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Regenerative Organic Agriculture: A Pathway to Ecosystem Restoration and Sustainable Agricultural Development

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Abstract: Modern high-input, intensive agricultural systems predominantly emphasize productivity and profitability at the expense of ecological balance. The Green Revolution, though instrumental in enhancing food security, relied heavily on mechanization, intensive cultivation, and high-yielding varieties, often compromising long-term sustainability. These practices have accelerated land use change and deforestation, leading to a substantial decline in soil organic matter (SOM), a reduction in terrestrial carbon sinks, and a rise in atmospheric carbon dioxide (CO_2) emissions. Under the increasing pressures of climate change—manifested in the form of drought, flooding, and pest outbreaks—the vulnerability of conventional farming systems has been exacerbated. In response to these challenges, regenerative organic agriculture (ROA) has been recognized as a holistic framework capable of restoring ecosystem functions, enhancing soil health, and supporting sustainable food production. This review synthesizes current research on ROA, with particular emphasis on practices that contribute to soil building and ecological regeneration. A meta-analysis of cover cropping practices across diverse soil types has demonstrated the potential to sequester soil organic carbon (SOC) between 0.32 and 16.70 $Mg \cdot ha^{-1} \cdot yr^{-1}$. Globally, an estimated SOC sequestration of 0.03 $Pg \cdot C \cdot yr^{-1}$ via cover crops could offset approximately 8% of anthropogenic greenhouse gas emissions. The physical, chemical, and biological improvements to soil properties facilitated by ROA have been systematically examined. Traditional Vedic agricultural practices in India have also been revisited for their ecological relevance and compatibility with regenerative principles. Integrated farming systems combining leguminous crops, agroforestry, horticulture, pasture, and animal husbandry have been reviewed for their synergistic effects on biodiversity enhancement, nutrient cycling, and climate mitigation. Additionally, the transition to renewable energy sources, reliance on self-saved seeds, and minimization of external inputs have been underscored as key strategies for achieving farm-level self-sufficiency and ecological sustainability. This review synthesizes scientific findings and traditional knowledge to highlight ROA as a holistic solution for restoring soil function, conserving natural resources, and advancing sustainable agricultural development.

Keywords: Soil building and regeneration; Crop rotation; Cover cropping; Renewable energy; Vedic agriculture; Reduced tillage

1. Introduction

Regenerative organic agriculture (ROA) means a sustainable approach to farming that revitalizes soil's physical, chemical, and biological properties, rejuvenates the ecosystem, and recreates the earth's microclimate besides biodiversity enhancement and carbon sequestration. It integrates organic farming practices focusing on regenerating soil health and environmental diversity, whereas organic agriculture emphasizes mainly organic crop production without any chemical use. On the other hand, ROA includes a complete package of all farming practices for mitigating climate change by enhancing soil organic carbon (SOC) content or augmenting carbon sequestration. ROA emphasizes largely natural and sustainable farming practices to make use of on-farm inputs rather than depending on others for farm inputs. It makes ROA more environmentally friendly and profitable than other farming systems besides enriching soil organic matter (SOM).

In general, topsoil contains 2-10% of SOM, of which 58% of the mass of organic matter has been found to exist as SOC (Kopittke et al., 2019; Magdoff & van Es, 2021). SOC content is one of the main quality indicators for soil health. Recently, SOM has been depleting quickly through modern agricultural practices like intensive tillage, extensive use of chemical fertilizers, mono-cropping, and climate change. Globally, 20-30 Gt of fertile soil is estimated to erode annually, leading to loss of nitrogen (23-42 $Mt \cdot yr^{-1}$) and phosphorus (15-26 $Mt \cdot yr^{-1}$) due to intensive and unsustainable agriculture practices (Kopittke et al., 2019). Hence, modern intensive agriculture includes extensive use of fertilizers, pesticides, and hybrids to compensate for the yield, ignoring ecological ill effects. Manufacturing and use of fertilizers and pesticides not only consume a lot of energy but also release toxic substances to the environment and contaminate soil and water (Montanarella et al., 2015). Worldwide, land use change and intensive cultivation practices have resulted in a carbon loss of approximately 3.8 $Gt \cdot yr^{-1}$ through CO_2 emissions, and simultaneously, carbon sequestration by land and forest ecosystems is estimated at 3.1 $Gt \cdot yr^{-1}$, contributing a carbon sequestration of 29% of total global emissions (Friedlingstein et al., 2022). Thus, ROA could be a potent tool to reduce carbon emissions and, at the same time, to enhance the carbon sink, and there is an urgent need to enhance carbon sequestration to alleviate climate change by practicing eco-friendly agriculture (Hatfield & Walthall, 2014; Toensmeier, 2016). Organic agriculture mainly avoids the use of synthetic pesticides, herbicides, and genetically modified organisms, whereas regenerative agriculture aims to restore and enhance natural ecosystems. Thus, there is a need to boost traditional sustainable agriculture practices in combination with innovative agriculture techniques to rejuvenate soil and the environment. Considering the conservation requirements of the earth, an attempt has been made to review ROA practices, a way to protect and restore natural ecosystems with particular reference to soil building and regeneration. This study aims to systematically analyze the main components, diverse cultural practices, ecological benefits, and sustainability evolution of ROA over a period of time.

