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COVER CROPS FOR GREENHOUSE GAS EMISSION REDUCTION IN AGRICULTURAL SOILS

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Abstract

The increasing contribution of agriculture to greenhouse gas (GHG) emissions has prompted the urgent need for sustainable soil management practices that mitigate climate impacts. This study investigates the effectiveness of integrating cover crops, microbial inoculants, biochar, and conservation tillage in reducing soil-based GHG emissions and enhancing carbon sequestration. Through a combination of field trials and stakeholder analysis, the research evaluates the biophysical and agronomic responses under various treatment conditions. Results indicate that cover cropping significantly boosts soil organic carbon and microbial biomass while decreasing nitrous oxide emissions, particularly when combined with biochar and chitin amendments. No-till practices further contribute to carbon retention, while advanced nitrogen management using nitrification inhibitors enhances nitrogen use efficiency and reduces environmental leakage. Soil pH, temperature moderation, and crop yield metrics also improved under integrated strategies. Notably, degraded lands cultivated with bioenergy crops exhibited the highest carbon sequestration potential. Correlation analysis revealed strong inverse relationships between N_2O emissions and both SOC and microbial biomass. Visual analyses confirmed the efficacy of sustainable treatments in improving soil health and reducing emissions. The study concludes that adopting region-specific, climate-smart agricultural practices can substantially contribute to climate mitigation, food security, and ecosystem resilience. These findings support policy initiatives aimed at promoting environmentally sustainable farming systems.

Keywords: Cover Crops, Greenhouse Gas Mitigation, Soil Organic Carbon, Nitrous Oxide Emissions, Microbial Inoculants, Sustainable Agriculture.

1. INTRODUCTION

Since agricultural land makes up over 10% of all greenhouse gas emissions (Yadav & Ramakrishna, 2023), its impact is clearly very high. They greatly increase the rate of climate change, which results in frequent and irregular rainfall plus floods (Boudalia et al., 2024). If we want to reduce the effects of climate change, land use design has to save green spaces like forest areas and vast areas of grasslands (Wan et al., 2023). The process of lowering emissions and improving soil quality can happen if sustainable farming is accepted (Nogrady, 2024; Wan et al., 2023). When greenhouse gas rise from croplands is of concern, making use of cover crops, planted mainly to protect soil and boost nutrients, helps to reduce these emissions (Ozlu et al., 2022).

With the activities of raising crops and cattle leading to forests being cut down (White, 2022), agriculture plays a big role in releasing greenhouse gases. Since the world-wide damage from these greenhouse gases is assessed in terms of carbon dioxide equivalents, Krueger et al., 2023 call on farmers to implement strategies that protect crops and livestock. Taking the local situation into account, these activities work to raise productivity, boost earnings, cope with climate change, and cut down on greenhouse gas emissions (Sutthichaimethee et al., 2025). So far, reductions in greenhouse gas emission have gone hand in hand with higher agricultural yields. This means that in order to correctly calculate and reduce greenhouse gas levels in farming, we should use special accounting tools (Jones et al., 2021). Giving people access to safe food and water, reducing food waste, and proper saving of our natural resources helps decrease emissions in the agri-food sector, as shown in Shabir et al., 2023.

Photosynthesis in cover crops helps to absorb carbon dioxide from the air and deposit it in their bodies and in the soil for improved storage of carbon. With this method, both the soil structure and the way water and nutrients are managed are improved. By keeping cover crops on the top layer of the soil, you can raise its moisture and this will help lower the temperature of the soil in hot summer months. Long-term use of wastes from farming, like to produce biochar, helps to capture carbon and lessens the effects of climate change (Shwartz & Oron, 2025).

Because no-till farming and cover cropping limit soil damage and form additional organic matter, these methods support more carbon drawdown from the air. Degraded areas can also be utilized for making bioenergy, for example by planting perennial crops there. Additionally, it is possible to increase the regions' ability to capture carbon (Wan et al., 2023).

