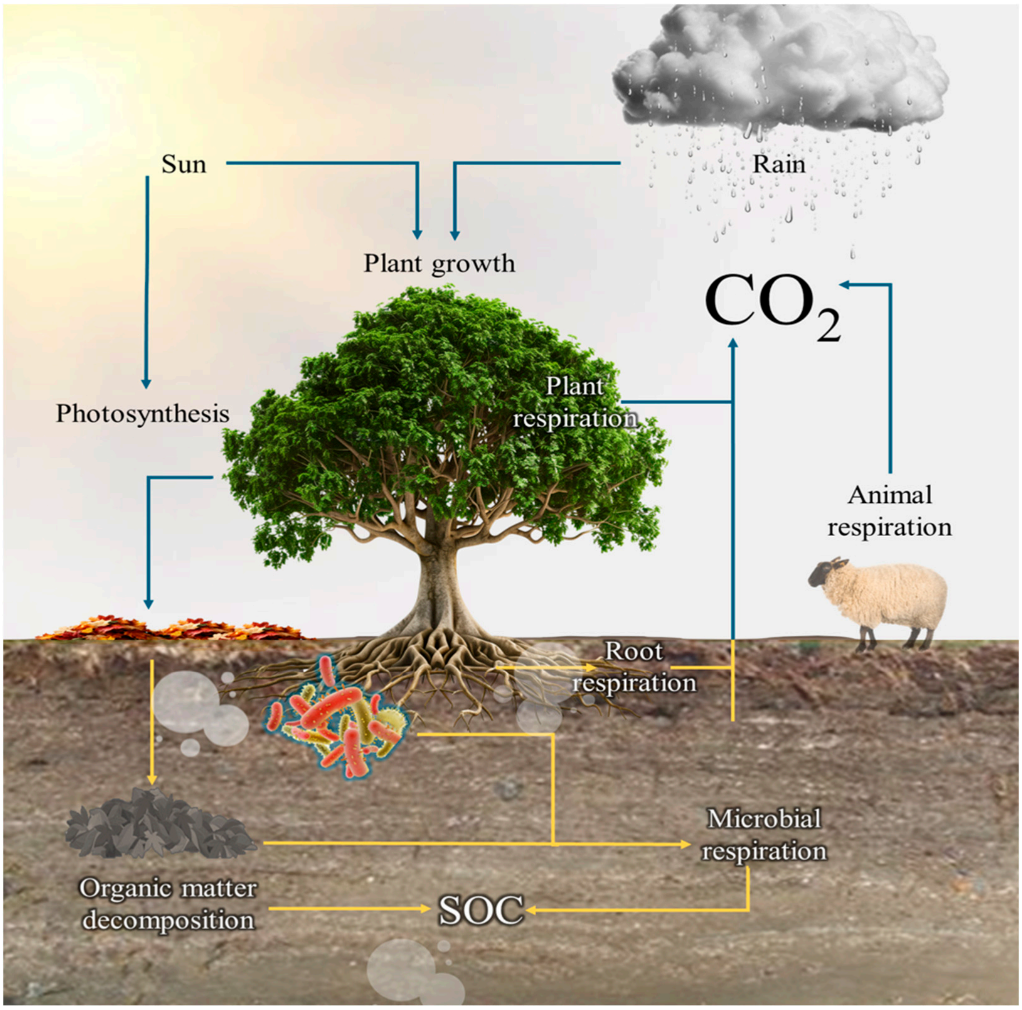

Figure 2. Carbon cycle within the soil-plant-atmosphere system. Through photosynthesis, plants assimilate CO_2 in the atmosphere and convert it into organic matter. A portion of this biomass enters the soil via plant residues, dead animals, and root exudates, undergoing microbial and chemical decomposition, which contributes to the formation of SOC. Concurrently, CO_2 is returned to the atmosphere through respiration by roots, soil microorganisms, animals, and plants (Source: Author).

The rhizosphere is full of roots and different types of macro and microorganisms. However, it is always enriched with root exudates, which attract a massive number of microbes and provide a conducive niche for their growth and C cycling [3]. The transfer of C from plant roots into the soil in the form of exudates leads to a large amount of C deposits or rhizodeposits. These exudates attract beneficial soil microbes, consequently improving the soil aggregates, structure, and population of the microbial community under conservation tillage, while on the other hand, these features are destroyed by CP [26]. The preserved microbial habitat increases the MBC in the soil due to the increased number of microbes.

3.2. The Role of Soil Microbes in Carbon Cycling

The beneficial microbes associated with plants in the rhizosphere have the potential to directly or indirectly shape the flow of C [27], and they are classified into three major categories, namely rhizospheric microbes, which include *Rhizobium*, *Pseudomonas*, and *Azospirillum* (they dwell in the soil surrounding plant roots), among others. Secondly, the epiphytic microbes (e.g., *Bacillus* and *Methylobacteria*) have been recorded to colonize the phyllosphere and roots, thus promoting plant growth, nutrient uptake, especially P, and increasing tolerance against environmental stresses [18,28]. Hence, the phyllospheric microbes indirectly play a big role in the accumulation of SOM on the soil surface, consequently decomposing to form SOC. Then endophytic microbes like *Enterobacter*, *Trichoderma*, and *Burkholderia* live inside plant tissues during all or part of their life cycle [29], alter the plant physiology, affecting the soil C cycle indirectly because they serve as chemical signals, thus stimulating plant growth [30]. For instance, endophytes can activate a plant's defense response against disease-causing microorganisms through a process known as induced systemic resistance [31], thereby leading to healthier plant growth and ultimately resulting in more C through roots and aboveground biomass [18]. Additionally, endophytes enhance the survival of plants against extreme conditions, indirectly leading to the continuous accumulation of organic C in the soil [32] after the death of plants. Rhizospheric microbes are major contributors to soil CO_2 efflux, mostly through SOM decomposition and utilization of root exudates, thus transforming it into MBC (Table 2). They have a direct impact on the soil C cycle by enhancing the solubilization of minerals, N fixation, and C sequestration, more so when soils are undisturbed for a long time.