2. Origin of ROA

The history of ROA goes way back to the Vedic period (circa 1500 BCE) in the Indo-Pak region, where the people reported practicing a systematic organic farming technique (Kansara, 1995). During the Vedic period, overstressing of drought animals was prohibited, and custom-made wooden plows were used for shallow cultivation (Sadhale, 1999). Vedic agriculture was found to be regenerative, maintaining fertile soil conditions, healthy animals, and ecological diversity. During the 10th century CE, trees were given the utmost importance over human beings, and this was described by Surapala in *Vrikshayurveda* (Sadhale, 1996). Landraces and locally adapted strains were cultivated along with the usage of cows as a source of manure, milk, and plowing in 700 CE (Kumar, 2008; Sadhale, 1999).

Table 1. Ancient agriculture practices vs. modern ROA

Evolution of Agriculture	Cultural Practices	References
Vedic agriculture (1500 BCE)	• Integration of agriculture, animals and trees. • Use of solar and lunar calendars for planting and harvesting. • Use of herbs for animal health and pest control.	(Kansara, 1995; Sadhale, 1999)
Ancient agriculture (10-700 CE)	• Worshiping trees and focusing on social forestry, agroforestry, and wasteland development. • Domestication of animals. • Rainwater harvesting, crop residue management and water conservation structures.	(Kumar, 2008; Sadhale, 1996)
Traditional agriculture (17th century)	• Composting, tree grafting, seedless fruit production, and seed saving. • Diversified crop cultivation: herbs, perennial fruit trees, flower crops, cereals, millets, aromatic, oil, and fiber-yielding crops.	(Razia, 2000; Sircar & Sarkar, 1996)
Biodynamic agriculture (1920s)	• Astrological sowing and harvesting. • Use of specific herbs and minerals for composting. • Use of horn silica and buried cow horn manure to enhance plant immunity. • Integration of plant, animal and soil.	(Darnhofer et al., 2010)
Permaculture (1970s)	• Integration of forestry, ecology, horticulture, animal husbandry, and aquaculture with organic agriculture practices. • Crop rotation, polyculture, composting, and recycling. • Water harvesting and use of energy-efficient techniques.	(Salleh et al., 2018; Yadav et al., 2023)
Modern ROA	• Integration of organic agriculture, which focuses on soil building and regeneration. • Minimum tillage, soil and water conservation structure. • Integrated farming system, crop rotation and diversification. • Energy-efficient practices and sustainable agriculture practices.	(Giller et al., 2021; Rodale Institute, 2014; Tittonell et al., 2022)

During the 17th century, farmers were aware of seed treatments by using animal manures to enhance germination, and they used to select suitable varieties for dry or wet regions (Razia, 2000; Sircar & Sarkar, 1996). Traditional agricultural practices signify the innate relationship between humans and nature and strive to perfect association. Emphasis was given to optimizing productivity rather than maximizing it, with a conscious avoidance of over-exploitation of natural resources (Kumar, 2008).

In 1920, the concept of biodynamic agriculture was developed by Rudolf Steiner in Germany, and later organic farming practices for ecological safety and rural development were initiated in the 1940s in Switzerland and the European Union (Darnhofer et al., 2010). Subsequently, a sustainable agriculture practice, "permaculture", was coined by Bill Mollison in the 1970s. It integrates forestry, ecology, horticulture, animal husbandry, and aquaculture with organic agriculture practices, and it has become popularized in Nepal, the United States of America (USA), and European countries (Salleh et al., 2018; Yadav et al., 2023). Later, the term ROA was coined by Robert Rodale in the 1980s from the Rodale Institute, USA, defining it as a practice that goes beyond sustainability to mitigate climate change (Rodale Institute, 2014; Tittonell et al., 2022). However, as per the reports, the "regenerative agriculture" phrase was not used as frequently as organic farming or sustainable agriculture till 2015, and recently, in the last two decades, the ecological benefits of ROA practices have been widely circulated globally and promoted among farmers (Giller et al., 2021; Newton et al., 2020). Various ancient agricultural practices along with modern ROA techniques, are listed and presented in Table 1.

