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COVER CROP AS APPROACH FOR SUSTAINABLE AGRICULTURE: A REVIEW

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ABSTRACT
Sustainable agriculture is essential for fulfilling the need of human beings in an eco-friendly manner without compromising the needs of future generations. The cover crop has been seen as the alternative and cost-efficient method to promote sustainability by enhancing nutrient cycling, fertility, good soil health, reducing climate change effects, and ultimately the better yield of crops. However, they are not grown worldwide and are not seen as a measure of sustainability. Only a few long-term trials and experiment has been carried out to examine its long-term effect on the ecosystem and it is still unsure if it can establish as the best method for maintaining sustainability in agriculture or not. So, various articles and journals were review and only those topics were covered which are considered as the measure to look at while evaluating sustainable agriculture. We found a cover crop to increase crop yield, weed suppression, improve the physical, chemical, and biological properties of soil, improve fertility, sequestrate carbon, be economically profitable, and maintain good soil health. Legume crops capable of biological nitrogen fixation and producing good biomass should be given priority while growing cover crops. Appropriate time, cropping patterns, season, management system, and species should be considered while growing cover crops. Hence, cover crops can be a good approach to sustainable agriculture.

KEY WORDS
Soil health, fertility, nitrogen fixation, cover crops, sustainable agriculture.

Sustainable agriculture is becoming an important term for productive, economical, environment-friendly, and socially desirable agriculture. It further promotes resource conservation and environmental protection and enhances global food production (Schaller, 1993). Over time, agriculture has undergone various changes and developments worldwide, with different practices and techniques being employed in different regions. However, the challenges faced by agriculture today are numerous and complex. Issues such as population growth, soil depletion, land scarcity, climate change, deforestation, water shortages, natural resource degradation, labor shortages, and overuse of non-renewable resources and chemical fertilizers have significantly impacted the agriculture industry. This has led to unsustainable water consumption, heavy irrigation, labor shortages, and rural-urban migration, resulting in declining food security. To address these existing problems, people and governments must work together by formulating effective policies to improve the condition of agriculture. This may include the development of different technologies and crop varieties that are resilient to natural calamities, as well as the adoption of strategies to ameliorate climate change effect, such as reducing the excess consumption of fossil fuels and increasing the use of renewable resources. It is important to encourage and support sustainable agricultural practices to ensure that food security is maintained and agriculture can continue to support human populations (Wendimu & Moral, 2021; Mondal, 2010; Veeck, Veeck, & Yu, 2020). A rapid change in climate with biodiversity loss and water scarcity has hinted at the need for sustainability toward global agriculture (Liz, et al., 2019). So, it is time to rush for the ecosystem-friendly farming practice for agriculture production to be sustained (Caesar, Abunga, Saa, & Nantui, 2018).

Cover crops are simply the crops that cover the soil. They are also called as "green manures", "catch crops", or "living mulch". They are first used in annual cropping system during lean period to reduce soil erosion (T.C. & J.W., 2011). Mostly two types of cover crops are grown worldwide; grasses and broadleaves (leguminous and non-leguminous). Grasses are valued for its quick breakdown and its ability to form a thick layer of soil coverage. Broadleaf plant species are favored for its rapid decomposition and release of nutrients into soil, while leguminous crops are looked for their capability to capture N from the air and incorporate it into the soil (Komlan, C, & Koffi, 2022). Cover crops are highly valuable for promoting sustainable agriculture production due to their exceptional ability to enhance soil health. These crops offer several benefits such as reducing wind erosion or water, improving soil structure by increasing aggregate stability, enhancing water infiltration by improving soil hydraulic properties, and boosting soil organic carbon (SOC) and microbial populations while decreasing nitrate N leaching. All these benefits play a vital role in reducing groundwater pollution. They also help in adapting with climate and mitigating greenhouse gas emissions. They achieve this by reducing soil erosion, which helps to mitigate carbon emissions that occur when topsoil is lost. Additionally, cover crops contribute to carbon sequestration (Sharma, et al., 2018).