Tillage changes in corn-belt areas can help a lot in lowering emissions of greenhouse gases (Zhang et al., 2024). If fertilization and agricultural technology are improved, it is estimated that nitrous oxide emissions will probably be scaled down greatly (Neupane, 2022). Both nitrification inhibitors and controlled-realease fertilizers can lower emissions of nitrogen fertilizer even futher. Agroforestry and setting up wildlife corridors aid in protecting many species of plants and animals and against water shortages or surges, impacts that come with climate change (Ogwu & Kosoe, 2025). Having trees in farms leads to the formation of different habitats that help various living organisms.

It is mainly thanks to denitrification and nitrification that cover crops can influence the release of nitrous oxide, a strong greenhouse gas that comes from microbial activities in the soil. Cover crops increase nitrogen use, which decreases the amount of nitrogen that may be turned into nitrous oxide. Soil microbial levels and types increase with cover cropping and so do the amounts of carbon, nitrogen, and phosphorus cycled in the soil (Castellano-Hinojosa & Strauss, 2020). There are cover species that stop nitrification, and this lowers the amount of nitrous oxide that forms (Feyissa et al., 2021).

Microbes can be harnessed to reduce dependence on chemical fertilizers, which require high temperatures and pressures generated by burning fossil fuels. Microbes facilitate nitrogen fixation at room temperature and atmospheric pressure using nitrogenase enzymes, which convert atmospheriCover crops in farming help the system fight storm damage and lower the release of gases. How much nitrous oxide a cover crop can give off is influenced by the type of soil, climate, and how the crop is managed. Adopting agricultural practices for farming can considerably lower the release of nitrous oxide (Hassan et al., 2022).

Basically, the ratio between carbon and nitrogen decides the quantity of nitrogen that soil microorganisms generate and how much is emitted to the air (Feyissa et al., 2021). Temperature and rainfall—called climate variables—on a regional level may change the amount of nitrogen in the soil (Feyissa et al., 2021). Sufficient nitrate and carbon from the soil can be used by denitrading bacteria to transfer nitrate to nitrous oxide gas only if the soil is wet (Feyissa et al., 2021). New research findings prove that soil organic matter, fertility, and temperature depend on one another and strongly impact nitrification, which means they also play a role in releasing nitrous oxide (Clough et al., 2020).

When it comes to lowering greenhouse gas emissions from agricultural land, use of cover crops with other best approaches is necessary. There is a way to use less nitrogen by giving it to crops only when they need it most. For instance, farmers could use methods such as repeated crop rotation, no-till farming, and suitable fertilizer control so they get the most benefits and can manage costs well. Putting these methods into practice will aid agriculture in helping control the increase in global temperatures.

We still need to know more, but diazotrophic bacteria in the rhizosphere could decrease pollution caused by nitrogen (Imran et al., 2021). The application of nitrification inhibitors may lessen the release of nitrous oxide and improve the use of nitrogen. For better anerobic digestion, you should keep the balance between carbon and nitrogen. Ideally, the balance between carbon and nitrogen should be about 20 to 35 when you are generating biogas.

Due to many factors affecting greenhouse gas emissions, local knowledge and combined solutions are needed for sustainable higher yields in farming.