3. Components of ROA

Based on the review, ROA can be broadly divided into five major components: soil building and regeneration, emphasis on locally available inputs, multiple cropping and heirloom varieties, integration of livestock and perennials, and the optimum use of renewable energy resources. Each and every component has its own role, and all these five principles are interconnected with each other to achieve the goal of ROA (Figure 1).

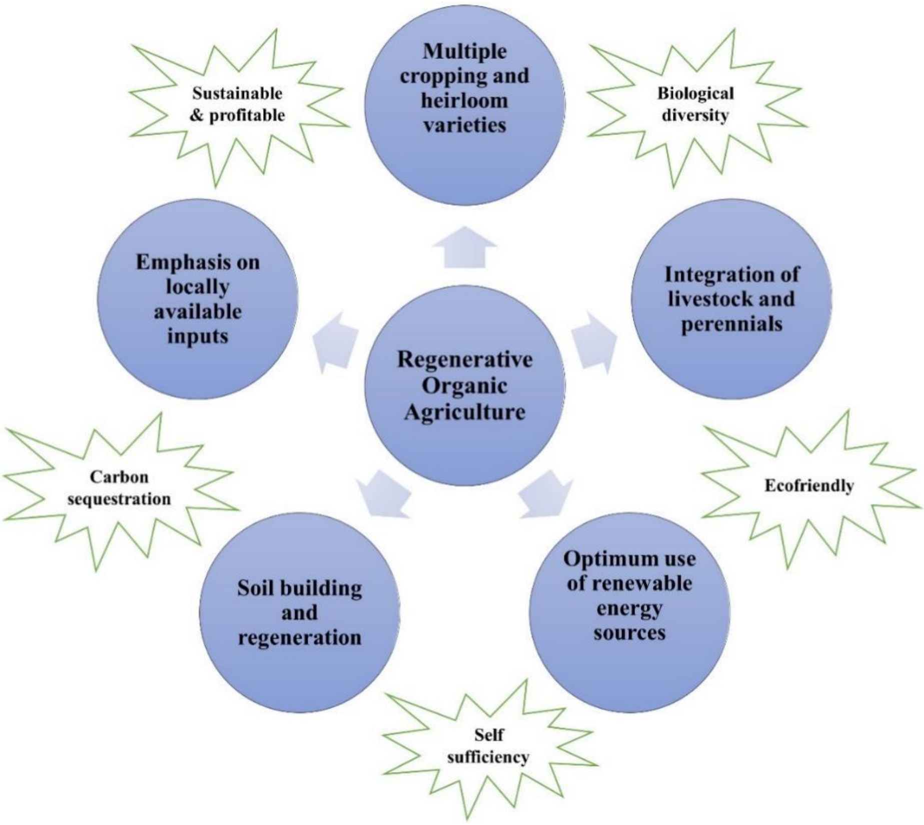

Figure 1. Components of ROA and its impact

3.1 Soil Building and Regeneration

Soil regeneration is essentially a program to make the soil more productive with minimum loss of essential nutrients, improve water relations, enhance SOM, rehabilitate poor, badly eroded, or infertile soils, or reclaim waterlogged or saline soils for optimum crop production. The regenerative farming practice integrates reduced tillage, crop rotation, cover cropping, mulching, composting, and soil micro-organisms to build a healthy soil structure, or, in other words, it enhances the physical, chemical, and biological properties of the soil. The major indicators of healthy soil are SOM, SOC, and soil micro-organisms, and they complement each other. The practices of regenerative agriculture not only enhance SOM but also maintain better soil structure and fertility. The cultural practices for soil revitalization and conservation are discussed below. The various regenerative agricultural practices to rejuvenate soil fertility and organic matter are depicted in Figure 2.