Cover crops (CC) are an indispensable unit of sustainable agricultural systems and are important for sustainable food production (YAO-CHI, BRADLEY, R, & A., 2000). They are an effective and environmentally friendly method for enhancing soil health and crop productivity. By this, cover cropping can increase the efficiency of nutrients, reduce the need for external nutrient inputs, and promote soil health. Cover crops can have positive effects on soil properties, such as reducing soil bulk density, improving soil structure, and enhancing water storage capacity. Additionally, cover crops can increase soil organic carbon and nitrogen levels, resulting in the availability of essential nutrients, such as phosphorus, potassium, calcium, iron, and magnesium, for crop growth. Additionally, cover cropping can foster a more favorable environment for microorganisms, contributing to a greater population and diversity of soil micro-organisms (Aurelio, et al., 2022; Komlan, C, & Koffi, 2022). They have the capacity to quickly take root in suitable conditions, requiring sufficient soil or dry matter, and are able to convert atmospheric nitrogen (N) into usable forms. Furthermore, cover crops can develop a deep root system that allows for nutrient uptake from lower soil depths, and they produce organic matter with a low-residue carbon/nitrogen (C/N) ratio. Moreover, they do not exhibit any phytotoxic or allelopathic effects on subsequent crops (N.K., V.C, & B.A., 2005). They are also reported to suppress the weeds and increase the availability of exchangeable nutrients such as Mg^{2+} and K^{+} (Sharma, et al., 2018). Thus, this review mainly focused on the objective to explore the ability of cover crops for sustainable agriculture. The key elements like soil health, nutrient management, weed management, carbon sequestration, and economic benefits were analyzed which are crucial and effective requirements for sustainable crop production.

Table 1 – List of cover crops belonging to different families and growing in different seasons with their scientific name

S.N.	Common name	Scientific name	Family	Growing Season
1	Crimson Clover	*Trifolium incarnatum*	Fabaceae	Winter
2	White clover	*Trifolium repens*	Fabaceae	Spring
3	Cowpea	*Vigna unguiculata*	Fabaceae	Summer
4	Alfa-alfa	*Medicago sativa*	Fabaceae	Spring-Fall
5	Soybean	*Glycine max*	Fabaceae	Summer
6	Hairy vetch	*Vicia villosa*	Fabaceae	Winter
7	Broad beans	*Vicia faba*	Fabaceae	Winter
8	Rye grass	*Lolium perenne*	Poaceae	Spring
9	Wheat	*Triticum aestivum L.*	Poaceae	Winter
10	Corn	*Zea mays*	Poaceae	Winter-Spring
11	Pearl millet	*Pennisetum glaucum*	Poaceae	Summer
12	Sudan grass (sorghum)	*Sorghum bicolor ssp. drummondii*	Poaceae	Summer
13	Oats	*Avena sativa*	Poaceae	Spring
14	Barley	*Hordeum vulgare*	Gramineae	Spring
15	Buckwheat	*Fagopyrum esculentum*	Polygonaceae	Summer
16	Arugula (salad rocket)	*Eruca sativa*	Brassiceae	Late summer-fall
17	Canola	*Brassica napus*	Brassiceae	Winter-spring
18	Forage radish	*Raphanus sativus*	Brassiceae	Late summer- early Fall
19	Mustard	*Brassica spp*	Brassiceae	Fall

The secondary data and research, including review and research articles are taken into account. Various journal articles, books, website, presentation, conference papers were review and analyzed. Only the key points related the topics and subject matter were included for this review.

Cover crop (CC) has the potential to increase crop yield by decreasing the requirement for chemical fertilizers. In an experiment in China to determine the factor affecting crop yield due to cover crop, they found CC types (legume or non-legume), CC season (winter or summer), and N input are different factor that plays a great role in crop yield. They reported a greater effect of legumes in increasing the crop yield (14.6 ± 4.0 %) than that of non-legume crops. It might be due to higher N concentration by legume crop through biological N-fixation and also due to differences in climatic and environmental conditions. Additionally, the rice system with winter CC in subtropical climate support rice growth with enough water and heat. The higher mean annual temperature (MAT) enhanced the activity of microorganisms in the soil, leading to faster decomposition of crop residues and increased nutrient availability for the next main crop. It also improves the quality of the topsoil by increasing the amount of water-stable aggregates, which can affect positively on the yield of the main crop and vice-versa for summer CC in wheat. Also, N input is negatively related to crop yield and shows a good response in lower N rates might be higher mineralization of CC residue at low N rates (Fan, et al., 2021). Multi-species cover crops are more beneficial as cover crops than single species. Soil health mixture (SHM), a multispecies containing five crops (Cereal Rye, Purple Top Turnip, Daikon Radish, Whole Oats, and Crimson Clover) are reported to enhance the crop yield by 15% than the control in Milan, Tennessee. They resulted in higher crop yield than the two-crop species. The SHM can conserve soil moisture and enhance inorganic N status (Chu, 2017). Also, the use of forage radish and hairy vetch is beneficial for increasing the barley yield by accumulating higher biomass and higher N availability for subsequent crops. They both increased the yield by 11 and 9% respectively but no increase in the grain yield was seen. Forage radish was reported to store a large amount of residual N (86 kg ha^{-1}) with its deep root from the deep soil layer and highest biomass (3178 kg ha^{-1}) and made available to the subsequent crop. It also requires less N, suppress weed, and makes soil less compact (Toom, et al., 2019). In Switzerland, cover crops in an organic system with reduced tillage contributed +24% in yield and the lowest yield in a conventional system with tillage (+2%) (Wittwer, Dorn, Jossi, & Heijden, 2017). In south-central Colorado, it was found that sorghum-sudangrass with and without hay covered yielded more potatoes. Both marketable tuber and total tuber yield were more in for 2 years (2006-2007) (Essah, Delgado, Dillon, & Sparks, 2012).