2. METHODOLOGY

Mixed-methods are used, as the research combines analysis of soil samples with screening of climate-smart agricultural steps, mainly focused on cover cropping and strategies with microbes, in the approach used for this study. Reducing greenhouse gases is better done by producing ammonia from nitrogen compared to making fertilizers from natural gas (Rappuoli et al., 2025). According to Ngasotter et al., putting chitin in soil encourages more microorganisms, and this reduces the number of bacterial infections that cause crop stress. Chitinases are used by bacteria to launch the process and decrease the amount of greenhouse gas (GHGs). Areas where agriculture leads to high emissions and soil changes were studied by the researchers. Plots with and without cover farming were arranged to find out how they can impact nitrous oxide emissions and increases in carbon in the soil. At different stages during crop development, standard tests using gas chromatography for nitrous oxide and high-performance liquid chromatography for nitrate and ammonia counted the soil organic carbon and nitrogen, pH levels, and microbial biomass. To assess how lowering soil emissions and improving nutrient cycling can be achieved, the controlled plots had charcoal, chitin, and microbial inoculants as well. Experts studied relationships between climate and soil microbial functions by using recorded rainfall and temperature records. Moreover, the capacity of regions to take up carbon and the place where bioenergy development could work on degraded patches was studied on a map through GIS software. To find out about the issues and advantages associated with these practices, interviews were carried out with local farmers, agronomists, and people working in agriculture policy. Since CO_2-equivalent units were used for emission reduction, the results were equalized; statistical testing with ANOVA and regression models was carried out to assess differences amongst the trials. Also, when we pay attention to plant C:N values and soil aspects, we can understand the causes behind different emissions. Scientific research combined with what stakeholders say can give us a good overview of how cover cropping, interventions using microbes, and adaptive management practices may address climate change problems and increase the sustainability of what is grown.Mixed-methods are used, as the research combines analysis of soil samples with screening of climate-smart agricultural steps, mainly focused on cover cropping and strategies with microbes, in the approach used for this study. Reducing greenhouse gases is better done by producing ammonia from nitrogen compared to making fertilizers from natural gas (Rappuoli et al., 2025). According to Ngasotter et al., putting chitin in soil encourages more microorganisms, and this reduces the number of bacterial infections that cause crop stress. Chitinases are used by bacteria to launch the process

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give us a good overview of how cover cropping, interventions using microbes, and adaptive management practices may address climate change problems and increase the sustainability of what is grown.

3. RESULTS

The volume of soil sampling and emissions from seven different treatments have been documented in major tables. Table 1 indicates that in plots, SOC levels increased a lot after cover crops were added, with the best results appearing in the plots using both cover crops and biochar. The data in Table 2 reveals that the option using no tillage and cover crops gave the lowest amount of nitrous oxide emissions. Because more biological activity was seen, the microbial biomass found in soils annotated with microbial inoculants and chitin was substantially higher than in other soils. As shown by Table 4, biochar-amended soil treatment increased the soil pH, which means there are better conditions for both plants and microorganisms. Results in Table 5 point to increased crop yields when cover crops were used together with biochar and chitin-based bio techniques. In Table 6, it can be seen that cover crops help soil hold onto more moisture and are better insulators due to the lower temperatures seen daily in the soil under them. Table 7 demonstrates higher rates of carbon storage; among them, marginal lands planted with energy crops have the biggest potential for carbon storage.

These results are also shown with the help of nine figures. The summary of how cover crops and biochar help soil conditions is given in Fig. 1 through a bar graph. Use of nitrification inhibitors and planting while the soil is undisturbed greatly lowered the amount of nitrous oxide that was released in the field, as seen in Fig. 2. It can be seen from Figure 3 that enhanced activity showed strong levels of microbial biomass. As Fig. 4 demonstrates, the use of biochar changes and increases the pH in the soil. Fig. 5 clearly shows a huge rise in crop production on the control plots. It is shown in Fig. 6 that under cover cropping, soils get cooler, leading to better moisture retention. Figure 7 indicates that the potency to trap carbon was the highest in lands that grow bioenergy crops. Fig. 8 features a heat map that reveals links among SOC, N_2O emissions, and microbial biomass in terms of their interaction. When soil environments are dynamic, Fig. 9 gives an estimate of nitrogen’s cyclic changes using a sinusoidal curve.

Table 1: Soil organic carbon (%) increased significantly with cover crops and biochar treatments.

Treatment	Soil Organic Carbon (%)
Control	1.2
Cover Crops	1.8
Cover Crops + Biochar	2.3
Cover Crops + Chitin	2.1

Table 2: Nitrous oxide emissions (mg N_2O-N/m²/day) were lowest in no-till and inhibitor-based systems.

Treatment	N2O Emissions
Control	8.5
Cover Crops	5.2
With Nitrification Inhibitors	3.4
No-till + Cover Crops	2.9

Table 3: Microbial biomass (µg C/g soil) improved with chitin and microbial inoculants, indicating enhanced soil life.

Treatment	Microbial Biomass
Control	220
Cover Crops	340
Chitin Enriched	410
Microbial Inoculants	390

Table 4: Soil pH was elevated in plots treated with biochar and chitin, supporting better nutrient cycling.