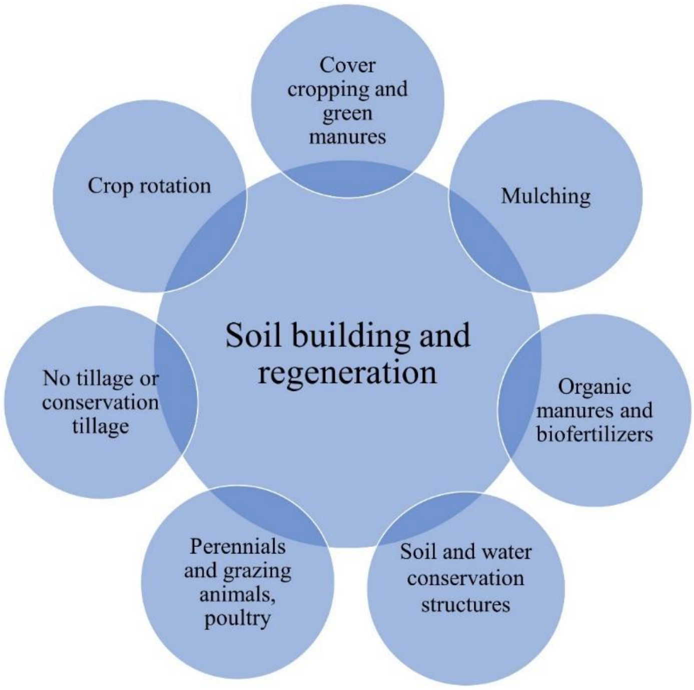

Figure 2. ROA practices for soil building and regeneration

3.1.1 Conservation tillage and no-till (NT)

Conventional tillage (CT) is a very common soil preparation practice by passing energy-intensive tillage machinery repeatedly in the soil to a depth of 12-30 cm until a uniform, fine-tilth seedbed is formed to facilitate sowing and subsequent cultural operations. Initially, it creates an ideal weed-free condition for seed germination and seedling growth (Magdoff & van Es, 2021). Meanwhile, in a restricted tillage system, soil preparation is restricted to narrow areas all along the sowing lines or planting areas. Reduced tillage ensures maximum soil coverage (> 30%) and less soil disturbance, as the tillage can be limited to only cropped strips. NT, zone tillage, strip-till, and ridge tillage are some of the energy-efficient conservative tillage practices to reduce the exposure of soil, as shown below.

3.1.1.1 Zone tillage

It is a conservation tillage practice, where tillage is practiced to create 15-25 cm wide rows as cropping zones up to 20 cm deep into the soil with the help of high horsepower tractors fitted with cutting colters, deep shanks, and rolling baskets (Magdoff & van Es, 2021). It is similar to NT or strip-till but more energy-intensive. Zone till is preferred over NT under heavy soils with soil compaction problems and cold and humid weather conditions where early soil drying is desirable. Zone tillage is considered an intermediate tillage system between conventional and NT and is easy to implement before switching to an NT system.

3.1.1.2 Strip tillage

A strip of sowing or planting line is tilled up to 20 cm depth with specially designed disc openers as per crop spacing. In early spring, it warms the soil quickly and creates weed-free and aerobic conditions within the strips. Seed sowing and manure application can be combined to reduce the number of passes. Although it requires high-power tractors, less fuel consumption makes it more energy efficient than CT (Magdoff & van Es, 2021; Toor et al., 2021).

3.1.1.3 Ridge tillage

It is also known as ridge-plant, which leaves 30-50% crop residues to cover the soil surface, and plants are grown on the ridges of the previous season with minimum soil disturbance (Carter, 2005). Every year, ridges are shaped by using planters equipped with horizontal disks or row cleaners at 1.27-5.00 cm soil depth. Since ridges warm up rapidly in the early spring, it is particularly used in vegetable production under poorly drained soils (Toor et al., 2021).