However, several research studies have suggested that cover crops may have adverse impacts on yield-related factors. Climate types, soil, species of cover crop, and its management plays a vital role in crop yield. From meta-analysis, it was reported that cover cropping reduces the yield of cash crops, soil water content, and soil N by 7%, 18%, and 25% respectively. Although some positive response was reported in the yield in tropical and continental climate types, the result seems degrading in dry-land (-11.1%) and temperate (-12.4%) climates. The vertisols soil type had conflicting responses to yield in the different climatic zone and reported a decrease of 30% in temperate. This might be due to differences in the rainfall pattern in tropical and temperate. Additionally, non-legume cover crops resulted in a decreased crop yield than that of legume cash crops. Cover crop belonging to the family like Poaceae and Brassicaceae decreases the crop yield. Similarly, the type of subsequent crops and the exact termination period of cash crops should be considered for getting better overall results (Garba, Bell, & Williams, 2022). Also, in a field trial using satellite imagining in accessing the influence the cover crop in yield, it was found that although 0.65% in maize and 0.35% in soybean yield increase were reported, but in the long term the yield is reported to decrease in Indiana, Ohio and Minnesota (Seifert, Azzari, & Lobell, 2018).

Soil physical properties, such as color, texture, density, structure, porosity, aggregate stability, and temperature, have a significant impact on various soil processes including infiltration, nutrient cycling, erosion, and biological activity. Cover crop helps in decreasing the bulk density and thus increasing the total porosity of the soil. Water infiltration and water retention capacity can also be improved due to improved soil structure by cover crops (Nakajima, Nakamura, Kawamura, & Mihara, 2020). Also, the use of CC with no-till and crop rotation is more beneficial in long run. They noted a 9% decrease in bulk density in the second year and in the third year 3% decrease, and the pore space increased by 12% by the use of rye. The moisture content was reported to be 16% greater with rye in soybean/corn interaction, especially at the soil surface at 10cm depth, which was observed to hold more moisture into the soil with the planting of rye. The moisture content was reported to be 16% greater with rye in soybean/corn interaction. However, concluded that nature is not easily predictable and more research is required for its verification (Haruna & Nkongolo, 2015). Similarly, it also effect on water retention, soil structure, and pore sizes. No-till with cover crops resulted in bimodal pore size distribution in the top 0-5cm soil layer with an effective diameter ranging from 4 and 500 µm. And while examining water retention and conductivity from the HYDRUS-2D irrigation simulation, CC in the top layer is found to have high water-storing ability. Thus, in the long run, no-till and the cover crop is found not only to improve the soil structure but also improve soil water conductivity and storage (Araya, Mitchell, Hopmans, & Ghezzehei, 2022). It is also reported that sesbania as a green manure helps to decrease on an mean bulk density by 5% and increase the total porosity by 8%. The surface soil showed a significant increase in porosity, mainly due to the added organic matter and sesbania's deep root system, which improved both macropores and mesopores. (Sultani, Gill, Anwar, & Athar, 2007). The use of rice straw as mulch and legume crops as CC is reported to decrease soil bulk density by 0.07 and 0.08 gcm^{-3} at depths of 0-10cm and 10-20cm, respectively. Additionally, porosity was increased by approximately 2.74% and 3.01%, and moisture retention was improved by 7% at the soil surface compared to the control. The maximum plant available water was 23% (Dung, Ngoc, Dang, & Hung, 2022). From an experiment in Texas, USA, it was reported that black oat as a cover crop effects soil temperature. No mowed cover crop had lowered soil temperature than that of sickle mowed or flail mowed. The flail mowed soil might had contained numerous light texture residue which absorbed more incoming radiation and also due to least mulching material to insulate the soil (Zibilske & Makus, 2009). In a two year trial (2018-2020) in Southwestern Ontario, Canada, under corn-soybean-winter wheat/cover crop rotation, soil temperature changed accordingly with CC. In winter, soil temperature under CC increased at the depth 15, 30, and 45 cm with maximum at 15 cm reached up to 5.7^0 C. In spring, the soil temperature was cool up to 2.4^0 C than that of control with no cover crop. These changes in temperature could have both varying impact in the crop production and environment (Yang, Reynolds, Drury, & Reeb, 2021). However, (Mendis, Udawatta, Anderson, Ansari, & Salceda, 2022), reported no differences in soil thermal conductivity by the use of cover crop but grass showed few soil thermal conductivity and suggested that long term experimentation is needed with the cover crop to observe the difference.