The rhizospheric microbes are primarily involved in the extraction of atmospheric CO_2 through C sequestration, which sequentially increases SOC stocks [32]. C sequestration has been defined by Don et al. [33] as the removal of C from the atmosphere in the form of CO_2 and subsequently stored in the soil through plants. It has been argued by Lei et al. [34] that approximately 60% of rhizospheric CO_2 efflux is due to respiration of decomposing organisms, root exudation, and respiration. Similarly, the findings by Spohn et al. [35] suggest that SOC formed by microbes in the rhizosphere from CO_2 contributes to the soil C pool, due to high microbial detritus stability in the soil compared to plant detritus under conservation tillage practices.

On the contrary, epiphytes minimally contribute to C turnover, whereas endophytes indirectly influence rhizospheric microbial respiration and CO_2 efflux through boosting plant biomass and root activity [29]. Additionally, approximately 30% of the C from photosynthetic fixation is sequestered through root exudates as a result of microbial metabolism [3]. For instance, AMF plays a direct role in soil C cycling as an obligate symbiont by obtaining C from the host plant [4], while the facultative symbiont, like Ectomycorrhizal fungi, mineralizes the organic C by producing enzymes that oxidize the SOM [4,27]. The AMF hyphae transport photosynthates from plant roots into the undisturbed soil matrix. This process is made seamless through the generated arbuscules within their cells, which primarily serve as the nutrient exchange sites and eventually facilitate C cycling between plants and soils. During N fixation in leguminous plants, photosynthetic C is provided to the symbiotic N-fixing bacteria by plants. Other fungi, like ecto- and ericoid mycorrhizal, have been found to enhance soil C by approximately 70% more than the AMF due to their ability to enhance decomposition rates (Table 2). However, a reverse process facilitated by the microbes takes place through autotrophic and heterotrophic respiration, which releases the sequestered C back into the atmosphere [4]. This process characterizes a short-circuit of the soil C cycle, and it can be accelerated by CP if not managed well. Research confirms that the primary and heterotrophic respiration processes release more than 8% of the CO_2 into the atmosphere every year, especially under the CP.

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Table 2. Microbial contributions to soil organic carbon cycling.

Microbial Activity	Impact on Soil Organic Carbon	Key Microbial Members	References
Decomposition	Break down easily degradable organic matter, convert organic C into CO_2 through mineralization, and incorporate part of the C into their biomass.	*Bacillus* (*B. Bacillus licheniformis*, *subtilis*, *thermoamylovorans*, *hisashii*, *thermoruber*, *amyloliquefaciens SL-7*, *thermolactis*), *Ammoniibacillus* (*A. agariperforans*), *Pseudomonas* (*P. putida*, *P. fluorescens*), *Sinibacillus* (*S. soli*), *Sphaerobacter* (*S. thermophilus*)	[36–38]
Formation of soil aggregates	Soil aggregates protect and stabilize organic C, controlling its storage, turnover, and CO_2 release in the soil C cycle.	*Azotobacter* (*A. chroococcum*), *Azospirillum* (*A. brasilense*, *A. lipoferum*, *A. amazonese*), *Bacillus* (*B. subtilis*, *amyloliquefaciens*), *Klebsiella* (*K. pneumoniae*), *Rhizobium* (*R. leguminosarum*), *Rhizobium* (*R. etli*)	[38–40]
Mineral formation	Bind minerals with organic matter form stable mineral-associated organic C, creating protection from decomposition and enabling long-term C storage.	*Pseudomonas* (*P. putida*)	[41,42]
Mycorrhizal associations	Regulate SOC accumulation and stabilization by modulating soil stoichiometric ratios (C:N:P), with mycorrhizal species promoting higher SOC and particulate organic C due to their slower nutrient cycling strategy.	*Rhizophagus* (*R. intraradices*, *R. aggregatus*), *Funneliformis* (*F. mosseae*), *Glomus* (*G. mosseae*), *Pseudomonas* (*P. mandelii*)	[30,33,34,39]

3.3. Carbon Fixation Pathway in the Soil

Soil microorganisms that fix CO_2 as soil inorganic C can be classified into chemical, light, and photoelectron microbes based on their energy source [43]. Some of the metabolic pathways utilized by microbes in C fixation include CO_2 induction to form carbonate crystals like calcite, photosynthesis, ammonification, and denitrification processes in the soil. The reductive pentose phosphate cycle or Calvin–Benson cycle is the primary metabolic pathway that autotrophic microbes use to assimilate inorganic C into organic matter within the plant–soil microbe interactions [8,43]. In these systems, stable soil aggregates and higher MBC under conservation tillage promote ongoing autotrophic activity. In contrast, CP disrupts soil aggregates, structure, and microbial habitats, which reduces the role of autotrophic C fixation and instead increases heterotrophic C turnover, limiting long-term C sequestration [44,45]. Moreover, Berg [8] reported that microbial distribution, shaped by tillage, modulates the activation of different metabolic pathways towards C fixation. Hence, the adoption of conservation tillage will go a long way to enhance soil aggregates, stratified microhabitats, and C fixation.