3.1.1.4 NT/zero tillage

It covers more than 70% of the soil surface, and only seed drills or NT planters are used to open narrow seed furrows through the residue of the previous season. The soil remains undisturbed from sowing to harvest, and from harvest to the next seeding cycle (Ogle et al., 2019). After assessing SOC of tilled and NT soils with a global meta-analysis study, Nicoloso & Rice (2021) found that over a period of 16 years, NT soils stored 6.7±1.9 $Mg{\cdot}C{\cdot}ha^{-1}$ and 1.1±0.4 $Mg{\cdot}N{\cdot}ha^{-1}$ more than tilled soils in 0-100 cm soil depth. In addition, it was observed that SOC stock over 11 years was 4.7±1.9 $Mg{\cdot}C{\cdot}ha^{-1}$ in 0-60 cm depth. On average, in a NT system, SOC can be increased annually by 0.4% (Graham et al., 2021; Minasny et al., 2017; Ogle et al., 2019). Franzluebbers (2010) reported a carbon sequestration of 30.2±1.4 $Mg{\cdot}C{\cdot}ha^{-1}$ under conservation tillage practices in a soil depth of 0-20 cm over 11 years. In contrast to this study, other research has reported that conservation tillage practices—particularly NT—tend to sequester SOC primarily in the shallow soil layers (0-15 cm), a phenomenon referred to as stratification. These findings suggest that NT has limited potential for increasing SOC stocks in deeper soil layers (Chambers et al., 2016; Horwath & Kuzyakov, 2018; Powlson et al., 2014). Although SOC sequestration largely depends on the agro-climatic conditions, crop intensification, type of crops, and soil profile, NT improves soil properties enormously and overshadows its limitations (de Oliveira Ferreira et al., 2021; Nicoloso et al., 2020; Ogle et al., 2012).

A case study on the comparison between tilled and NT soils of tropical Africa revealed 36% runoff in CT due to heavy rainfall, whereas NT practice resulted in only 25% runoff. Similarly, soluble carbon loss was 0.9 $g{\cdot}L^{-1}$ in NT compared to 2.2 $g{\cdot}L^{-1}$ in tilled soils (Mchunu et al., 2011). NT not only reduced soil erosion (> 60%) and soil carbon loss (50%) but also dropped a runoff silt load (> 87%) in a sloppy land and increased infiltration rate around 3.7 times more than CT (Pasricha, 2017; Valentin et al., 2008; Zhang & Huang, 2007). However, under poorly drained soils and in temperate regions, it is difficult to follow NT due to excessive soil moisture in the early spring (Garcia-Franco et al., 2018; Nicoloso & Rice, 2021). Hence, a modified NT, such as strip-till, can be followed in compact soils. Lower yield in the initial years of NT can be compensated by adding higher organic manures to the soil. In organic agriculture, it is difficult to differentiate NT and conservation tillage. Depending on soil and weather conditions, the tillage system should be wisely chosen along with mulching or proper cover crops to maintain better physical, chemical, and biological properties of the soil to augment crop yield. A practice of suitable conservation tillage with integrated crop management practices such as crop rotation with legumes, mixed crops, cover cropping, residue mulching, and adding organic amendments can enhance crop productivity as well as carbon sequestration over a period of time.

Table 2. Comparison between different systems of tillage with their benefits and limitations

Systems of Tillage	Advantages	Disadvantages	References
Conventional tillage (CT)	• Creates weed-free, fine-tilth conditions for crop growth. • Easy seed and manure application. • High aeration and infiltration initially.	• Release large amounts of CO_2 • Formation of hardpan below the surface, restricting the root growth • Exposure of bare soil, leading to loss of nutrients and soil microbes • Highly susceptible to soil erosion and splash erosion • Destroys natural soil aggregation • Requires high-energy machinery	(Magdoff & van Es, 2021; Nicoloso & Rice, 2021; Pasricha, 2017)
Reduced/ Conservation tillage (zone till, strip-till and ridge till)	• Creates weed-free strips or ridges for seeding/planting. • Allows quick drying and heating of soil. • Fertilizers can be applied while tilling. • Minimum soil disturbance, better infiltration, and less erosion. • Better carbon sequestration.	• It can be used for limited crops with broader spacing • Adjusting the tillers as per crop spacing in each season for different crops is time-consuming • Formation and maintenance of ridges are difficult	(Carter, 2005; Magdoff & van Es, 2021; Pasricha, 2017; Singh et al., 2018)
No-till (NT)	• No soil disturbance, and SOM and aggregate strength can be maximum. • Soil biological activity found to be optimum. • Low-cost and energy-efficient • Higher infiltration, porosity, minimum soil erosion, and eco-friendly	• Initial crop productivity can be less • Weed infestation • Difficult to follow if the soil has a compaction problem	(Busari et al., 2015; Graham et al., 2021; Mchunu et al., 2011; Nicoloso & Rice, 2021; Ogle et al., 2019)

