J.Mycopathol.Res. 63(3) : 491-501, 2025, ISSN : 0971-3719 (Print), 2583-6315 (Online) 10.57023/JMycR.63.3.2025.491

REVIEW

Microbial dynamics under changed ecology of conservation agriculture

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Received : 12.07.2025 Accepted : 24.08.2025 Published : 29.09.2025

Conservation Agriculture (CA) employs minimal soil disturbance, permanent soil cover, and crop rotation to improve soil health and sustainability. Compared to conventional agriculture, CA reduces disease cycles, increases microbial populations (e.g., phosphate solubilising bacteria and *Azospirillum*), and boosts enzyme activity, especially with no-tillage and residue retention. Seasonal fluctuations in microbial and enzyme levels are less pronounced under CA practices. Tillage combined with residue retention or bio-inoculation raises CO_2 emissions, while zero-tillage consistently yields more than conventional methods.

A metagenomic study conducted at Uttar Banga Krishi Viswavidyalaya compared different combinations of tillage, residue management, and bio-inoculation. Soil from selected plots was analyzed using next-generation sequencing, confirming that CA enhances beneficial bacterial diversity and reduces certain pathogens. Unique genera such as *Amycolatopsis* and *Methylobacterium* were found exclusively under CA, and overall microbial balance improved. Key increases included Hyphomicrobiales, *Pseudomonas*, and *Mesorhizobium*, while significant declines were noted for Nocardioides and others, indicating that CA fosters a healthier and more resilient soil microbiome.

Keywords : *Amycolatopsis, Azotobacter*, *Azospirillum*, *Bradyrhizobium,* Fluorescent *Pseudomonas*, *Methylobacterium, Microbacterium, Paenibacillus, Sphingomonas*

INTRODUCTION

Ever increasing human population and climate change events are supposedto be the major challenges of the agricultural systems. In developing countries population growth rate is still alarming. It has been estimated that the population of the world will reach to 9.7 billion in 2050 from the present-day population of 7.7billion (United Nations,2019) and the real problem is to achieve food security for this huge population. Under the problems of degradation of lands, scarcity of water, increases in climate variability and limited scope for expansion of are under agriculture, The agricultural system has to be sustainable and climate resilient in one hand, and on the other hand, it has to meet the food security of the globe.

17th Professor S.B.Chattopadhyay Memorial Award Lecture delivered on 6th December 2024 at National Conference of Indian Mycological Society, Department of Botany, CU held at Ramakrishna Mission Cultural Centre, Golpark, Kolkata

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Conservation agriculture (CA) is perceived as the system which could meet the ever-increasing food demand worldwide with sustainable in tensification of crops and various resources (Lal, 2015). Actually CA is a farming system that is designed to hasten the sustainability of the agricultural systems through conserving natural and biological resources in combination with external inputs. CA is characterized by three major principles (i) minimum soil disturbances/ minimum traffic on any agricultural operations; (ii) maintaining and managing crop residues (atleast 30% of the total crop load) and (iii) diversification of crop species (may be spatial or temporal) including legumes (FAO,2019). Again, site specific nutrient management or pest management strategies may be helpful further for achieving its desired success (Thierfelder *et al.*2018).These principles are to be applied based on a particular situation/environment and have to be linked with the specific agronomic, environmental and social aspect of that region in particular making it more site-specific approach.

CA was introduced in Brazil in early 1970s to control the problem of soil erosion initially but considering its positive effects on crops, it took another twenty years and it was in early 1990s when there was a significant adoption level in CA in *Latin American* countries like Brazil, Argentina, Paraguay and Uruguay. CA spread to the developed industrialized countries like USA, Canada, Australia with a big momentum in its adoption thereafter in end 1990s.The total are a under CA worldwide was estimated to155Mha during 2013-14 (Kassam *et al.*2014), increased further to 180Mha during 2015-16 spreading over 78 countries having diverse climatic condition including Gangetic plains (Kassam *et al.*2019).

Conservation agricultureinRice-wheat Cropping system

The Indo-Gàngetic Plàins (IGP), which àccounts for làrger portion of rice ànd wheàt produced in the region, are home to the rice-wheàt cropping system (RWCS)that is predominant àgriculturàl system in South Àsià (Làdhà *et àl.*2003).In this fàrming system, CÀ hàs emerged às màjor àpproàch to àddress the key chàllenges likesoil degràdàtion, wàter scàrcity ànd declining productivity(Jàt *et àl.*2014).CÀ pràctices include permànent soil cover (residue retention),minimum soil disturbànce (no tillàge) ànd crop diversificàtion or rotàtion. These pràctices improve soil heàlth, increàse wàter use efficiency ànd stàbilize crop yields in the RWCS (Shàrmà *et àl.* 2019).