On the other hand, heterotrophic microbes can also fix C through dark fixation pathway [43]. This metabolic process takes place in a wide range of environmental conditions, including temperate, semi-arid, and cropland soils [35]. All microbes use inorganic carbon (CO_2) for metabolism, which is the primary source of C for chemotrophs and phototrophs to derive energy, in contrast to heterotrophs, which rely on organic C and inorganic C through pathways such as dark CO_2 fixation [27]. So, the addition of organic C has been found to enhance microbial respiration, which is highly related to dark CO_2 fixation. Hence, the different microbial communities found in a specific soil type may significantly influence the process of dark CO_2 fixation, especially bacteria. Spohn et al. [35] reported that bacteria play a vital role in the dark CO_2 fixation compared to fungi. In this case, gram-positive bacteria were found to enhance dark CO_2 fixation in temperate forest soils more than the fungi. Hence, the fixation of CO_2 through the dark metabolic pathway remains a key element of the soil C cycle.

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Despite limited research on dark CO_2 fixation under different tillage practices, we can assume that no-tillage systems enhance dark CO_2 fixation indirectly by preserving soil aggregates and microbial biomass, fostering stable microhabitats for bacteria that drive these pathways [46]. CP disrupts soil aggregates, exposes soil to oxidation, and accelerates heterotrophic turnover [47], initially suppressing dark CO_2 fixation by reducing autotrophic competitors. Therefore, due to the complexity of the soil nexus, various metabolic pathways can be utilized by heterotrophic or autotrophic microbes to fix CO_2 into soil inorganic or organic C [27]. However, other pathways of C sequestration and distribution of chemoautotrophic microbe metabolism have been suggested by Wu et al. [27] to be limited; hence, more research should be conducted to gain more understanding.

4. Microbial Nutrient Interactions Under Different Tillage Practices

The natural soil systems, in most cases, are deficient in essential nutrients, especially N and P, which are the most restrictive nutritional elements [48]. However, studies confirm that N and P have a direct effect on soil nutrient status and the microbial activities [49]. Due to this challenge, soil microbes come in handy to fill in the gap during the plant–soil microbe interactions, as they provide nutrients to the host plant roots and, in return, obtain energy and C for their metabolism. Fungi and bacteria are the most important microbes and play key roles in nutrient cycling in their symbiotic relationship between plants and soils in the rhizosphere. However, tillage practices have a significant effect on the availability and uptake process of nutrients in the soil [50].

Generally, tillage systems are categorized into two basic groups: conventional (plowing) and conservation tillage. CP involves the disturbance of the entire soil surface [51] while leaving less than 15% of crop residue. It is associated with accelerated decay of organic matter, nutrient-depleted soils, and erosion, especially when followed by bare soil surfaces, increased rates of soil moisture loss, high costs due to the usage of machinery at different stages of tillage, and increased soil temperature [52]. These outcomes threaten the quality of soils [53], eventually leading to increased GHG emissions, especially CO_2 [54] and the decline of SOC. Additionally, primary nutrient elements like N, P, and K have high chances to be lost under such conditions [55,56]. Conservation tillage, on the other hand, entails the retention and management of crop residues on the soil surface with minimum soil disturbance [51] with the intention to reduce erosion, conserve moisture, and enhance soil health through increased nutrients and microbial activities [57]. Several types of conservation tillage practices include no-tillage, minimum tillage, ridge tillage, and strip tillage.

No-tillage favors fungal biomass and mycorrhizal networks by minimizing disturbance, enhancing P uptake via extended hyphae, and stabilizing organic N, as shown in a meta-analysis by Bowles et al. [58] who reported 30% higher mycorrhizal colonization under no-tillage. In long-term trials, soil under CP contained 21% less amino sugar C across the entire plow layer (0–20 cm) compared to soil under no-tillage, reflecting a lower accumulation of microbial cell wall residues [59]. This difference is primarily attributed to a lower deposition of fungal-derived C in the microaggregates contained within macroaggregates in plowed soils, which affects soil structural stability.

Most studies indicate conservation tillage to be of great significance towards sustainable soil health and agricultural production. Gashi et al. [21] reported that reduced tillage significantly enhanced soil biodiversity, offering a conducive niche for microbial communities to thrive. Additionally, they indicated that the improved soil structure due to undisturbed microbial habitat and soil aggregates promoted the mobilization of nutrients in the soil and uptake by plants. The soil aggregates protect the microbial necromass and metabolites against any physical changes in the soil, leading to stabilization of SOC [60]. Under no-tillage practices, there is a tendency for enhanced plant diversification, which eventually leads to a more balanced, rich, and diverse soil food web with increased nutrient availability. A related study by Pelosi et al. [61] confirmed that there was enhanced MBC accumulation and diversity of species under reduced tillage, which improved SOM decomposition and soil structure. Nugroho et al. [62] reported that the increased capacity of soil-nutrient supply due to extended periods of conservation tillage offers a promising management strategy for the sustainability of essential nutrients. This creates an enabling environment for plant-available nutrients in the soil. Hence, the diverse microbial communities in the soil facilitate nutrient recycling and keep disease-causing microorganisms in check. A high amount of organic matter under conservation tillage, coupled with a high level of resistance to erosion, contributed to a higher concentration of available nutrients in organic forms, especially potassium (K), NH_4, Ca, NO_3, and total P in the upper layer of the soil [62].

