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CONTRIBUTIONS OF COVER CROPS TO SUSTAINABLE AGRICULTURE IN GROWING WORLD POPULATION: A REVIEW

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ABSTRACT

Cover crops have a crucial role in promoting sustainable agriculture by providing a range of ecosystem services that furnish soil health, nutrient management, and environmental sustainability. This paper reviews the benefits, challenges, and opportunities linked with the use of cover crops in agricultural systems. Cover crops offer numerous advantages, including enhancement of soil fertility through nitrogen fixation, soil erosion control, weed suppression, and improvement of water infiltration and retention. Moreover, they support biodiversity, mitigate climate change by sequestering carbon, and deduct the need for synthetic inputs such as fertilizers and herbicides. However, the acclimatization of cover crops faces challenges related to their adaptability to diverse growing conditions, competition with cash crops, management complexity, and economic feasibility. Climate variability and soil characteristics further influence the performance of cover crops, necessitating tailored approaches for successful implementation. Despite these challenges, ongoing research and innovation efforts are exploring new cover crop species, management techniques, and integration strategies to enhance their effectiveness and scalability in sustainable agriculture. Collaboration among researchers, farmers, policymakers, and other stakeholders may eliminate the obstacles and maximize the utilization of cover crops in encouraging agricultural sustainability, resilience, and food security. Overall, using cover crops represents a promising approach for addressing pressing environmental and socio-economic challenges while fostering regenerative farming practices and enhancing the long-term viability of agricultural systems.

***Key words*:** Sustainability, Weed suppression, Integration, Biodiversity, Conservation agriculture

Introduction

Indian agriculture is robust and the biggest in the world. The expansion of Indian agriculture has helped the country achieve food security at the National level over the past few decades. However, the agricultural food systems are facing challenges to meet the increasing population's demand, which is estimated to be approximately 10 billion by 2050 (Vos and Bellu 2019). With the rapid increase in global population, the agricultural systems need to be evaluated sustainably to lower the utilization of external inputs, reduce environmental constraints, and enhance the soil status in the country.

Agriculture is one of the prominent sectors of the world's economy and a provider of biodiversity. The recent production of food and fiber is dependent on synthetic inputs, regular ploughing continuous mono-cropping, and excessive use of mechanization and water for intercultural operations that lead to improper nutrient cycling in soil, destruction of beneficial microorganisms, depletion in the groundwater level, high pest and disease infestation, increased operational costs and reduced returns of the farmers without thinking of the environmental, social and edaphic constraints (Sarvade *et al.*, 2019). Thus, resulting in the depreciation of the resources for the upcoming population. So, a sustainable approach to farming is essential.

In earlier times, the concept of sustainability was hereditarily present in the farmers as they used to grow crops for their consumption but the commercialization of the crops and the introduction of the green revolution in

India has shifted the mindset from self-consumption to earning profits. The shift has resulted in multiple developments in the domain of agriculture but with time has increased the tension regarding the soil and climatic problems as well (Amundson *et al.*, 2015). So, the current generation needs to optimize the utilization of the available resources.

Sustainable agriculture is a farming practice that aims to meet the food and nutrition requirements of today's generation without any concessions to the demands of upcoming generations. It is concerned with adopting techniques that reduce environmental damage, preserve natural resources, maintain economic sustainability for farmers, and improve the quality of life for communities. The key principles of sustainable agriculture include promoting biodiversity, reducing chemical inputs, conserving water, and soil, and fostering local and resilient food systems (Snapp 2017). By employing these techniques, sustainable agriculture seeks to improve soil health, lower water usage, minimize greenhouse gas emissions, and conserve ecosystems. Additionally, sustainable agriculture emphasizes the importance of social equity, ensuring fair treatment and economic opportunities for farm workers and rural communities (Rajbhandari 2015). Overall, sustainable agriculture offers an integral approach to farming that balances economic profitability with environmental stewardship and social responsibility, ultimately striving to create a more buoyant and unbiased food system for present and upcoming generations (National Research Council 2010). Hence, sustainable agriculture is a truly indigenous notion that not only emphasizes on the optimization of production but also increases the efficiency of the inputs and conserves them. It also reduces the economic challenges faced by farmers in conventional agriculture. Practices like agroforestry, conservation agriculture, organic farming, and integrated pest and disease management are examples of sustainable agriculture.