According to Guptà ànd Seth (2007), the Indo-Gangetic Plàins'RWCS which spàns region from Punjàb to West Bengàl, is pàrticulàrly vulneràble to unsustàinàble àgriculturàl pràctices like residue burning ànd intensive tillàge. These conventionàl pràctices reduced water àvàilàbility, increàsed green house gàs emissions ànd depleted soil orgànic màtter (Kàssàm *et àl.*2019). CÀ lowers the dependency on chemicàl inputs ànd wàter-intensive pràctices, hence act as à viable alternative .Research showed that CÀ pràctices not only reduce production costs ànd environmentàl effects but àlso RWCS's resilience to climàtic extremes (Làl,2015). By improving soil structure ànd soil orgànic màtter ànd supporting beneficiàl microbes, CÀ promotes long-term sustainability ànd biodiversity in these systems (Ghosh *et àl.* 2021).

The economic viability in rice-wheàt cropping system is àlso noteworthy. CÀ pràctices can lead to increased profitability particularly for small holders who dominate the RWCS in South Àsià, by reduced làbour, fuel and àgrochemicàl requirements (Jàt *et àl,* 2019).CÀ supports sustainable intensification by conserving resources ànd improving efficiency in response to population growth and climate change (Kàssàm *et àl.* 2019). As such, CÀ offers àn efficient solution to challenges faced by rice-wheat cropping systems, ensuring their long-term productivity ànd environmentàl sustàinàbility (Bhàtt *et àl.*2016).

Ràni *et àl.*(2017) examined the impact of Resource Conservation Agricultural Practices (RCÀPs) on rhizospheric microbes in rice-wheàt cropping system with different residue management practices (burning, removal, incorporation, surface retention) and nitrogen doses(100,150,200kg/hà).They observed variations in rhizospheric microbes, root architecture and dehydrogenase activity with different residue and nitrogen management options. Surface retention of crop residues after harvest was found best for soil and plant health. The impact on wheat diseases was inconclusive.

Conservation Agriculture and Plant Diseases

Leaving crop residues under no/minimal tillage conditions may impact the incidence and severity of various soil- and residue-borne pathogens. Altering tillage practices can lead to changes in the physical and chemical properties of soil, which are likely to influence the occurrence of plant diseases (Singh *et al.* 2004). Key factors in the occurrence and severity of plant diseases include pathogen survival and activity levels, host susceptibility, and the population of other soil microorganisms. Reduced tillage can favor pathogens by lowering soil temperatures, increasing soil moisture, altering root growth, changing nutrient uptake, and modifying the population of plant pathogen vectors.

Soil densification and reduction in microporosity also affect many diseases, particularly abiotic root diseases. Changes in soil aeration and permeability can alter qualitative and quantitative differences between soil rhizospherical populations and the survival and distribution of pathogen inoculum. Furthermore, anaerobic soil conditions can influence root-pathogen interactions leading to plant disease development. The quality of the soil's physical environment is a critical indicator for root health under conservation tillage, especially in humid climates. Phytotoxins released due to the decomposition of rice plant residues may stimulate toxin-producing microorganisms, predisposing plants to pathogen attack (Sturz e*t al*.1997). The rise of conservation tillage necessitates a deeper understanding of plant diseases and disease interactions in temperate and tropical humid agriculture, where excessive crop residues, constant moist soil conditions, and soil compaction pose potential constraints.

The concentration of plant debris under conservation tillage and the subsequent effect of microbial biomass in the top 5 to 15 cm of soil promotes pathogen survival. However, disease-causing microbes constitute only a proportion of the rhizospherical population. High soil microbial activity can lead to competition effects that may ameliorate pathogen activity and survival and counteract high pathogen inoculum pressures. Microbial antagonism in the root zone can also result in the formation of disease-suppressive soils. This phenomenon, essential for the adoption of conservation tillage in humid climates, can be influenced by soil and crop management practices, primarily crop rotation. High soil microbial activity can lead to competition effects that can affect pathogen activity and survival, thus reducing harmful pathogen inoculum pressures. This microbial antagonism in the root zone can benefit farmers by forming disease-suppressive soils. Leaving plant debris on the surface or partially buried may allow pathogens to survive to the next crop and make conditions more favorable for the biological control of plant pathogens (Sumner *et al*. 1981).