The accumulation of crop residue from the cover crops helps in the enhancement of the soil organic carbon (SOC) along with the addition of N and P, K, Ca, Fe, and Mg (Komlan, C, & Koffi, 2022; Sharma, et al., 2018). In an experiment in a citrus orchard in Vietnam, it was found that at the top surface soil (0-10cm) macronutrients like Ca, K, and Mg increased in concentration by the repeated use of cover crops for 3 years. The use of rice straw mulch (RSM), and legume straw mulch (LCC), increased the Ca and K nutrient in the soil. The content of micronutrients such as Cu, Fe, Zn, and Mn were also increased when the rice straw and legume were used as a cover crop (Dung, Ngoc, Dang, & Hung, 2022). Also, (Khan, et al., 2021) in the greenhouse trial in Canada reported a 20% higher concentration of SOC due to crop residue with the highest for buckwheat (3.12%). The soil pH, P, and K concentration were also increased in the brown mustard and Ca concentration was highest for phacelia+pea treatment. Also, in field trials the mixture of cover crop helped in increasing the soil organic matter. The soil organic carbon (SOC), and hydraulic conductivity can be enhanced but a significant effect on the soil pH and electrical conductivity (EC) was not found. However, soil compatibility can be improved by improving SOC due to cover crops (Nakajima, Nakamura, Kawamura, & Mihara, 2020). It was found that legume monoculture (pea) acquired maximum N (118 kg N ha^{-1}) while non-legume accumulated 30-46 kg N ha^{-1}.

Pea cover crop yielded more N even against combined non legume cover crop + 300 kg N ha^{-1} manure and stand as the cost efficient method and source for N (Kaye, et al., 2019). From a field trial in Spain, it was found minimum organic matter (OM) in the site ST2 and ST3 in June-Oct when the ground cover was lowest and moderate to highest OM when ground cover was moderate (Nov-Feb) and highest (Mar-May). Minimization in the erosion might be due to greater ground coverage, strong holding of the soil or by minimizing the rain water impact by cover crops (Vicente, Seas, Alvarez, & Cerda, 2020). In a review, they observe cover cropping with no tillage improve the organic C and N and inorganic nutrients (Farmaha, Sekaran, & Franzkuebbers, 2021). Soil organic matter (SOM) was reported 3.03% higher on field pea than Rajma bean. The mixing of legume residue improved the total nitrogen uptake and available phosphorus in the maize in succeeding season. Among chickpea, berseem, garden pea, field pea, and lentil, berseem (36 kg ha^{-1}) produced highest available phosphorus. This ultimately increased the maize production (Rijal, Pandey, Shah, & Chaudhary, 2021). In Tanzania, higher yield of Cassava was reported by the use of legume cover *Macuna prueiens* by increasing the N content along with K, Ca, and Mg due to high amount of biomass (Matata, Passos, Masolwa, Marcolan, & Ribeiro, 2017).