Plant nutrient availability is also influenced by specific rhizospheric microbes, which can convert the insoluble nutrients into soluble forms, making them readily available for uptake and utilization. The AMF is a good example with an extensive network of hyphae that enhance solubilization of P minerals for easy plant assimilation [50]. P is an immobile nutrient element that can only be accessed where it is placed; thus, the AMF is key in its acquisition and supply to the roots. Similarly, some bacteria are able to convert the insoluble forms of micronutrients, for example, zinc (Zn) and iron (Fe), to soluble forms, which leads to enhanced uptake and utilization. However, these accrued benefits from microbes might be easily impeded by CP. For instance, studies confirm that CP can destroy the habitat of microbes, reduce bacterial populations and biomass, therefore breaking the soil aggregates and structure [16]. This affects nutrient availability to plants, formerly enhanced by microbes, coupled with reduced MBC and total N.

Even so, bacteria enhance nutrient cycling in plants through processes such as N fixation, solubilization of P, and regulation of hormones like auxins, ethylene, gibberellins, and cytokinins [63]. Moreover, they have a multifaceted ability to add to the availability of plant nutrients, hormone regulations, and stress resistance. These bacterial processes are essential for making nutrient elements more bioavailable to plant roots. The filamentous actinomycete bacteria play a major role in plant health and protection due to their comprehensive ability to produce compounds that protect crops against abiotic factors like soil-borne diseases. The deferoxamine actinomycetes, which can produce siderophores, enhance the acquisition of iron, which is an essential nutrient element for microbes and plant utilization [63]. Additionally, soil aggregate and structure are enhanced by actinomycete bacteria through breaking down complex organic matter, thus enriching the soil microbiome and enhancing nutrient availability. This process, in turn, encourages root development, consequently improving the overall plant growth and soil health.

Fungi are well known for their ability to break down recalcitrant organic matter, which is high in cellulose and lignin. Furthermore, they tend to have a high C use efficiency ranging between 40 to 55%, which allows them to recycle and store more C and less N in their cells (at a C: N ratio of 10:1) than bacteria. The AMF hyphae, in particular, form a symbiotic relationship with plant roots, which results in an extended network in the soil, increasing the capacity of nutrient acquisition, especially P [63]. AMF have the capacity to colonize both root tissues and soil particles, leading to the formation of stable soil aggregates, thus enhancing soil C sequestration (carbon stabilization). More emphasis is laid by Morris et al. [64], who found that AMF improves soil structure as a result of enhanced soil aggregation, thus contributing immensely towards increased MBC, total N, and SOC stocks. This is attributed to its high surface area coupled with reduced hyphae diameter, which enables them access the interiors of soil aggregates and small soil pores that tend to be inaccessible by roots [27]. It is evident that fungi have larger and longer hyphae under non-rotated tillage systems compared to CP. This is mainly ascribed to less soil disturbance, which results in improved soil moisture content [65] that provides a conducive environment for fungal growth. The moist soil stimulates enzymatic activities and other biological processes, which eventually facilitate the stabilization of SOC. Studies have also indicated algae to be beneficial due to their ability to photosynthesize effectively in the rhizosphere, producing oxygen, which ensures an oxygen-rich environment. This improves microbial activities in the soil, increasing chances for MBC, SOC accumulation, and nutrient cycling [60]. In addition, Ammar et al. [66] reported that algae have been found to immobilize harmful metals in the soil, leading to improved soil health.

During conservation tillage, especially no-tillage, the diversification of both bacteria and the microscopic fungi increases, leading to elevated levels of microbial activities and biomass [67]. This, however, suggests that in the absence of tillage, the population and activities of soil microbes can be greater due to the preservation of organic matter in the soil. The improved soil aggregate stability leads to reduced loss of mineral nutrients, and increased C and N substrates, which are converted into microbial biomass and necromass. Hence, enhanced proportions of microbial necromass bind with other nutrients and clay particles to form mineral-associated organic C, thus stabilizing SOC [68]. Moreover, it is recorded that microbial necromass could contribute up to 50% of SOC under croplands when using amino sugar biomarkers.

A study carried out by Sandor et al. [65], found that soil loosening (strip tillage) had a more favorable effect on parameters influencing soil biological activities. This was evident in the significant increase in MBC and microbial biomass N by over 80%, in addition to the enhanced rate of dehydrogenase activity. Another study done by Liu et al. [69] reported a strong correlation between N and soil enzymatic activities; thus, the alteration of soil conditions through tillage causes a significant effect on soil enzymatic activities, which in turn negatively influences the availability of nutrients, like N. Additionally, soil microbial and enzymatic activities were found to be more active in C cycling and N fixation processes than during P cycling in warm seasons [70]. Similarly, warming the soil enhances root respiration and metabolic processes, which in turn accelerate the aging and senescence of roots, eventually increasing the rate of rhizodeposits and sugar components, which are primary sources of food and energy for microbes [71]. As microbes thrive, they drive the soil nutrient cycling process through the secretion of extracellular enzymes, which actively regulate the decomposition of litter [70]. These findings clearly indicate that there is a direct relationship between plant–soil microbe interactions and mineral nutrient cycling within the rhizosphere. Therefore, it is of great importance to ensure a conducive environment for enhanced microbial activities in the soil through sustainable management practices (conservation tillage) towards improved plant nutrient availability.