The plants cultivated primarily for the protection and enrichment of the soil rather than for harvest are known as cover crops. Cover crops play an eminent role in sustainable agriculture by providing numerous environmental, economic, and agronomic benefits. They are often planted during seasons when the main cash crop is absent and can provide many advantages such as reducing soil erosion, improving soil fertility, suppressing weed infestation, aiding in the management of pests and diseases, and enhancing biodiversity (Das *et al.*, 2021). By fixing the atmospheric nitrogen from the atmosphere, cover crops devote to soil health and minimize the dependence on synthetic fertilizers, thus mitigating nutrient runoff and water pollution. Economically, they can provide additional revenue streams through livestock grazing or biomass production. These kinds of crops are frequently utilized in landscaping to improve a property's appearance (Sherman 2021). They can be either grown as a mixed crop or mono-crop. Additionally, it has been exemplified that cover crops improve agricultural diversification on farms, breakthrough plow pans, add organic matter to the soil and draw pollinators. Cover crops are considered an extended investment in better farm management and soil fitness. According to Sustainable Agriculture Research and Education (SARE), Cover crops can boost soil organic matter by 15-30% over time, which would improve soil prolificacy and water-holding ability (Saba and Christy 2021). Examples of cover crops include legumes like clover and vetch, grasses like rye and oats, and brassicas like radish and mustard.

While cover crops can serve several purposes in an agroecosystem at the same time, their primary objective is usually to prevent soil erosion. Soil erosion is a process that has the potential to permanently lower productivity from soil. Dense cover crop stands physically slow down rainfall before it reaches the soil surface, eliminating the risk of erosive surface runoff and soil splashing (Toungos and Bulus 2019). Furthermore, extensive networks of cover crop roots serve to both increase soil porosity and stabilize the soil, thereby establishing appropriate habitat networks for soil microfauna and macrofauna. Cover crops maintain the soil's enrichment for a couple of years.

The involvement of cover crops in novel agricultural systems provides alternative possibilities for sustainable farming. Researchers and farmers are increasingly accepting of the growing of cover crops in conjunction with zero-tillage management, which is classified as a conservation agriculture (CA) technique (Quintarelli *et al.*, 2022). Cover crop cultivation in conservation agriculture promotes the growth of a varied range of valuable soil flora and fauna, which contribute to nutrient cycling and influence plant nutrition. Crop diversity increases the constitution and quantity of soil microbes, which can improve nutrient uptake and cycling. Cover crops have the potential to generate residues while also diversifying the CA system (Shrestha *et al.*, 2020). Indeed, one of the core tenets of conservation agriculture is to maintain soil cover using crop residues that remain on the soil's surface. Nevertheless, crop residues become insufficient to cover the soil when an excessive amount of time passes between the harvest of one major crop and the planting of the next, leaving a gap where the soil is uncovered to the elements (Fischer and Connor 2018). Cover crops are an important component of conservation

agriculture that can help to close this gap and improve the enhancement of the CA system, not only by enhancing soil characteristics but also by promoting greater biological variability in the agroecosystem.

Although cover crops relate to sustainable cropping systems and positively influence crop productivity and the environment, their successful adoption raises several issues that must be addressed to prevent misleading farmers from implementing efficient agroecosystems. Thus, the primary goal of this analysis is to provide a critical overview of the utilization of cover crops to evaluate the changes in environmental characteristics and cropping patterns because of the adoption of cover crops.