Changes in soil pH and electrical conductivity could be a result of the incorporation of cover crops, which can alter soil organic matter content, decomposition rates, and crop types in different cropping systems (Feng, Sekaran, Wang, & Kumar, 2021). In southern Brazil, an experiment involving cover crops and onions utilized an exponential decay model, which revealed that rye had the highest values for remaining dry matter (DM), total organic carbon (TOC), lignin percentage, cellulose, non-structural biomass, and remaining N, P, K, Ca, Mg between 0-90 days, compared to other cover crops. These findings were attributed to the amount of lignin content and C: N ratio (Oliveira, et al., 2016).

Soil biology is pivotal driving force of the soil environment. It helps in decomposition of the complex material into a simple form. The biological properties of soil such as microbial mass (SMB) and diversity, respiratory activities, enzymatic functions, and mycorrhizal associations are necessary for sustainability in agriculture (Amoakwah, 2021). It was reported from an experiment in the USA that microbial activities and enzyme activity were influenced by the addition of residual biomass of cover crops. Beta-glucosides which are the source of energy for microbes were increased with the use of crimson clover, winter pea, and berseem clover which ultimately increased the microbial biomass. They reported the greater influences of arbuscular mycorrhiza fungi (AMF), gram-bacteria, and total bacteria in the fall of 2015 under the *Brassica* family (forage radish) due to C: N ratio, leftover, and time of incorporation (Sanchez, 2016). Similarly, an increase in enzymes (beta-glucosides, arylsulfatase) and soil bacterial community upon the use of cover cropping and cropping system was reported. The long-term (20 years) use of no-till maize-based cover crops with oat, soybean, and wheat increases the β-glucosidase (1.2 times), arylsulfatase (0.8 times), and bacterial community by (1.2 times). The increase in the microbial community might be due to chemical from root exudates and the decomposition of residual biomass of cover crops. However, short-term effect (3-6) years did not show any significant effect on such parameters and concluded to use cover crops for the long term (Feng, Sekaran, Wang, & Kumar, 2021). Also, in organic peach orchards, it is found that the use of white clover to form a root mat where the 6 species of earthworm were dominant. They improved the porosity and increased the soil infiltration which is beneficial for controlling run-off and soil erosion (Parveaud, Gomez, Bussi, & Capowiez, 2010). Soil microbial community increases by 52% and 73% by the use of leguminous cover crops in Sri Lanka and gramineous CC for long-term (8 years) also showed distinct differences in the bacterial community (Senarathne & Udumann, 2021; Arias-Giraldo, et al., 2021). Mustard as a cover crop can suppress the number of soil bacteria (<800 species) than other cover crop as of result of bio-fumigation caused by isothiocyanates. They found pea to house more uniformity in microbial community and radies house more number of species (Harber, Rogers, & Tan, 2017).

Cover crops contribute to soil health by controlling nutrient cycles, managing soil properties, preventing erosion, and adding organic matter. Although the benefits of cover crops are well-documented in research, adoption can be slow. However, lessons from smallscale farming systems in developing countries and agro-ecological research have demonstrated improvements in soil health and cost savings in crop production (Gliessman, 2020). From a study in Missouri- Colombia (USA), several health indicators such as soil moisture, bulk density total organic carbon (TOC), active carbon, potentially mineralized nitrogen (PMN), and microbial community were considered. With the long-term crop rotation and soybean-corn cropping system, not only the yield but the soil parameters were also improved. Soil quality was enhanced in terms of physical, chemical, and biological properties, while crop yield was maintained (Young, 2020). Similarly, in a study from 2014-2019, six soil health indicators (active carbon, SOM, respiration, stability of aggregate, available water capacity, and soil protein) were analyzed. Among them, four indicators (active carbon, SOM, respiration, aggregate stability) showed change. Aggregate stability changed by 1.02% and soil organic matter by 0.01% per annum and suggested that cover crop would be beneficial in long run (Bowman & Wood, 2022). In research in Nebraska, a decrease in soil erosion with an index score (IS=0.48) was the prime motivation to adopt CC for soil health management (Das, Berns, McDonald, Ghimire, & Maharjan, 2022). In Boone County, Iowa, USA, on 5-year trials, two soil health indicators potentially mineralizable nitrogen (PMN), and particulate organic matter carbon (POM-C) were affected by the treatment. Under no-till no corn stovers removal (NT0) treatment on the soil surface (0-5cm), 1.9 folds higher POM-C was reported. Similarly, with no-till under rye cover with 35% stover removal (NTR35) and, no-till under rye cover with 60% corn stovers removal (NTR60), the PMN increased at the surface from 0-30 cm and suggested that removing of corn stovers up to 60% of biomass may be used as the animal’s food and also protect the soil health. However, further research was recommended (Obrycki, Karlen, Cambardella, & Kovar, 2018).