Comparisons between different tillage systems with their benefits and limitations are presented in Table 2, and the influence of various tillage practices on soil's physical and chemical properties are depicted in Table 3. Even though the infiltration rate was less under NT conditions in sandy clay loam soil under a semi-arid environment in Tunisia, the runoff and sediment loss were recorded 2.33 and 5 times less in NT than CT in the Northwestern Himalayan Region of India (Amami et al., 2021; Singh et al., 2023). Physical properties of the soil, like bulk density and porosity, were better in conservation tillage practices with vegetation cover than in CT and NT (Osanyinpeju & Dada, 2018). Formation of soil aggregates, water stable aggregates (WSA), macroaggregates (2-4.5 mm), and microaggregates (0.25-2 mm) was observed more in NT and conservation tillage than in CT (Jin et al., 2023; Weidhuner et al., 2021; Zheng et al., 2018). Similarly, SOM, SOC, and total nitrogen (TN) were found to be higher under NT and reduced tillage systems than under CT (Table 3) (Jin et al., 2023; Zheng et al., 2018). However, the improvement of physical and chemical properties of the soil based on the tillage technique varies depending on soil type, climatic condition, topography, vegetation, cultural practices, etc. However, long-term conservation tillage practices were found to enhance soil properties to a great extent (Singh et al., 2023; Zheng et al., 2018).

Table 3. Influence of different tillage practices on physical and chemical properties of the soil

Soil Properties/ Tillage Practices	Conventional Tillage (CT)	Reduced Tillage	No-Till (NT)	References
Water infiltration rate ($cm \cdot min^{-1}$)	0.069	0.062	0.043	(Amami et al., 2021)
Runoff (%)	43.42	36.96	18.61	(Singh et al., 2023)
Sediment loss ($t \cdot ha^{-1}$)	14.05	7.59	2.83	(Singh et al., 2023)
Soil bulk density ($g \cdot cm^{-3}$)	1.53	1.45	1.60	(Osanyinpeju & Dada, 2018)
Porosity (%)	41.93-42.64	44.32-49.90	37.90-41.17	(Osanyinpeju & Dada, 2018)
WSA (%)	43-64	55-72	64-75	(Jin et al., 2023; Weidhuner et al., 2021; Zheng et al., 2018)
SOC ($g \cdot kg^{-1}$) (0-40 cm)	5.59-9.06	5.88-9.76	8.22-12.36	(Song et al., 2019)
SOM ($g \cdot kg^{-1}$) (0-40 cm)	8.35-13.61	10.67-15.62	10.53-16.89	(Jin et al., 2023)
TN ($g \cdot kg^{-1}$) (0-40 cm)	0.76-0.96	0.72-1.03	0.66-1.24	(Jin et al., 2023)

3.1.2 Crop rotation

Crop rotation is the systematic practice of sequentially cultivating different crops on the same piece of land over a defined period to improve soil health and microclimatic conditions. A healthy regenerative farm should develop a five-year crop rotation calendar with diversified crops (row crops rotated with legumes, millets, cover crops, and fodder grasses) considering soil, agro-climatic conditions, and food habits of that region (Alhameid et al., 2017). Crop rotation not only enhances soil fertility and crop yield but also augments soil micro-flora, improves soil structure and the chemical properties of the soil, and helps to reduce weeds, pests, and diseases (Jalli et al., 2021; Shah et al., 2021). Generally, high nitrogen-demanding crops (cereals such as paddy, maize, wheat, jowar, bajra, etc.) are rotated with crops that need low nitrogen (legumes and millets) (Asseng et al., 2014). A case study on the influence of long-term crop rotation diversification of agriculture reported increased maize yield (28.1%) across all states of the USA. Besides, diverse crop rotation was also found to reduce yield loss (14.0-89.9%) under unfavorable conditions such as drought (Bowles et al., 2020). Thus, crop rotation has been shown not only to improve soil quality but also to enhance yield, particularly under adverse climatic conditions.

Similarly, crop rotation was found to improve carbon sequestration significantly over a period of time. An average of 15 ± 11 $g \cdot m^{-2} \cdot yr^{-1}$ carbon stock was reported under a crop rotation system depending on the crop biomass production and root input. However, SOC sequestration was more rapid (0.73 ± 0.39%$\cdot yr^{-1}$) with a paradigm shift from CT to NT (Al-Kaisi & Lal, 2017; West & Post, 2002). Likewise, Zuber et al. (2015) studied the influence of crop rotation and tillage practices on physical and chemical properties of the soil in Illinois, USA. A long-term (15 years) cultivation of land under NT recorded 2.4% higher bulk density and water aggregate stability (WAS) than CT. In the same way, three years of corn-soybean-wheat rotation resulted in higher WAS, TN, and exchangeable potassium levels than continuous soybean, indicating the need to shift the tillage practice along with diversified crop rotation for better soil health (Zuber et al., 2015). The influence of various crop rotations on soil, crop yield, pest incidence, and profitability around the world is described in Table 4. A long-term rotation of cereals with cover crops (corn-soybean-cover crops; corn-alfalfa, corn-mungbean, and wheat-soybean cover crops) significantly increased SOC, TN and phosphorus and improved soil microflora.