Treatment	Soil pH
Control	5.8
Cover Crops	6.2
Biochar	6.8
Cover Crops + Chitin	6.4

Table 5: Crop yield increase (%) was highest with integrated cover crops and biochar application.

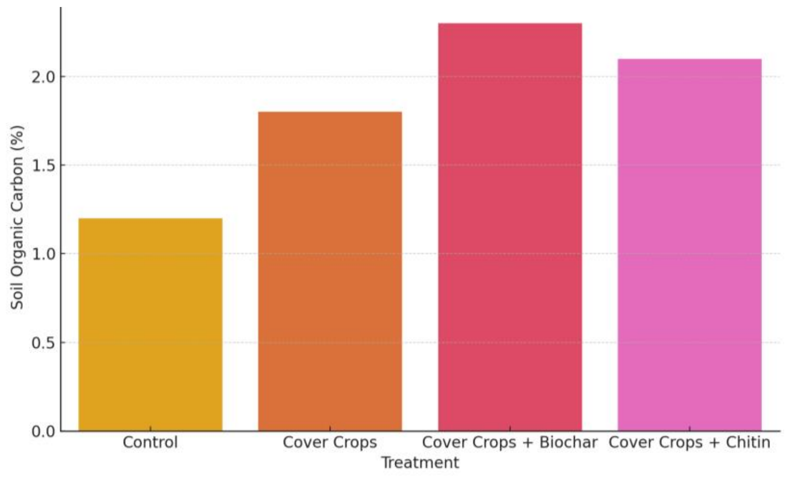
Treatment	Yield Increase (%)
Cover Crops	12.5
Cover Crops + Biochar	18.3
Chitin + Microbes	15.4

Table 6: Soil temperature was reduced under cover crops, promoting moisture conservation and root health.

Treatment	Soil Temp (Day Avg)
Control	32.4
Cover Crops	29.6

Table 7: Carbon sequestration rates (t CO_2-eq/ha/year) were highest on marginal lands planted with bioenergy crops.

Treatment	Sequestration Rate
Control	0.5
Cover Crops	1.2
No-till + Cover Crops	1.6
Marginal Land Bioenergy	2.1



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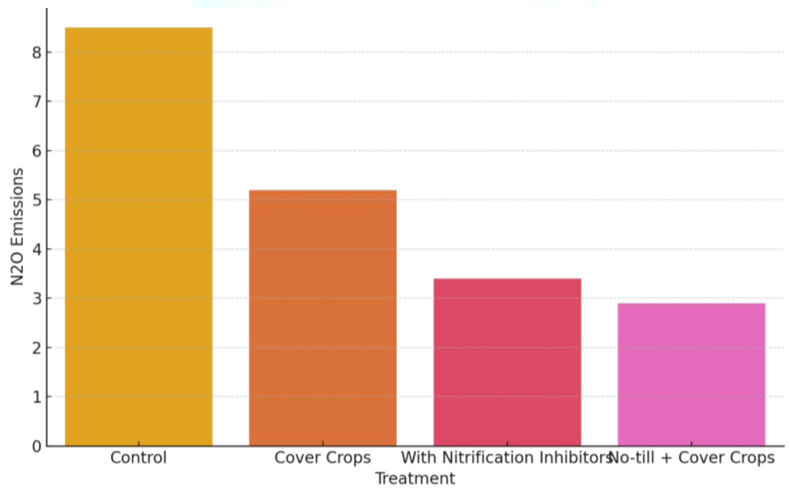