5. Influence of Tillage Systems on Soil Organic Carbon and CO_2 Emissions

A study done by Engell et al. [72] in four countries, namely Germany, Spain, Romania, and Sweden, found that tillage systems with less CP were recommended because minimum and no-tillage resulted in microbial biomass C and N accumulation on the upper soil layers, with variation on specific sites. Similar to this finding, Gashi et al. [21] also recorded increased microbial dynamics at the upper layer of the soil under reduced tillage. Thus, the increased number of microbes in the soil pool may translate to high accumulation of MBC after the death of both fungi and bacteria, which adds to the soil C pool. This could have the potential to enhance microbial activities and C stocks in the soil [72].

Tillage has been found to significantly affect both CO_2 emissions and SOC stock in the soil. For instance, less disturbed soils have a greater chance to sequester C in the soil, hence reducing the emissions of CO_2 into the atmosphere [73]. Research by

Nugroho et al. [62] also confirmed that less soil disturbance significantly yielded high concentrations of total organic C and labile C under conservation tillage treatments. They also reported a significant increase in organic matter in the upper soil layer. In a study done by Jia et al. [2], no-tillage and ridge tillage were found to significantly increase SOC concentration in the upper soil layer (0–5 cm). This was attributed to the higher rate of microbial respiration, which consequently led to the accumulation of MBC. However, there was a significant reduction of SOC in the lower soil layers. On the other hand, approximately 6.1 Mg ha^{-1} CO_2 can be emitted annually, attributed to the increased rate of organic matter decomposition and enhanced microbial activities under CP practices [74]. Moreover, research by Casazza et al. [75] has confirmed that soil disturbance through CP reduces the presence of fungi, which is the primary source of C in the soil, and reduces the population of bacteria because of the fluctuating temperature and soil moisture during and after tillage (Table 3). This takes place because the C supply network, which happens in the symbiotic relationship in the rhizosphere between plant roots and fungi hyphae, is cut off as the soil is disturbed with CP [76]. Plant diversification under conservation tillage, especially no-tillage, is a prerequisite element that can enhance root C input and soil microbial activities and metabolic processes through increased root C concentration in the rhizosphere [3]. Similarly, the interaction of plant microbes with the AMF under elevated CO_2 has been reported to increase SOC residence time, decomposition process, as well as deposition of the mycorrhizal residues, which improves C sequestration in the soil.

Table 3. Tillage practices and their effect on CO_2 emissions.

Tillage System	Average CO_2 Emission	Effect on Microbes	References
Conventional tillage	Increased emissions by 27%. Dissolved SOC, reduced C allocation in the soil, and CP led to high SOC near the bottom of the plow layer	Reduced microbial diversity and population due to continuous soil disturbance	[75–77]
Reduced tillage	Enhanced organic C stocks	Increased microbial biomass content up to 22%. Increased enzymatic activity	[77]
No-tillage	Reduced emissions by 20%. Increased organic C on the soil surface (0–5 cm), Stabilization of carbon in the soil	Increased bacterial diversity. Higher activity of dehydrogenases and β-glucosidase	[76–78]
Strip tillage	Reduced emissions 45–51%	Increased microbial activities	[59]

Similarly, as reported by Mühlbachová et al. [79], the lower intensity tillage practices reduced the rate of CO_2 emissions approximately by 45 to 51% under reduced and no-tillage, respectively, as compared to CP [79]. Regional variations can have a huge influence on this emission, including local climate, soil type, and management factors. Li et al. [80] showed using structural equation modeling that no-tillage reduced annual CO_2 emissions by about 20%, with the magnitude of reduction strongly controlled by soil type and crop system, being more pronounced in fine-textured, C-rich soils. A global meta-analysis showed that tillage emitted 27% more CO_2 than no-tillage in arid climates. This difference was larger compared to humid areas, where tillage emitted 16% more CO_2 than no-tillage [81]. The general context supporting this difference is that high soil moisture at humid sites favors high decomposition rates, resulting in small differences between tilled and untilled soils, while large differences develop in arid climates with much lower soil moisture content.

Studies have put more emphasis and focus on the positive impact of conservation tillage and how the whole process influences soil nutrient accumulation and enzyme activity. Research by Sadiq et al. [82] found that conservation tillage significantly enhances the nutrient circulation in the soil, especially SOM, N, P, and microbial activity, contributing to long-term soil fertility and sustainable agricultural production. Furthermore, Liang et al. [83] reviewed the effects of conservation tillage on GHG emissions, highlighting its role in reducing CO_2 and CH_4 emissions while improving soil C sequestration towards the enhancement of general soil health. Isaboke et al. [84] found that farmers who left crop residues on their farms after harvesting increased the SOC content, which is a fundamental factor influencing the enhancement of C accumulation [85], and increased soil aggregation. Likewise, conservation tillage contributes to climate resilience by indirectly or directly lowering GHG emission rates and improving SOC stocks [86], which in turn helps in the mitigation of environmental pollution. Additionally, Mohammed et al. [22] observed the highest emissions in the tillage systems as compared to no-tillage systems. They reported that the no-tillage system conferred positive impacts on the mitigation of soil C towards minimizing GHG emissions from agricultural soils.