Table 4. Influence of various crop rotations on soil, crop yield, pest incidence, and profitability around the world

Crop Rotation	Benefits	Country	Contributor
Corn-alfalfa	• Rotation of row crops with legumes and cover crops was found to increase SOC content. • SOC content of alfalfa gradually increased from 2.4% to 3.0%, whereas SOC content of the cornfield reduced from 2.6% to 2.4% over a period of five years.	USA	(Magdoff & van Es, 2021)
Maize-mungbean-maize Maize-sesame-maize Mungbean-chilli-maize	• All crop rotations improved SOC, TN, and available phosphorus in the alluvia soil than monocropping. • Mungbean-chilli-maize rotation was found to be the best.	Vietnam	(Dang & Hung, 2022)
Pea–winter wheat–winter triticale	• The grain and straw yield of winter wheat cultivated in continuous monoculture was reduced by 32%, and weed infestation was 57.1% higher than in the crop rotation. • Organic carbon, TN, and the number of earthworms were significantly high in crop rotation soil.	Poland	(Woźniak, 2019)
Spring wheat-turnip rape-barley-pea	• 4-year rotation increased the main crop yield by 30% under NT conditions and 13% in plowed land compared to monoculture of wheat. • The pest, disease, and weed incidence was significantly reduced over a period of time in crop rotation fields compared to monoculture. • Nitrogen and phosphorus uptake was also higher (14% and 17%, respectively) in plowed land, and in NT, it was 30% more nitrogen and more 27% phosphorus uptake than in the monoculture.	Finland	(Jalli et al., 2021)
Potato-oats and potato-fodder maize	• Enhanced soil ecosystem multifunctionality such as soil fertility, beneficial microflora diversity, and keystone taxa. • Inhibit disease-causing pathogens such as *Alternaria*, *Fusarium*, *Verticillium dahiae*, *Gibberella*, *Plectosphaerella*, *Colletotrichum*, *Phoma*, and *Lectera* more than monocropping.	China	(Li et al., 2023)
Wheat-soybean-cover crops (white oats, black oats and forage radish) Maize-soybean-cover crops	• The diversified crop rotation under an 8-year NT system significantly increased the profitability compared to the traditional wheat/corn-soya rotation. • The crop rotation, along with conserving farm resources, was found to be economically competent.	Brazil	(Garbelini et al., 2022)
Rice-potato Rice-watermelon	• The rice-potato rotation recorded fivefold profit compared to continuous rice. • All physical and chemical properties of the soil were better in rotated land than in mono-crop rice • Heavy metal content was significantly high in continuous rice cropping.	China	(He et al., 2021)
Corn-soya-wheat Corn-soya-wheat-red clover Corn-soya-wheat-rye	• Diversified crop rotation increased carbon mineralization by 125% and hydrolytic enzyme activity by 46% and decreased oxidative enzyme activity by 20%. • Soils from diverse cropping systems decomposed residues faster (0.2–8.3%) compared to monoculture corn.	USA	(McDaniel et al., 2014)

3.1.3 Cover crops, green manure crops, and mulching

3.1.3.1 Cover crops

Crops that are sown in alleys with the objective of protecting the soil with a vegetative cover are called cover crops. The purpose and type of cover crops depend on the climatic conditions prevailing in that area and the cropping system. For instance, cover crops are sown with the onset of monsoon to prevent soil erosion and runoff in wet tropical regions, whereas they are sown before the onset of fall in temperate regions with the objective of covering the soil and keeping the soil warm during early spring and the dryland cover crop is mainly used to prevent soil loss by wind (Baumhardt & Blanco-Canqui, 2014; Koudahe et al., 2022; Sharma et al., 2018). A cover crop should have quick growing habits, maximum albedo potential, be drought hardy, produce large biomass in a short time, have easy decomposing ability, and should not compete with the main crop for water and nutrients (Reddy, 2016). However, the cover crop can be selected based on the soil type, cropping pattern, and climatic conditions. Although the main principle of cover cropping is to cover soil and reduce runoff, it significantly enhances soil's physical, chemical, and biological properties. In addition, diversified cover crops positively impact the soil-water relationship by increasing infiltration rate and SOM content and by reducing evaporation losses (Joyce et al., 2002; Sharma et al., 2018; Zhang et al., 2016). Furthermore, cover crops have been found to be very effective in weed suppression, carbon sequestration, pest management, and enhanced biodiversity by improving microbial flora and earthworm population besides attracting more pollinators (Clark, 2012; Fogliatto et al., 2020; Roarty et al., 2017; Sharma et al., 2018).