Cover Crops

Cover crops are a fundamental integrant of sustainable agriculture. Cover crops, also termed as service crops are herbaceous plants cultivated during the fallow period when the chief crop is absent in the field. It is a close-growing crop grown used largely to safeguard and enhance soil between seasons of ordinary crop production or between trees and vines in orchards (Sherman 2021). It maintains both the physical equilibrium of the soil and crop. They are alternatively grown with agronomic crops to provide multiple benefits to edaphic and environmental conditions. The different terms associated with cover crops are intercrops, border crops, companion crops, intermediate crops, border crops, green manure crops, break crops, trap crops, non-commercial crops, scavenger crops, nurse crops, rotational crops, insectary crops, nitrogen crops, mixed crops, and so on.

Kinds of Cover Crops

Diversified crops can be used as cover crops depending on the cropping systems. Over the years, legumes and grasses have been extensively used as cover crops (Quintarelli *et al.,* 2022). Now-a-days, brassicas are also used as one of them. However, it is classified into three major categories. They are as follows:

- **Leguminous cover crops**: Legume crops, such as beans, clover, peas, and vetch, can fix atmospheric nitrogen with nitrogen-fixing bacteria present in a symbiotic relationship in the root nodules. They improve the soil's fertility for future crops by adding nitrogen to it. When plants grow, their taproot system helps to loosen the compaction beneath the surface.
- **Grass-cover crops**: It is commonly recognized that the wide root systems of grass-cover crops, such as barley, rye, oats, and wheat, improve soil structure, stop erosion, and scavenge nutrients. They provide robust ground cover and efficiently inhibit the growth of weeds. Their protective root systems are made of fibrous threads that withstand erosion.
- **Broadleaf non-legumes**: The deep taproots of brassica cover crops, such as rapeseed, mustard, and radish, aid in improving drainage and breaking up compacted soil layers. Additionally, they release chemicals that can suppress nematodes and other pests that live in the soil.

Benefits of Cover Crops in Sustainable Agriculture

Cover crops offer numerous benefits in enhancing edaphic conditions, crop productivity, and environmental sustainability. Cover crops offer a myriad of benefits in agricultural systems, making them an essential tool for sustainable farming practices. They are a valuable source of forage for livestock, diversifying farm income streams. Overall, integrating cover crops into agricultural rotations fosters resilience, sustainability, and long-term productivity, making them an invaluable component of the modern agricultural system. The several advantages of the cover crops are:

Soil Health Improvement

Cover crops minimize erosion by holding soil in place with their root systems. They also boost soil organic matter, enhance soil structure, and amplify soil fertility by fixing nitrogen and other nutrients. First, their large root systems reach deep into the soil and remove compacted layers, reducing topsoil loss. Additionally, cover crops contribute to the accumulation of organic matter in the soil by depositing their biomass upon decomposition. This organic matter serves as a source of nutrients for soil microorganisms and promotes the formation of stable aggregates, which further improves soil structure and fertility (Pontifex 2019). Several cover crops, particularly legumes like clover and vetch, establish symbiotic relationships with nitrogen-fixing bacteria to fix the atmospheric nitrogen. This process upgrades the soil with this needed nutrient, benefitting subsequent crops and reducing the reliance on synthetic fertilizers (Kakraliya *et al.,* 2018). Overall, by enhancing soil structure, fertility, and nutrient cycling, cover crops contribute significantly to promoting extended soil health and sustainability in the agricultural system.

Weed Suppression

Cover crops compete with weeds for light, water, and nutrients, thereby reducing weed pressure and the utilization of herbicides. Cover crops create a dense canopy that shadows the soil and prevents weed seeds from sprouting and growing. Additionally, the vigorous

root systems of cover crops physically disrupt weed growth and establishment. This natural weed management approach lessens the dependence on herbicides, thereby reducing synthetic inputs and minimizing environmental impact (Hodgdon 2013). Furthermore, as cover crops break down, they refine the soil with organic matter, enhancing soil structure and fertility, which further contributes to weed suppression over time. Integrating cover crops into crop rotations or as intercrops can provide continuous weed control throughout the year, promoting sustainable and ecologically friendly agricultural weed management practices.