Cover crop suppresses the weed in multiple ways. Its ability to change the soil environmental scenarios impairs the seed growth, germination and keeps the seeds dormant. They are capable of fluctuating the soil’s temperature, light availability, quality, trapping nitrogen and making them less available to the weed which ultimately reduces their emergence and density. Their characteristics to house for different insects and allelopathic effects help them to suppress weeds (Sias, Wolters, Reiter, & Flessner, 2021). Herbicide resistance to the weed is becoming serious issue. So, in this context, use of cover crop for their biomass and allelopathic effect is crucial for weed management, however the disadvantages of the negative allelopathic also should be taken care (Mennan, Jabran, Zandstra, & Pala, 2020). Along with that, the species of cover crop, establishment time, and canopy cover should also be considered while selecting for weed management (Soti & Racelis, 2020). Crops that are used as cover crop are rye, vetch or Brassicaceae plants are capable of suppressing weeds (Mennan, Jabran, Zandstra, & Pala, 2020).

A cover crop can reduce weed growth and seed germination by competing for resources like light and nutrients, due to increased canopy cover and biomass. A similar result was observed in a two-year field experiment in an organic vegetable farm located in Edinburg. During the first eight weeks of growth, the biomass of sudangrass, a type of cover crop, increased significantly, leading to a 57% less light reaching the soil surface in the first year and a 32% reduction in the last year. The decrease in the soil's weed seed bank resulted in reduced weed emergence (Soti & Racelis, 2020). Both the sowing date and the cover crop resulted in decreased biomass of weed in the corn field in Iran. The high establishing rate of the clover and vetch suppress the weed and its density and boosts the corn yield (Yeganehpoor, Salmasi, Abedi, Samadiyan, & Beyginiya, 2015). Also, similar decrease in the weed seed bank was reported with the use of winter rye (*Secale cereal* L) in maize- soybean field as cover crops for a long-term weed management. Increase in the biomass of cover crop should be considered for the criteria in suppressing the weed; however it was not reported from this experiment. They also decreased the weed community with less number of water-hemp seed (Nichols, English, Carlson, Gailans, & Liebman, 2020).

In Sicily, Italy, a long-term field experiment was conducted to investigate the impact of cover crops on weed abundance in a Mediterranean climate. The study found that subterranean clover was particularly effective in reducing the weed seed bank, as well as decreasing above-ground weed biomass and the number of weed species. The allelopathic properties of subterranean clover, which are released directly into the soil or through the decomposition of its biomass, may be responsible for this effect (Scavo, et al., 2020). The breakdown of glucosinolate, a compound found in Brassica spp. plants, including rapeseed, radish, and mustard, produces allelochemicals known as isothiocyanates. These substances aid in reducing weed germination. Additionally, the chemicals released during cover crop decomposition can support various microorganisms, such as fungi and bacteria, which enable the soil to suppress weeds (Farmaha, Sekaran, & Marshall, 2020).

The use of cover crop (CC) was believed to have conflicting positive and negative impact on the carbon sequestration, however, now the present studies has been opposing these ideas constantly. The quantity of biomass added to the soil is a key factor in determining the effectiveness of carbon sequestration, rather than the type of cover crop. They have been found to sequester up to 300 $kgha^{-1}$ of carbon. However, a thorough study and analysis is necessary to prove this logic. The humification of the crop residue is also important in understanding the carbon sequestration (Justes, 2017).