One of the major contributions of conservation tillage to the soil is the maintenance, stabilization, and enhancement of the SOC in various climatic zones. It is easier and more effective to increase the amount of C in the soil using conservation tillage rather than using CP, which might decrease the soil C rates after continuous cultivation of the same piece of land for a long time [85]. Conservation tillage has been proven to enhance C sequestration and, to a larger extent, boost the levels of organic C and SOM [86]. No-tillage and minimum tillage have gained global attention in recent decades due to their effective contribution in agriculture towards enhancing climate change mitigation and food security [87]. Similarly, during no-tillage, most farmers leave crop residues on the soil surface to act as mulch, which conserves moisture and later decomposes to provide beneficial nutrients to crops and microorganisms as food and energy. These will, in turn, establish a physical barrier between organic materials and microbes in the soil, thus enhancing the development of long-term micro and macro soil aggregates, which improve the soil structure (Figure 3). They further concluded that regarding microbial activities and interactions in the soil, the region's climatic and soil characteristics must be put into consideration for each applied tillage practice.

Heterogeneity of CO_2 Emissions Under Conservation Tillage

The impact of conservation tillage on soil CO_2 emissions varies based on multiple interacting factors. Conservation tillage can either reduce or increase soil CO_2 emissions, depending on the interplay between C inputs, microbial processes, and soil protection mechanisms [87]. Less soil disturbance encourages residue retention, higher root-derived C, buildup of microbial biomass, and aggregate formation, all promoting C stabilization and reduced CO_2 emissions [88]. However, greater substrate availability near the surface can boost microbial activity, leading to a short-term increase in respiration, especially with optimal moisture and temperature [87]. Contrary to popular expectations, some studies have indicated specific cases where increased rates of CO_2 were observed under conservation tillage due to elevated rates of temperatures. This does not undermine soil C sequestration as a climate mitigation approach but instead highlights the short- to medium-term equilibrium between C inputs and microbially mediated losses [88]. For instance, deep tillage resulted in an overall increase in CO_2 emissions by 4.9–37.7% compared to rotational tillage, even though it was intended to conserve soil moisture and reduce heat. Wang et al. [67], Basheer et al. [1], and Li et al. [80] indicated that no-tillage increased CO_2 emissions by 50% as compared to CP. These higher emissions are typically linked to boosted microbial respiration triggered by warmer soil conditions fostered by residue retention and minimal soil tillage [89].

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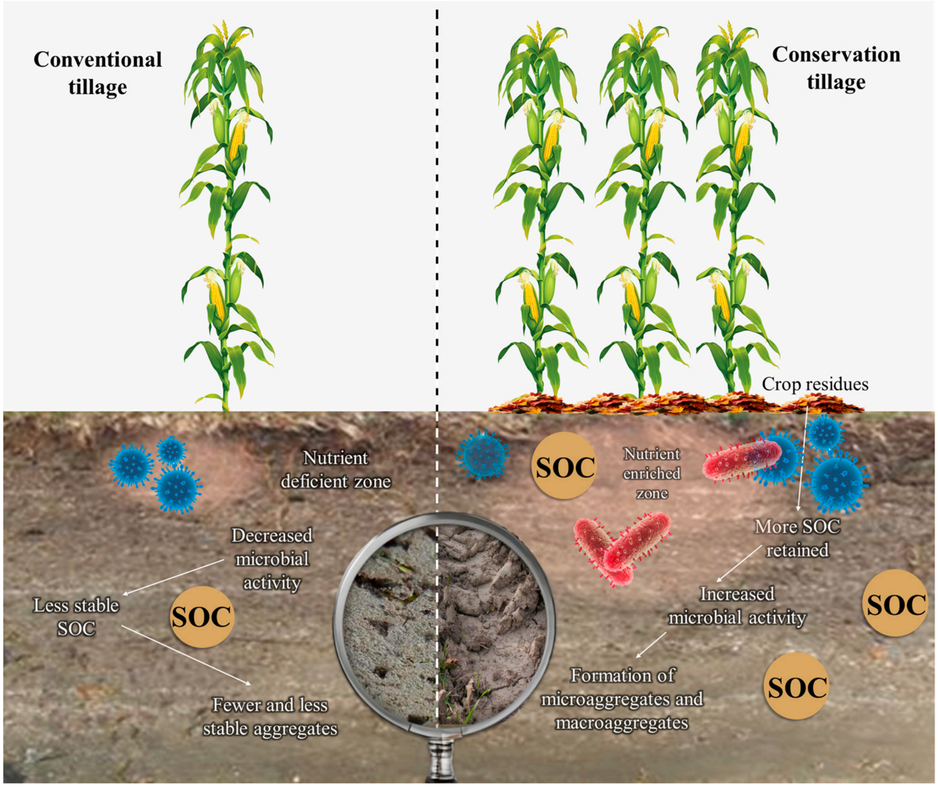

Figure 3. Comparison of conventional tillage (**left**) and conservation tillage (**right**), highlighting their contrasting effects on SOC stabilization and microbial activity. Under conventional tillage (plowing), disturbance leads to fewer and less stable soil aggregates, decreased microbial activity, and reduced SOC retention. In contrast, conservation tillage practices enhance microbial activity, promote the formation of microaggregates and macroaggregates, and increase the stabilization and storage of SOC (Source: Author).