Nutrient Management

Certain cover crops, like legumes, fix the atmospheric nitrogen, making it abundantly available to subsequent crops. This minimizes the need for synthetic fertilizers and enhances soil fertility. Additionally, cover crops scavenge and hold onto nutrients, preventing them from leaching into groundwater or being lost through runoff. These nutrients are released back into the soil by the decomposing cover crops, enriching it and acting as a natural fertilizer for the crops that follow. In addition to increasing soil fertility, this nutrient cycle lowers the possibility of nutrient imbalances and overfertilization, encouraging more environmentally friendly farming methods (Rosolem *et al.*, 2017). Moreover, by enhancing soil health and fertility, cover crops contribute to the extended productivity and dependence of agricultural ecosystems, offering a cost-effective and environmentally friendly solution for nutrient management.

Water Management

Cover crops can help manage water by reducing runoff and increasing water infiltration, thus improving water regulation in the soil. When cover crops are grown during non-cropping periods or between cash crop cycles, their dense root systems penetrate deep into the soil, creating channels for water to infiltrate. This increased infiltration capacity helps to mitigate soil compaction and surface sealing, allowing water to percolate more effectively into the soil profile. Consequently, water retention within the soil is improved, eliminating the threat of waterlogging and nutrient leaching. Furthermore, cover crops perform like a protective barrier against erosion, minimizing the loss of topsoil and sediment runoff during heavy rainfall events (Datta *et al.*, 2022). Overall, the implementation of cover crops in agricultural systems enhances water infiltration, reduces runoff, and improves water retention, contributing to more sustainable water management practices.

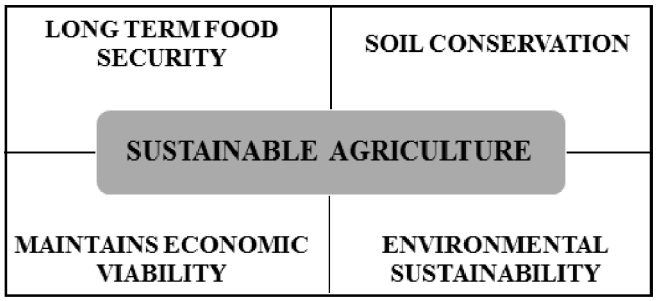

Fig. 1: Benefits of Sustainable Agriculture.

Pest and Disease Management

Some cover crops, like certain brassicas, secrete compounds that reduce the population of soil-dwelling pests and diseases, reducing the utility of chemical pesticides. These compounds known as biofumigants, can restrict the growth of pathogens and nematodes, reducing their populations in the soil. The dense foliage and vigorous root systems physically obstruct pests' access to the soil and subsequent crops (Didenko *et al.*, 2021). Furthermore, by enhancing soil quality and microbial activity, cover crops create an environment that is less favorable for pathogens, thereby reducing disease pressure. Integrating cover crops into crop rotation systems can disturb pest and disease cycles, minimizing dependence on chemical pesticides and promoting sustainable pest management practices (Sherman 2021).