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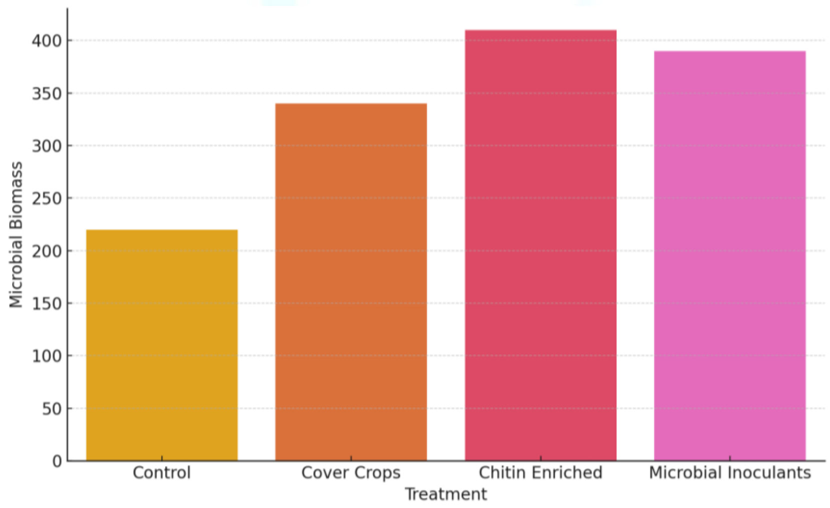

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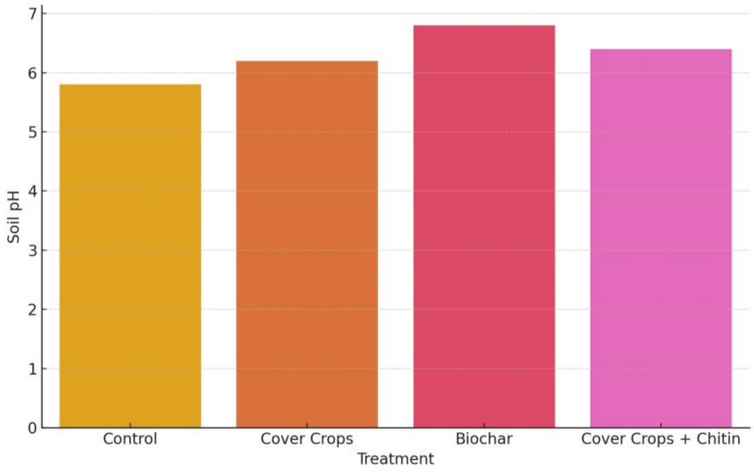

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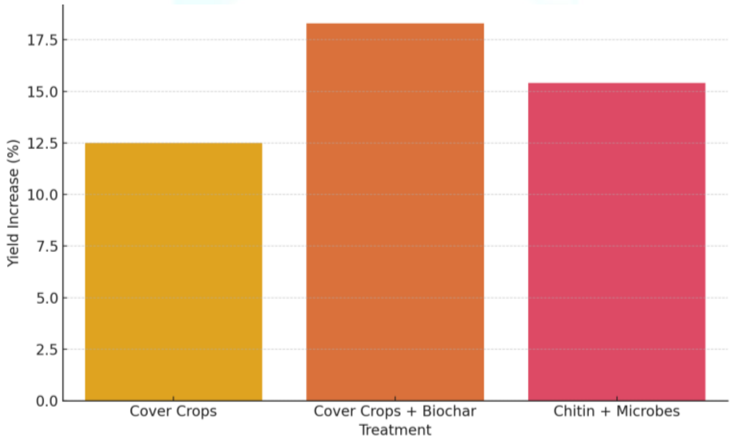

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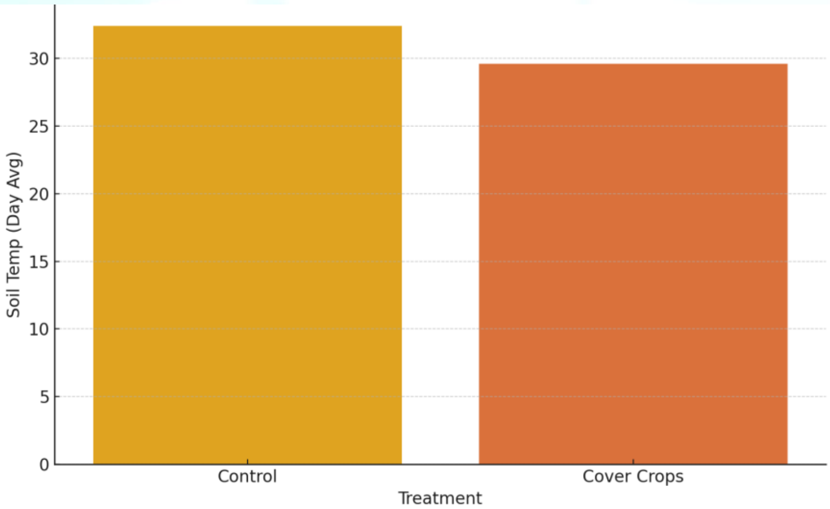