There are several instances where less disease is recorded. Adopting reduced tillage can partially or entirely control wheat pathogens such as *Bipolarissorokiniana, Fusarium graminearum, F. culmorum*, and *F. avenaceum*due to increased soil moisture and disruption of spore movement from straw to crop by large amounts of straw (Sumner *et al*. 1981; Sturz *et al*. 1997; Bhathal and Loughman, 2001).

Singh *et al*. (2004) explored rice and wheat disease under the rice-wheat cropping system. They recorded no significant variation in the occurrence and type of microbial flora between resource conservation and conventional tillage. Adopting reduced tillage and surface seeding of wheat does not impact *Bipolaris sorokiniana* and *Pyrenophora tritici-repentis*. Further, the severity of rice disease due to *Rhizoctonia solani* and *Cochliobolus miyabeanus* depends on location, date of sowing, and variety regardless of cultivation practices.

A study in Madagascar examined the impact of conservation agriculture on rice blast disease and yield performance. Rice was planted biennially after oats (*Avena sativa*) following beans (*Phaseolus vulgaris*), using conventional tillage and no-tillage methods. Two fertilization levels were tested: organic and organic + mineral. Over five years, disease severity was lower in no-till systems compared to conventional tillage. Mineral fertilization increased blast severity. The interaction between cropping system and fertilization showed varying impacts; yields were higher with conventional tillage when blast incidence was low, but better with no-tillage when blast levels were high. Soil cover influenced soil nitrate and ammonium content, potentially offering silicon from crop residue degradation. Silicon improves rice tolerance to blast (Seebold *et al.*2004).

At Uttar Banga Krishi Viswavidyalaya, extensive studies have been conducted on the dynamics of rice and wheat diseases in conservation agriculture systems followed continuously for five years. The most important disease of rice (sheath blight caused by *Rhizoctonia solani*) and wheat (spot blotch caused by *Bipolaris sorokiniana*) in different crop varieties were estimated both under CA and conventional systems. Both diseases were high in the initial year of cultivation regardless of the variety under the CA system compared to conventional tillage; however, there were no significant differences recorded from the third year onwards. In some varieties, the disease incidence was lower than in conventional systems (Chowdhury *et al.* 2017). The survival of the pathogen in the soil and crop residue was also the same in both systems. The antagonistic population of *Trichoderma* and *Pseudomonas fluorescence* and dehydrogenase enzymes in soil were higher under CA when analyzed after five years of continuous practice (Ranjana Devi, 2022).

Microbial communities in soil are influenced by changes in carbon allocation, mixing intensity, moisture, and temperature. Suppressive soils maintain low disease levels despite pathogen presence due to factors like fungistasis—where the soil restricts fungal growth. This suppression is mediated by soil microorganisms competing for nutrients and producing antagonistic compounds. Agricultural management can impact microbial activity and biomass, potentially affecting soil suppressiveness. Understanding how management changes microbial community structures is essential for optimized practices since these communities play a central role in soil processes. Modern microbiological methods should analyze tillage management to reveal microbial diversity and its implications on soil health.

Soil heàlth vs. Plànt diseàse

The term soil health is often used interchangeably with soil quality in many literatures. However, Karlen *et al.* (2003) noted that soil quality is a term typically used by soil scientists, while farmers prefer the term soil health. A distinction between soil quality and soil health was clarified earlier by using soil quality to refer to the level of soil suitability for a specific purpose, whereas soil health refers to a broader concept encompassing the overall interaction among various soil functions, with an emphasis on integrated soil dynamics involving the living components of the soil (Kibblewhite *et al.* 2008).

Natural soil ecosystems are believed to be healthier than managed agro-ecosystems due to their greater diversity of soil microbes and lower prevalence of disease problems (Buckley and Schmidt, 2001). It has also been suggested that organically managed farms do not negatively impact the soil microflora compared to c*onventi*onally managed crops, by maintaining soil biological diversity and stability (vanBruggen and Semenov, 2000). However, some evidence argues there is no difference in soil biodiversity (Lawlor *et al*. 2000). *More re*cent literature *indicat*es that organic agriculture increases microbiome heterogeneity, while the metabolic quotient—a stress indicator for microbes—remains unchanged in both conditions (Lori *et al*. 2017; Lupatini *et al.* 2017). Nonetheless, it has been definitively demonstrated that soil organics support and increase the abundance of soil microbiota overall.