Soil Organic Carbon (SOC) increased to 11-22% which increased the sequestration of carbon of 10-20Mg C ha^{-1} at all research site in Ontario, Canada in an experiment which might be due to the quick proliferation of cover crops and accumulation of biomass (Chahal, Vyn, Mayers, & Eerd, 2020). Similarly, it is also reported that the increase in SOC stock with the addition of CC with average annual carbon sequestration rate of 0.32± 0.08 Mg $ha^{-1}yr^{-1}$. Although they did not find any significant variance due to management parameters (elevation, depth), CC species, and soil management (tillage and no-till), they found the long-term productive effect of CC on soil organic carbon and predicted that the 54 years of long trial collected 12.7 Mg C ha^{-1}, which is same as an average annual carbon sequestration rate of 0.23 Mg $ha^{-1}yr^{-1}$ (Poeplau & Don, 2015). In a research trial in Germany, the sequestration potential of soil organic carbon was determined with the help of RothC and C-TOOL which uses the effect of weather and the seedling date and was reported increasing the yearly C input from 3.68 to 4.13 Mg C ha^{-1} a^{-1} and in next five decades, 35 Tg of greater SOC in the top 30cm of the soil (Seitz, Fischer, Dechow, & Don, 2021). Also, from a research trial in Spain at the Olive groove, CC reported fixing 47% and 5% more C in the 20cm soil depth. Branchypodium contributed more C in the soil in the first year which was 1.5, 1.9, and 1.9 times higher than the other three CC while in the third year spontaneous weed contributed more. Studies have shown that the carbon residue from the cover crop (CC) is capable of sequestering carbon in all layers of the soil. Among the CCs, Sinapsis has been found to fix the highest amount, which is 7.7 Mg ha^{-1} over a period of three years. This represents an increase of 44%, 47%, and 54% compared to the amount fixed by Brachypodium, spontaneous weeds, and Eruca, respectively. The order of the CCs' carbon sequestration ability is as follows: Sinapis > Brachypodium > spontaneous weeds > Eruca. (Torres, Carbonell-Bojollo, Alcántara-Braña, Rodríguez-Lizana, & Ordóñez-Fernández, 2012). Similar effect of SOC accumulation that helps in C sequestration was observed by (Blanco-Canqui, 2022; Olson, Ebelhar, & Lang, 2014; Tellatin & Myers, 2018). It is also reported by (Lugato, Cescatti, Jones, Ceccherini, & Duveiller, 2020) that by 2050 due to the accumulation of the CC in soil, cumulative sequestration rate of carbon will ranged between 5.2 to 17.0 Mg CO2 ha^{-1}. By that time, carbon sequestration will be the major climate mitigating effect but with slightly diminishing ability with biogeochemical mitigation potential of 1336 Tg in EU.

Factors like species of cover crop, management techniques, production system, cultivation time, etc. should be taken into account while analyzing the benefit of using cover crops. The policymakers from the government side and subsidy programs should be encouraged so that farmers could reconstruct their cropping pattern to include cover crops which will help their farms to remain profitable (Bergtold, Ramsey, Maddy, & Williams, 2017). In a four-year trial in North-central Missouri, it was found that cover crops in the short term might have negative revenue but in the long term as reported in the final year of the trial, they can increase the revenue by increasing the main crop productivity by protecting the soil from eroding and by adding nutrient to soil. They had an annual average cost of $109.74 per hectare for cover crops (Cai, et al., 2019) Also, in a winter cover cropping trial in California, long-term use of CC showed a profit than the short term by improving soil function and increasing the yield of tomatoes and almonds (DeVincentis, et al., 2020). An Integrated Crop-Livestock system (ICLS) in South Dakota reported that the first-year net effect on the economy by cover crops will be \$17.23 ac^{-1} which will increase consequently as the price of fixed cost is not included each year. In the second year, revenue will be \$43.61 ac^{-1} which will keep on increasing (Tobin, Singh, Kumar, Wang, & Sexton, 2020). However, some reported the use of CC in low yield which is not suitable from economic point of view. Conventional tillage without cover crop in cotton performed better and had more lint revenue than that of non-tillage rye and mixed cover with gross margins of \$878 and \$1238 ha^{-1} in 2016 and 2017, respectively (Keeling, Lewis, Mccallister, Delaune, & Burke).

CONCLUSION

In conclusion, cover crops have emerged as a promising approach for sustainable agriculture that offers numerous environmental, economic, and agronomic benefits. By planting cover crops, farmers can improve soil health, ameliorate soil erosion, overpower weeds, and enhance biodiversity. Additionally, cover crops can reduce fertilizer and pesticide use, increase crop yields, and improve the overall resilience of farming systems. While cover crops require additional investment and management, their benefits far outweigh the costs in the long run. As such, promoting the adoption of cover crop practices should be a key priority for policymakers, agricultural extension services, and other stakeholders involved in the agriculture sector. Legume crops should be given priority while selecting as a cover crop along with the planting date, production and management system, and cropping pattern. However, further long-term research and review is necessary to be sure about the contribution of cover crop for sustainable agriculture. Overall, cover crops represent a powerful tool for promoting sustainable agriculture and ensuring the future productivity and resilience of our food systems.

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