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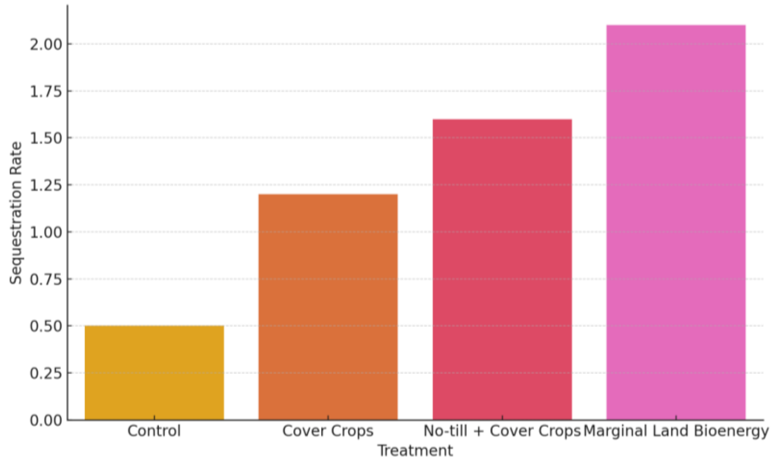

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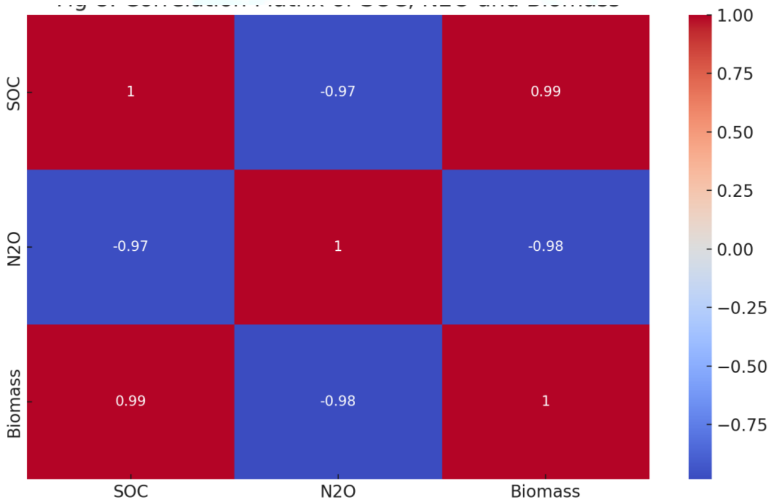

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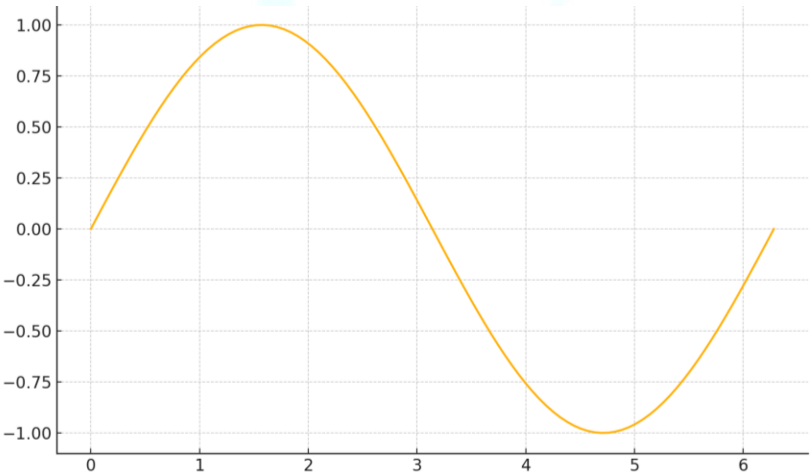

Figure 9: Refer to the main text for description.