Conservation agriculture improves soil health through changes in structural stability, water infiltration, nutrients, and biodiversity. These modifications redefine the ecological niche of microbes, particularly soil-borne ones, affecting microbial population and activity. A healthy soil ecosystem, which results from balanced mineral and organic substrates, living components, nutrient and energy flows, organism diversity, functional interactions, stress resilience, and low disease incidence, is achieved through integrated practices (Rapport, 1995; vanBruggen and Semenov, 2000).

Conservation agriculture, with its components including low soil disturbance, residue retention, and crop diversity throughout the year, offers numerous benefits such as improved soil water storage (Pàge *et àl.* 2019), enhanced soil quality (Somàsundàràm*et àl.* 2019), reduced erosion (Montgomery, 2007), and better economic outcomes (Pr*àdhàn e*t *àl*. 2018;Pàge *et àl*. 2019). Additionally, it increases soil organic matter, particularly at the surface profile, which likely serves as a key driver for many accrued benefits of conservàtion agriculture, including higher biological diversity compared to conventional tillage (Làl, 2015).

Various attributes have been suggested by different researchers to assess soil health, often utilized for distinct purposes. The most common indicators of soil health encompass physical properties such as texture, aggregate stability, bulk density, water holding capacity, and infiltration; chemical properties including total or particulate organic matter, pH, electrical conductivity, extractable nitrogen, phosphorus, and potassium; and general biological parameters such as microbial nitrogen and carbon, soil respiration, and earthworm population (USDÀ-NÀRCS, 2001; Moebius-Clune *et àl.* 2016). However, biological assessment remains incomplete without considering microbial community structure, population, and soil enzyme activities, which indicate soil biological biodiversity and ecological balance (Màrtinez-Sàlgàdo *et àl.* 2010; Njirà and Nàbwàmi, 2013).

The literature on the effect of conservation agriculture on diseases presents variable conclusions. Some generalizations suggest that soils with unstable structures become compacted with less air space and may be characterized as wetter soils, favoring diseases caused by *Phytophthorà* and *Verticillium* spp. However, this condition may not be conducive for *Rhizoctonià* spp. In a classical experiment by Workneh *et àl.* (1999), examining four different pathogens in soybeans under conservàtion and conventional tillage across different soil textures, it was indicated that the effect of tillage depends on texture concerning population density and detection frequency of various pathogens. A recent study indicates significant variation in pathogen abundance with soil types, regardless of the source of pathogens being soil or irrigation water (Obàyomi *et àl.* 2019).

Apart from textural classes, tillage operation or crop establishment technique also influences the bulk density of the soil, though the effects vary according to different studies. Changes in bulk density impact plant diseases, with higher bulk density leading to soil compaction that has been strongly correlated with root diseases such as club root of crucifers (Gossen *et al*. 2016), *Phytophthora* in soybean (Moots *et al*. 1988) and spring cereals (Carter and Johnston, 1989). Research by Alexander and his associates on various physical parameters of soil in relation to *Fomes annosus* infection in pine plantations found that bulk density and capillary pores were positively related, while capillary pores and organic carbon were negatively related to the severity of the infection (Alexander *et al*. 1974).

Conservation agriculture (CA) boosts soil organic carbon, enhancing physical, chemical, and biological properties. Increased microbial diversity and activity from added organic matter can suppress pathogens. Studies show eucalyptus mulch in avocados suppressing Phytophthora and traditional mulching in Mexico reducing soil-borne diseases (Downer *et àl.*2001). Microorganisms occupy diverse niches and perform various metabolic functions. Metagenomics allows for comprehensive analysis of microbial communities without culturing, utilizing whole genomes to reveal genetic information (Handelsman *et al*. 2007). Root-associated microbes are vital for plant growth, with metagenomics identifying unculturable microorganisms and their traits.

Metagenomics, involving high-throughput sequencing, facilitates understanding of microbial assemblages and their ecological roles (Schloss and Handelsman, 2005). It advances agroecosystem studies by uncovering microbial diversity useful for therapeutics, biotechnology, and sustainable agriculture, moving beyond traditional methods focused on cultivable microbes (Mishra *et al*. 2016).