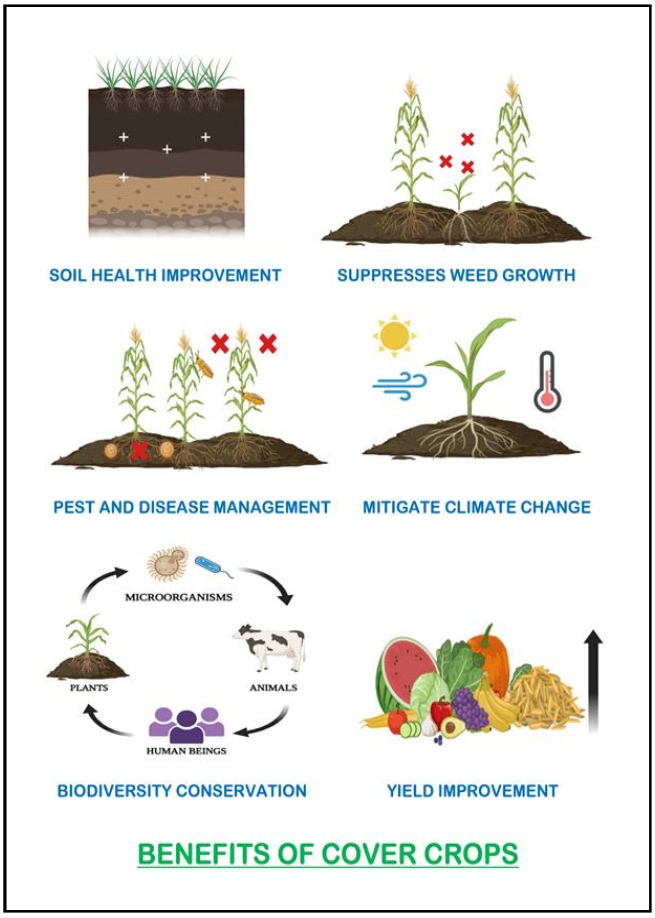

Fig. 2: Benefits of Cover Crops.

Table 1: Examples of Cover crops.

Crops	Examples
Cereals and Grasses	Cereal rye, Wheat, Oats, Barley, Sorghum, Pearl millet, Ryegrass, Sudangrass, Annual fescue
Legume Crops	Chickpeas, Cowpeas, Cluster beans, Moth beans, Sunhemp, Velvet beans, Pigeon peas, Tepary beans, Lablab beans, Alfafa, Kura clover, Red clover, Sweet clover, White clover, Lentil
Brassica Crops	Rapeseed, Mustard, Cauliflower, Cabbage, Broccoli, Turnip, Radish, Kale, kohlrabi, Rutabaga, Canola, Collard, Komatsuna, Tatsoi, Rapini, Brussels sprouts
Fruit Crops	Blackberry, Blueberry, Cranberry, Raspberry, Strawberry, Grapes, Kiwi, Mulberry, Passionfruit, Fig
Other Plant Species	Sunflower, Safflower, Squash, Chicony, Buckwheat, Beet, Flax, Spinach, Phacelia, Chards, Edible Amaranth

Overall, cover crops contribute to an integrated approach to pest and disease management, enhancing the resilience and sustainability of agricultural systems.

Biodiversity Conservation

Cover crops can provide shelter and feed for beneficial birds, insects, and other wildlife, promoting biodiversity in agricultural landscapes. Flowering cover crops attract pollinators such as bees and butterflies, promoting pollination services essential for crop production and wild plant reproduction (Wilson *et al.*, 2018). Cover crops can also serve as host plants for natural enemies of pests, helping to maintain a balance in insect populations, and lowering the need for chemical pesticides. Moreover, the presence of cover crops enhances soil health, which indirectly supports biodiversity by providing a more hospitable habitat for soil organisms like bacteria, earthworms, and fungi.

Climate Change Mitigation

Cover crops aid in the diminution of climate change by lowering atmospheric carbon dioxide levels through the sequestration of carbon in the soil. During photosynthesis, carbon dioxide is absorbed by cover crops and transformed into organic matter. This organic matter is then incorporated into the soil as the cover crop decomposes, where it can remain stored for extended periods. By maximizing soil organic matter content, cover crops enhance soil carbon sequestration, effectively removing carbon dioxide from the atmosphere and mitigating its effect on climate change (Lal, 2015). They contribute to reducing greenhouse gas emissions by improving soil health and minimizing the need for synthetic fertilizers, which are significant sources of emissions. As such, integrating cover crops into agricultural systems can play a major role in extenuating climate change by both captivating atmospheric carbon and promoting more sustainable farming practices.