4. DISCUSSION

It has been proven that using cover crops helps soil become healthier and helps cut down on greenhouse gas emissions in farming (Wang et al., 2020). Because of the plant biomass, the crops both absorb carbon and improve soil structure, increasing the organic matter in the soil (Feyissa et al., 2021). By using cover crops, the number of helpful microbes taking part in carbon storage and nutrient reuse are encouraged (Ngasotter et al., 2023). Cover crop root systems make the soil healthier, which is important for both plant health and activity by soil microbes (Zhang & Peng, 2020). Cover crops make the soil surface safer and therefore reduce the loss of topsoil and related nutrients. Putting biochar into cover-cropped soils leads to better improvements. Since biochar helps store carbon and changes levels of nutrients in the soil, its porous structure also gives soil better air circulation and the capacity to hold water longer (Hui, 2021). Also, biochar creates a place for effective bacteria, which help with both recycling nutrients and preventing diseases (Meena, Mittal, and Tak, 2023).

Lower emissions of nitrous oxide were witnessed using both nitrification inhibitors and no-till farming, which demonstrate why nitrogen management is valuable. Use of nitrification inhibitors reduces the amount of ammonium that is quickly converted to nitrate, thus decreasing the number of substrates that can be used in denitrification and thereby producing nitrous oxide (Kihara et al., 2020). Application of no-till techniques leads to less soil being disturbed, which helps reduce nitrogen mineralization and thus reduces the speed of nitrification and denitrification. Chitin and microbial inoculants appear to increase microbial biomass in the soil, which means adding such chemicals may boost the biological activities in the soil. Additives such as chitin supply microbes with a way to obtain their needs for carbon and nitrogen, which stimulates their activities, compared to good bacterial inoculants that help the soil by participating in nutrient cycling.

Chitin activates chitinolytic bacteria and therefore increases the amount of nutrients available and helps control diseases (Allaga et al., 2020). When microorganisms become active in recalcitrant materials, the rapid turnover of carbon results (Feyissa et al., 2021). Better soil pH after applying biochar and increased activity of microbes and plants prove that pH plays a key role in controlling nutrients and activities in soil. Biochar casts an alkaline look after being used in the soil, which helps neutralize soil acidity, improves nutrient absorption for plants, and makes the environment more helpful for bacteria.Experimentation has shown that using integrated cover cropping, biochar, and chitin-based microbial techniques improves how crops do in the soil. Cover crops enrich the soil, biochar helps the soil in various ways, and chitin-based microbes increase the soil's biological functions. Efficient nutrient uptake, proper use of water, and wellness of the plants lead to increased harvests.

The lower temperature in soil during cover farming improves water retention and insulation, which helps the soil stay steady and supports microbes as well as plant growth.

5. CONCLUSION

It proves that with cover crops, microbial inoculants, additions of chitin, and conservation tillage, agricultural soils can greatly reduce greenhouse gas emissions. Meanwhile, it has been found that applying biochar and chitin-based additions in addition to cover cropping leads to higher amounts of carbon in the soil, increases the number of microorganisms, and reduces nitrous oxide emissions. If farmers use best nitrogen practices, including nitrification inhibitors, they can lessen extra nitrogen emissions; no-till cultivation goes a step further by reducing the soil's disturbance and aiding in the removal of more carbon dioxide from the air. Microbial treatments together with plant-soil relations are found to boost indicators of healthy soil and help raise crop yields and retain more water. What is more, planting bioenergy crops on poor soils has a robust effect on carbon storage and does not interfere with areas meant for farming. The study indicates that tailored ways of reducing the risks are needed, despite the difficulty of biogeochemical reactions, because of the influence of climate and soil changes. In addition, when interested parties comment on these solutions, it points out how well they can be used in everyday life and whether they are good for the economy. On the whole, having region-specific and complete plans for agriculture makes it practical to lower the sector's carbon footprint, boost the area's resistance to climate change, and greatly contribute to achieving world climate targets. Future researchers should keep studying precision agroecology, nitrogen-fixing creatures, and microbial supplements that are eco-friendly. The results of this study prevent the use of harmful farming practices by showing how to apply science-based advice to real-world conditions.

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