Microorganisms are integral to soil health, nutrient cycles, and plant development, forming part of the holobiont that encompasses plant-associated microbial taxa (Suárez and Stencel, 2020; Igiehon and Babalola, 2021). Metagenomics enables detailed analysis of microbial community structures and functional genes, aiding studies of bacterial, archaeal, and fungal compositions (Philippot *et al*. 2013; Martínez-Porchas and Vargas-Albores, 2017). Addressing agricultural challenges like biodiversity loss, climate change, and soil degradation requires strategies for balancing environmental impacts and meeting food demands, with metagenomics playing a crucial role in unraveling microbial dynamics (Power, 2010; Tilman *et al*. 2011). Advances in metagenomics sequencing have led to the discovery of beneficial microbes, supporting biofertilizers and biopesticides in sustainable agriculture (Scholes and Scholes, 2013; Park *et al*. 2013).

Microbiomes in soil are critical for biogeochemical cycles, influencing nitrogen, carbon, and sulfur dynamics, as well as metal transformations like iron and mercury (Handelsman, 2003). Disruption in these systems can lead to negative impacts such as acid mine drainage and environmental degradation. Metagenomics addresses these challenges by studying microbial diversity and functions in soil (Fierer *et al*. 2013).

The rhizosphere hosts complex microbiomes that enhance plant health, nutrient cycling, and soil fertility. These microbiomes vary by plant species, soil type, and agricultural practices, demonstrating the importance of metagenomics in sustainable agriculture (Subrahmanyam *et al.*2020). Current agricultural challenges include environmental threats, urbanization, and pollution, which metagenomics advancements aim to alleviate through improved soil management and ecological balance (Gupta *et al*. 2018). This approach promotes new perspectives on soil as "living" and "laboring," fostering an agroecological revolution (Granjou and Phillips, 2019).

Conservation Agriculture and Soil Microbiome

Dehydrogenase activity was found higher in CA plots than in conventional plots for most of the period of a year (Fig.1). Dehydrogenase activity (DHA), a crucial indicator of microbial activity in soils, increases under conservation agriculture practices such as residue retention and no-tillage. This activity reflects soil microbial health and oxidative capacity (Navnage *et al.* 2018; Kaur and Kaur, 2021)

Studies show conservation agriculture enhances microbial activity, with residue retention boosting DHA significantly (Habig *et al*. 2015; Jat *et al*. 2020). Seasonal fluctuations in DHA, as observed in Mediterranean climates, were highest during moderate temperature and moisture conditions (Vazquez *et al*. 2017).Long-term trials affirm that conservation agriculture improves soil biological health, making it a preferred sustainable farming method (Cho et al. 2008).

Tillage practices, residue retention, and bio-inoculation significantly influence CO_2 emissions, (Fig.2) with tillage combined with residue and bio-inoculation producing the highest emissions due to accelerated organic matter decomposition (Karlen *et al*. 1994). No-till methods enhance biological activity, moisture content, and aggregate stability, leading to greater organic carbon levels in soil (White and Rice, 2009). Residue application alongside no-tillage generally improves total soil carbon concentration, but when tillage is introduced post-residue and biofertilizer application, decomposition speeds up, increasing CO2 emissions. Organic matter in soil is ultimately mineralized and emitted as CO2 through microbial and fauna activity (Hopkins and Gregorich, 2005; Wolf and Wagner, 2005).

Conventional tillage practices erode soils, damage the environment, and pollute through fertilizers and pesticides, reducing beneficial soil microorganisms and increasing phytopathogens like Fusarium, which harms crops and produces harmful mycotoxins. Sustainable agriculture, such as conservation practices and the milpa agroecosystem, balances soil microbiota, mitigates conventional farming issues, and fosters beneficial microbial interactions (Fig.3). The analysis compared bacterial diversity between Conventional Tillage (CT) and Conservation Agriculture (CA) plots, focusing on the top 15 genera. Key findings include:

♦Genera unique to CA: *Amycolatopsis* and *Methylobacterium*, absent in CT, showed a 100% increase.The milpa agroecosystem, practiced in El Boxo, Hidalgo, Mexico, cultivates maize varieties alongside other crops with minimal soil disturbance, maintaining soil health and microbial diversity. Key soil-associated phyla include Proteobacteria, Acidobacteria, and Actinobacteria, which recycle organic matter, inhibit pathogens, and produce bioactive compounds. Actinobacteria strains from milpa soil, particularly *Amycolatopsis* BX17, show potential for biological control against *Fusarium graminearum* infections in maize (Cabrera, *et al.* 2020).*Methylobacterium* spp., often found in the phyllosphere, are pink-pigmented bacteria utilizing one-carbon compounds like methanol from plant leaves. They act as plant-growth-promoting bacteria (PGPB) by providing nutrients, modulating phytohormones, and protecting plants from pathogens. *Methylobacterium* spp., including those reclassified into the *Methylorubrum* genus, are prevalent in the phyllosphere of crops like rice, clover, and soybean. Strains such as *M. extorquens* PA1 and M. oryzae promote plant growth and are found in various plant parts, including roots and shoots. These bacteria are applied in agriculture to boost yields in crops like wheat, corn, and tomato, showcasing their potential as microbial agents (Zhang *et al.*2021).

♦Increased populations in CA: Hyphomicrobiales (+29.69%), *Pseudomonas* (+19.70%), and *Mesorhizobium* (+14.54%). Symbiotic nitrogen-fixing bacteria associated with legumes belong to the Phylum Proteobacteria, categorized into Alphaproteobacteria, Betaproteobacteria, and Gammaproteobacteria. Alphaproteobacteria are the most widespread, while Betaproteobacteria are less common and linked to specific legumes. Alphaproteobacteria include 17 genera within seven families under the order Hyphomicrobiales (Das and Nath, 2023).*Rhizobium, Sinorhizobium, Mesorhizobium*, and *Bradyrhizobium* are common rhizobial species. Slight increase under conservation agriculture was noted in â-Rhizobia *include Cupriavidus, Paraburkholderia*, and *Trinickia*from the Burkholderiaceae family. *Paraburkholderia* and *Trinickia* were previously classified as *Burkholderia*based on genome analysis(Fig.4).*Microbacterium* (+0.98%)involves mechanism to promote plant growth may improve soil nutrient content and increase the production of auxins, enzymes(Liu *et al.* 2022).

♦Polycyclic aromatic hydrocarbons (PAHs) are toxic organic pollutants often found in soil due to incomplete combustion of fossil fuels and biomass. They pose risks to plants, animals, and humans by entering the food chain. While chemical methods exist to reduce PAH contamination, microbial solutions such as rhizosphere bacteria, endophytic bacteria, and arbuscular mycorrhizal fungi offer eco-friendly alternatives. These microbes degrade PAHs, enhance plant tolerance, and boost soil health.*Mycobacterium* species are effective PAH degraders, utilizing high molecular weight compounds as carbon sources. For instance, *Mycolicibacterium*sp. Pyr9, isolated from *Eleusine indica* roots in contaminated fields, was found to reduce pyrene uptake in white clover when colonized on its roots. This study highlights the potential of microbial biofilms to mitigate soil pollution and protect crops (Yang *et al.*2021). Reduction of *Mycolicibacterium* (-5.36%) indicated an improvement in soil health by reduction in pollutants under conservation agriculture.

♦Nocardioides thrive in contaminated soil and industrial wastewater, showcasing their ability to degrade pollutants. Figure 3 highlights eight habitat types, with contaminated soil being the most prevalent and industrial wastewater as a significant source (Ma *et al* 2023). Significant reduction (-54.61%) also indicates the improved soil health by less accumulation of pollutants or contaminants in CA system.

♦Variovorax however, may be considered as plant growth promoting rhizobacteria, but it also is a potential threat to human health due to its ability to cause blood infection (Payne *et al.* 2024) was found absent in CA system. *Anaeromyxobacter*, essentially an anaerobic nitrogen fixer especially in paddy field with puddling got wiped out of the system due to increased porosity of the CA system (Eze *et al*. 2020) making it aerobic without propensity towards water logging normally seen in paddy fields.

Take home message

Conservation Agriculture (CA) practices, particularly No-till with residue and bioagents, have been shown to significantly improve soil health and reduce spot blotch disease severity in wheat. The adoption of CA increases the prevalence of beneficial microorganisms such as *Azospirillum, Bacillus*, and *Pseudomonas*, while reducing harmful pathogens like *Ralstonia and Xanthomonas*. These practices enhance nitrogen cycling, soil fertility, and overall microbial diversity, promoting sustainable agricultural systems that are both environmentally friendly and agronomically effective.