Improved Crop Yields

Cover crops can enhance subsequent crop yields by improving soil health, nutrient availability, and water retention, leading to healthier plants and higher productivity (Sharma *et al.*, 2018). Cover crops, such as legumes, enrich the soil with this essential nutrient by fixing the atmospheric nitrogen for succeeding plants. Moreover, by suppressing weeds, cover crops reduce competition for resources like water, light, and nutrients, allowing the main cash crops to thrive without interference (Hodgdon 2013). Cover crops translate into improved crop productivity, as healthier soils and reduced competition result in higher yields and better-quality harvests for farmers.

Erosion Shield

The dense rooting systems of cover crops help to stabilize soil, lowering erosion caused by water and wind. Cover crops effectively protect the soil from the erosive forces of wind and water. The extensive root systems penetrate deep into the soil, binding soil particles together and increasing soil stability. This root network acts as a barrier, preventing soil erosion by keeping the soil in place and lowering the impact of rainfall and runoff (Toungos and Bulus 2019). Additionally, the aboveground biomass of cover crops intercepts raindrops, dissipating their energy and minimizing soil detachment. Overall, the implementation of cover crops as part of erosion control strategies not only mitigates soil loss but also helps in maintaining soil fertility and structure, promoting sustainable agricultural practices, and safeguarding the long-term productivity of farmland.

Economic Benefits

While there are costs associated with planting and managing cover crops, the extended benefits, such as enhanced soil health, reduced production costs, and increased yields, can outweigh these expenses, providing economic benefits to farmers. Cover crops help to mitigate the impact of extreme weather events by reducing soil erosion and improving water retention, which can ultimately safeguard against crop losses and protect farmers' investments (Tribouillois *et al.*, 2018). Additionally, cover crops contribute to weed suppression, lowering the need for costly herbicides and labour-

Table 2: Primary Benefits of Various Cover Crops (Moncada and Sheaffer 2010; Presley *et al.*, 2012).

Categories of Crops	Examples	Primary Benefits
Winter Cover Crops	Brassicas, Hairy vetch, Oats, Red clover, Winter rye	Controls or prevents soil erosion and nitrogen fixation, enhances soil structure, increases soil organic matter
Summer Cover Crops	Buckwheat, Cowpea, Sorghum Sudan grass, Sunhemp	Boosts soil organic matter, enhances soil microbial count, reduces weed population, reduces soil erosion
Legumes	Beans, Crimson clover, Hairy vetch, Peas, Red clover	Nitrogen fixation prevents soil erosion, increases organic matter concentration, supports beneficial insects and pollinators
Non-legumes	Annual ryegrass, Buckwheat, Barley, Brassicas, Oats, Wheat	Prevents soil erosion and nutrient scavenging, provides ground cover, reduces weed population

intensive weed management practices. Over time, the cumulative benefits of improved soil health, increased yields, and lowered production costs can result in significant long-term economic gains for farmers, making cover crops a valuable and sustainable investment in agricultural profitability.

Limitations of Cover Crops in Sustainable Agriculture

While cover crops have numerous benefits in sustainable agriculture, they also come with some limitations:

Increased Cost of Cultivation

While cover crops offer various benefits, such as soil health improvement and weed suppression, they also incur additional expenses for farmers. Firstly, there are upfront costs associated with purchasing cover crop seeds, which can vary depending on the species and quantity needed. Additionally, farmers may need to invest in specialized equipment or modify existing machinery for cover crop planting, termination, and management. These equipment costs can be significant, especially for marginal or resource-limited farmers who may not have access to suitable machinery. Moreover, cover crop management requires additional labour and time, from planting and monitoring to termination and incorporation. This can strain farm resources, especially during busy planting and harvesting seasons when labour is already in high demand (Kaye and Quemada 2017). Furthermore, there may be indirect costs related to potential yield reductions in cash crops due to competition with cover crops for water, nutrients, and sunlight. While cover crops can enhance soil fertility and lower input costs in the long run, the initial investment and ongoing management expenses may pose challenges for farmers, particularly those operating on tight budgets.