Soil properties and environmental conditions have been reported to play a key role in the emissions of CO_2 into the atmosphere [87]. For instance, elevated levels of soil temperature and moisture will enhance the rate of CO_2 emissions due to increased rates of respiration in the soil. Therefore, multiple factors should always be put under analysis to evaluate the interactions affecting CO_2 emissions under conservation tillage. The highest CO_2 emissions were observed under 10–12 cm chiseling was done [90]. Additionally, chiseling to 10–12 cm with only 15% of residues on the soil surface increased CO_2 emissions twice as compared to those tillage practices with above 30% cover. This could be due to less soil cover, leading to an increased rate of evaporation and increased soil temperatures. Similarly, the basal SOM mineralization was increased by 38% when temperatures increased from 15–20 °C, which consequently led to higher CO_2 emissions. Another research by Mühlbachová et al. [79] indicated that straw residues left on the soil surface increased the CO_2 fluxes. This clearly means that well-incorporated residues in the soil increase the rate of CO_2 emissions due to enhanced microbial activities and faster decomposition. Residue retention conserves soil moisture and moderates temperature fluctuations, conditions that favor microbial activity and accelerate decomposition, particularly in the early years following adoption [91]. Straw residues are attributed to conserving soil moisture, which is essential for enhancing microbial activities in the soil. Other findings show that crop residues, for instance, the incorporation of maize straw, led to an approximate increase of 32% CO_2 emissions under reduced tillage [92]. Contrary to this finding, Wegner et al. [93] found that using corn residue with cover crops (soybean) had a significant reduction in CO_2 emissions under reduced tillage.

The microbial activities in the rhizosphere, which are activated by the C substrates from the organic residues, determine the stabilization of C or the respiration of CO_2. Jiao et al. [94] recorded that higher soil moisture provides a conducive environment for soil microbial activities, thus promoting CO_2 production. Increased soil temperatures attributed to the warmer soil surfaces lead to increased rates of CO_2 emissions. In another study, CO_2 emissions increased significantly at the beginning of September 2020, coinciding with the season's warm weather and previous precipitation [90]. However, under hot and dry weather, decreased CO_2 emissions were observed in both conservation and CP [79]. The hot and dry weather might have led to reduced soil microbial activities and decomposition of organic matter [95].

6. Plant–Microbe Interactions, CO_2 Emissions, and Microbe Availability Under Different Agro-Climatic Conditions

Agro-climatic conditions have been found to modulate soil moisture, temperature, structure, and, to a significant level, the nutrient cycling process, which consequently affects plant-microbe interactions in the soil. Research evidence by Juhász et al. [96], found that the best-fitting models of factors affecting soil CO_2 emissions are dependent on the local environmental conditions. However, they also concluded that in the future, an increase in CO_2 emissions is expected from bare soil in the warm, dry, and temperate agro-climatic zones. A meta-analysis in 2023 found that soil respiration increased by approximately 33% with elevated precipitation, indicating that moisture availability significantly enhances microbial activity and CO_2 emissions [97]. On the contrary, according to Wang et al. [98], high rainfall reduced the rate of soil respiration due to decreased microbial activities in the soil, negatively affecting soil nutrient cycling. This could be attributed to the high moisture levels in the soil hindering the microbes from functioning normally.

Recent research has revealed a significant relationship between soil biological activities and the supply of mineral nutrients, both of which are greatly influenced by environmental factors [62]. Less extreme environmental conditions enhanced a balanced and slower decomposition of organic matter under conservation tillage as compared to CP, which culminated in a balanced rate of nutrient mobilization and gradual release of nutrients into the soil [62]. Mohammed et al. [22] found that CO_2 emissions were higher in a semi-arid agro-ecological region than in the continental region. Nevertheless, they also found that the highest CO_2 emissions were recorded under cultivated or tillage systems compared to the no-tillage system in both agro-climatic regions. This clearly indicates that, as much as environmental factors influence CO_2 efflux, anthropogenic activities, especially tillage, play a primary role in the acceleration of CO_2 emissions from the soil.

Acidic soil conditions caused by acidic rains were recorded to have reduced enzyme activities in the soil (urease, sucrase, invertase). Moreover, the gram-negative biomass decreased significantly, whereas gram-positive bacteria, fungi, and actinomycete biomass increased, contrary to several studies where soil moisture as a result of precipitation has been reported to increase microbial activities [99]. This signifies that the gram-negative bacteria are more sensitive to any slight changes in the soil than gram positive bacteria, especially soil pH [100]. This is because bacteria have different types of cell membranes, which make them adapt to specific environments. However, to enhance plant-microbe interactions, manipulations can be done during agricultural production to cushion the negative effects of agroclimatic factors and enhance microbial activity and biomass. Some of these anthropogenic manipulations include mulching, precision irrigation, use of cover crops, incorporation of organic matter such as organic manure into the soil, and agroforestry.

Therefore, it is evident that plant populations tend to struggle to survive or even exist in a new environment without the fundamental role of bacteria in the soil. This is due to their ability to modify the soil environment and ecosystem for the survival, existence, and proliferation of most plant species. Moreover, certain photosynthetic bacteria usually form and colonize areas where soil genesis is taking place, which simultaneously take part in the cycling of essential elements such as C, N, P, and other micro elements towards the production of the first organic matter. Some of the beneficial microbes within the root zone, especially the AMF with some specific types of rhizobacteria, have been found to enhance drought tolerance through promotion of plant water uptake using their hyphae network system and increased rate of root development. Additionally, the accumulation of osmolytes has also been recorded, which helps retain water within the plant cells and tissues [3].