The long-term implementation of CA practices demonstrates a crucial shift towards sustainable wheat production. By fostering beneficial microbial populations and reducing disease-causing pathogens, CA not only improves crop yield but also contributes to healthier ecosystems.

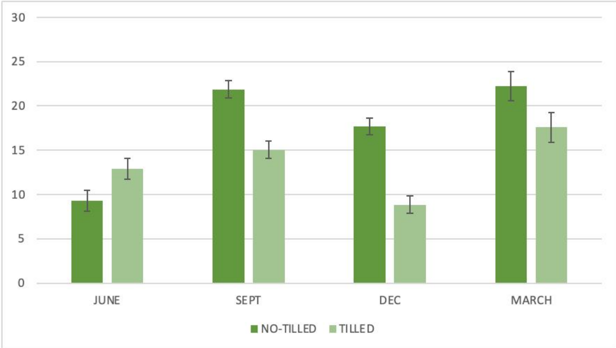

Fig. 1: Dehydrogenase activity due to tilled and no-tilled plots in a year

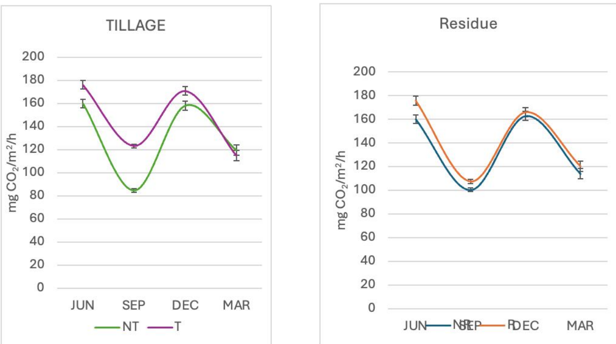

Fig 2: Effect of tillage and residue retention on carbon dioxide emission per m^2 per hour (NT-No tillage; T-Tillage; NR-No residue retention; R-Residue retention)

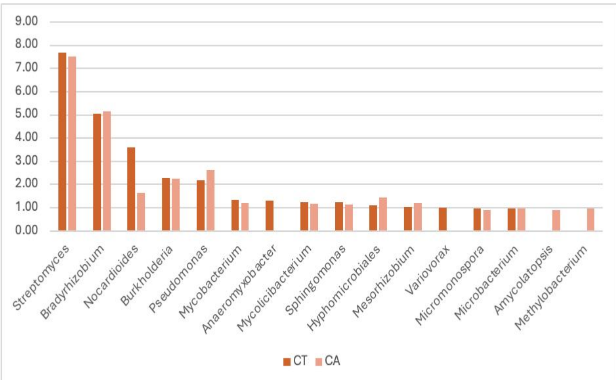

Fig 3: Major bacterial genera presentin conventional and no-tilled soil system

The integration of residue and bioagents under No-till conditions emerges as a vital strategy for addressing contemporary agricultural challenges, ensuring both productivity and environmental stewardship. Meanwhile, No-till without residue and bioagents proves less effective, highlighting the importance of holistic approaches for optimal outcomes in disease management and soil health.

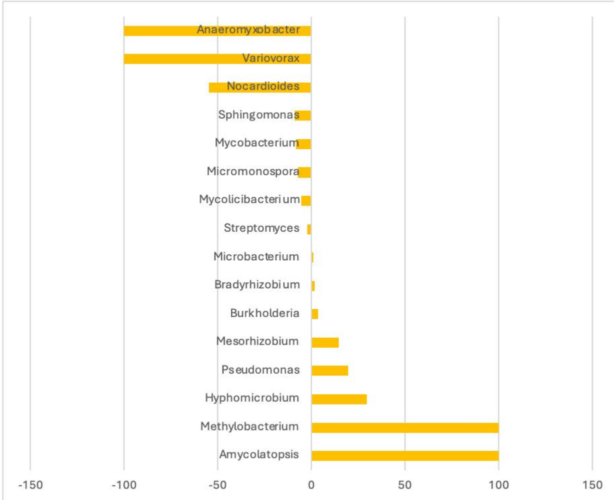

Fig 4 : Percent change in population of major bacterial genus due to no-tillage over tilled plots

ACKNOWLEDGEMENT

The author acknowledges the help of Prof. A. K. Chowdhury, Prof. A. K. Sinha, and students Dr. S. Chakraborty and Ms Arshiya Taj for preparing the manuscript.

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