Competition with Cash crops

Cover crops can compete with cash crops for water, nutrients, and sunlight, potentially reducing yields if not managed properly. Farmers must meticulously choose cover crop species and timing that can minimize competition. Additionally, the complexity of managing cover crops alongside cash crops adds another challenge, requiring careful planning and coordination to optimize both cover crop benefits and cash crop production (Bergtold *et al.*, 2019). Failure to effectively manage this competition can result in decreased profitability and productivity, highlighting the need for strategic management practices and tailored solutions to ensure the effective adaptation of cover crops into sustainable agricultural systems.

Harbor Pests and Diseases

Certain cover crops can host pests and diseases that may affect subsequent cash crops. Certain cover crops, like brassicas, may harbor pests such as aphids or diseases like clubroot, posing risks to crop health. They can inadvertently provide refuge and breeding grounds for pests and pathogens (Didenko *et al.*, 2021). These challenges farmers aiming to minimize reliance on chemical pesticides and maintain crop health within sustainable farming systems. Additionally, if cover crops are not managed effectively, they may contribute to pest and disease pressure by providing suitable habitats and increasing pest populations (Sherman 2021). Therefore, farmers must carefully select cover crop species and employ appropriate management practices, like timely termination and crop rotation, to mitigate any risk of pest and disease outbreaks and warrant the extended sustainability of the farming system.

Limited Adaptability

Some cover crop species may have limited adaptability to specific soil conditions or cropping systems. Farmers in certain regions or with cropping practices may have fewer options for suitable cover crop species. Limited adaptability may also result in lower establishment success rates and reduced performance of cover crops, ultimately diminishing their potential contributions to soil conservation, nutrient management, and overall sustainability in agriculture (Kaye and Quemada 2017). Addressing this limitation requires ongoing research and

development efforts to identify and breed cover crop varieties that are more adaptable to diverse agricultural environments and management practices, thereby enhancing the scalability and effectiveness of cover cropping as a sustainable agriculture strategy.

Conclusion

The cover crop is a vital component of sustainable agriculture. Cover crops can aid in engineering the idea of sustainable agriculture i.e., economic viability, environmental compatibility, and social acceptability; by offering and promoting both direct and indirect advantages. To develop and maintain soil quality to support economic crop production with enhanced ecosystem services, cover crops, or a blend of cover crops, help give microbes food and energy to carry out tasks related to soil biodiversity and efficiency, soil chemical balancing, and soil physical stability. Cover crops can also be used as a living or dead surface mulch. They can reduce soil compaction, improve soil aggregation and structural stability, improve water infiltration, minimize soil erosion, provide home-grown nitrogen, recycle nutrients, and lessen insects and pathogens by increasing predator biodiversity. Rapidly proliferating cover crops can inhibit the population of weeds and minimize the use for herbicides, lowering the possibility of environmental contamination spreading widely. Legume cover crops' annual infusion of biologically fixed nitrogen can significantly lessen reliance on expensive chemical fertilizers. Cover crops also provide a chance to incorporate crop diversification in the current cropping season. The main barriers to cover crop adoption in agricultural production systems include higher costs, timely termination, crop rotation design, and insufficient economic analysis research. Future studies should use a systems-based approach to better understand cover crop multifunctionality and address hurdles to integration in various production systems and environmental situations. While challenges remain in optimizing cover crop selection, management, and integration into cropping systems, ongoing research, innovation, and knowledge-sharing efforts hold promise for overcoming these barriers and unlocking the full potential of cover cropping in sustainable agriculture. Therefore, fostering widespread adoption and effective implementation of cover crops represents a critical pathway towards achieving agricultural sustainability, resilience, and food security in the face of evolving environmental and socio-economic challenges. It has been demonstrated that cover crops can build soil organic matter and sequester carbon, improving the soil's condition. However, increased crop productivity and boosted agroecosystem services result from developing and enhancing soil quality using cover crops in sustainable agriculture. So, cover crops are well adopted in today's farming system to enhance productivity and provide more profitable returns to farmers along with the conservation of resources for the upcoming population.

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