7. Climate Change Impacts on Soil Microbial CO_2 Emissions

Climate change disrupts the intricate interactions between soil, plants, and the atmosphere by altering critical processes such as C exchange, water cycling, and photosynthesis, processes essential for agricultural productivity and ecological balance. Persistent changes in rainfall patterns and rising temperatures impact soil and plant functions, threatening the ecosystem services they provide and undermining natural climate regulation [101]. The effects of climate change on soil microbes and their role in nutrient cycling and GHG emissions, especially CO_2, vary widely across local environments and remain difficult to predict [102]. Generally, increasing temperatures accelerate microbial decomposition of SOC, leading to elevated CO_2 emissions [103]. Long-term soil warming experiments across temperate and boreal ecosystems have consistently shown sustained increases in microbial respiration, with reported soil CO_2 efflux increases ranging from up to 40% under 4 °C warming scenarios, confirming the strong temperature control of microbial activity. Similarly, a 12-month study confirmed warming enhanced microbial metabolic quotients and heterotrophic respiration by more than 20% in cool seasons, aligning with temperate patterns via fast-growing taxa shifts [34].

However, this response depends heavily on the nature and stability of soil C. Soils rich in clay or with strong mineral associations tend to chemically and physically protect organic C by sorbing and isolating it from microbial decomposition, thereby reducing decomposition sensitivity to temperature and limiting CO_2 release under warming [104]. Earth system model simulations incorporating mineral-associated organic C pools further predict that such soils exhibit delayed C losses under future warming compared to sandy soils dominated by particulate organic matter [105]. This occurs because the climatological temperature sensitivity of particulate C is, on average, 28% higher than mineral-associated C, as stated by Georgiou et al. [88]. Conversely, soils containing more labile C exhibit heightened microbial activity and temperature sensitivity, often resulting in increased CO_2 emissions.

Beyond decomposition rates, climate change profoundly shapes the composition and functional traits of soil microbial communities. Factors such as warmer temperatures, altered moisture regimes under conservation tillage, and elevated CO_2 prompt microbes to acclimate and adapt, modifying their growth dynamics and metabolic processes [106]. Field-based warming and drought manipulation experiments, such as those of Lei et al. [34], have shown that grassland communities shift toward copiotrophs, with metabolic quotients and boosted C-decomposition enzymes under +2 °C warming, and that drought amplifies shifts toward stress-tolerant taxa. Similarly, Knight et al. [107] demonstrated multi-site convergence to drought or heat-resistant taxa, with functional genes for C-cycling upregulated under combined stresses, confirming broader changes in microbial structure and enzyme production for C and N cycling. This adaptive process frequently shifts community composition toward fast-growing or stress-tolerant species [108]. For example, microbial communities in tropical croplands exposed to simulated drought and warming demonstrated increased growth, respiration, and C use efficiency after rewetting, indicating improved drought resilience [109].

Such shifts in microbial communities can significantly influence ecosystem functions. Adapted microbial populations may accelerate decomposition rates, causing higher soil CO_2 emissions and amplifying climate-warming feedback loops [110]. Process-based soil C models integrating microbial functional traits predict that acclimated microbial communities can offset initial thermal suppression, ultimately sustaining or increasing long-term CO_2 emissions under warming scenarios, leading to twice the projected global soil C losses in the next 100 years [111]. Variations in microbial community composition strongly affect the temperature sensitivity of microbial growth and respiration, which in turn regulates soil C mineralization and CO_2 fluxes in warmer environments. Because microbial temperature responses are often phylogenetically conserved, climate-driven changes in community structure can alter the soil's overall respiration sensitivity, impacting global climate feedback mechanisms [112]. Ultimately, as microbes adjust to these environmental pressures, they contribute substantially to increasing GHG emissions, perpetuating a feedback cycle that both responds to and accelerates climate change [113].

8. Conclusions

This review primarily examines how tillage practices directly influences plant–soil microbe interactions under climate change and their role in advancing sustainable agriculture production. Studies confirm that conventional plowing (CP) has a great influence on soil physical, chemical, and biological properties as it negatively affects microbial activities and nutrient cycling, accelerates SOC depletion, and increases CO_2 emissions. However, most reviewed studies confirm that conservation tillage, especially strip, ridge, and no-tillage, increased the microbial community, which enhanced the MBC, consequently increasing the SOC stocks in the upper soil layers. Similarly, increased root respiration under conservation tillage speeds up the accumulation of rhizodeposits, which are not only a primary source of food for microbes but also add to the pool of SOC storage and increased availability of mineral nutrients for plants. Moreover, enhanced SOC stabilization and optimization of nutrient utilization under conservation tillage practices are evident as microbial habitats are preserved, enabling the microbial fungi (AMF, which is attracted by flavonoids) and bacteria to facilitate nutrient exchange and uptake by plant roots. This study also suggests that conservation tillage (no till) enhances dark CO_2 fixation due to the preserved soil aggregates and stable microhabitat for bacteria to thrive and drive the process.

Although conservation tillage practices are applied to reduce CO_2 emissions and enhance SOC stocks, several challenges remain, particularly variations in soil types and differences in agro-climatic zones, which require the application of site-specific problem-solving strategies. It is therefore imperative to expand research on beneficial microbes that enhance C stabilization and root exudate compounds, which trigger the specifically needed nutrients in the rhizosphere under conservation tillage. With advancements in agricultural technology, there is significant potential to improve the tillage application techniques towards enhancing nutrient availability, utilization, and stabilization of C in the soil for both plants and microbes. Therefore, the incorporation of these scientific findings into practical measures and policies towards better tillage practices and enhancing plant-beneficial microbes will lead to future sustainability in soil health, crop production, and climate change adaptation.

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