A 12-year study on the influence of cover crops on soil carbon sequestration in tilled and NT soil was conducted in corn and soybean fields in southern Illinois, USA (Olson et al., 2014). A 220% increase in SOC accumulation in NT with cover crops (1.21 $Mg \cdot C \cdot ha^{-1} \cdot yr^{-1}$) was observed compared to NT without cover crops (0.33 $Mg \cdot C \cdot ha^{-1} \cdot yr^{-1}$). At the same time, similar trends were seen under tilled conditions without any increase in crop yield over a period of time. Similarly, a meta-analysis of SOC sequestration through cover crops in various soil types of Brazil, Canada, India, Europe, the USA, Mexico, and Japan resulted in a mean annual SOC sequestration of 0.32-16.70 $Mg \cdot ha^{-1} \cdot yr^{-1}$ (Poeplau & Don, 2015). It was also estimated that an SOC sequestration of 0.03 $Pg \cdot C \cdot yr^{-1}$ via cover crops globally would have the potential to compensate for 8% of greenhouse gas emissions annually. Likewise, several cover crops were reported to increase SOC (7-74%) based on soil type, weather conditions, and cover crop diversity (Koudahe et al., 2022).

Table 5. Nitrogen-fixing ability of different legume cover crops with their seed rate and growing season

Cover Crop	Seed Rate ($kg \cdot ha^{-1}$)	Season	Nitrogen-Fixation ($kg \cdot N \cdot ha^{-1} \cdot yr^{-1}$)	References
Temperate and subtropical				
Alfalfa or lucerne (*Medicago sativa*)	13-17	Spring/ winter	200	(Issah et al., 2020)
White clover (*Trifolium repens*)	10	Early spring	80-100	(Caradus et al., 2023)
Red clover (*Trifolium pratense*)	11-12	Early spring	50-350	(McKenna et al., 2018)
Crimson clover (*Trifolium incarnatum*)	20-30	Winter	75-175	(Clark, 2012)
Persian clover (*Trifolium resupinatum*)	3.5-7.0	Winter	82	(Ovalle et al., 2006)
Sub clover (*Trifolium subterraneum*)	11-22	Winter	45-80	(Ovalle et al., 2006)
Berseem clover (*Trifolium alexandrianum*)	17-22	Summer	225-317	(Clark, 2012)
Austrian winter pea/Singletary pea/Caley pea (*Lathyrus hirsutus*)	55	Winter	70-170	(Clark, 2012)
Faba bean (*Vicia faba)*	30-40	Winter	107	(Hossain et al., 2016)
Hairy vetch (*Vicia villosa)*	22-28	Winter	225	(Clark, 2012)
Lentil (*Vicia lens*)	30-40	Winter	86	(Hossain et al., 2016)
Field pea (*Pisum sativum)*	40-45	Winter	68	(Hossain et al., 2016)
Soybean (*Glycine max)*	60	Summer	150	(Berriel & Perdomo, 2023)
Cicer milkvetch (*Astragalus cicer*)	7-14	Summer	128	(Issah et al., 2020)
Sainfoin (*Onobrychis viciifolia*)	30	Summer	65	(Issah et al., 2020)
Tropical				
Sunn hemp (*Crotalaria juncea)*	25	Year-round	57	(Berriel & Perdomo, 2023)
Cowpea (*Vigna unguiculata)*	30-35	Year-round	337	(Mndzebele et al., 2020)
Velvet bean/Cowage (*Mucuna pruriens*)	35-40	Year-round	46	(Berriel & Perdomo, 2023)
Pigeon pea (*Cajanus cajan*)	15-20	Year-round	149	(Berriel & Perdomo, 2023)
Dolichos/Hyacinth bean (*Lablab purpureus*)	10-12	Year-round	38	(Berriel & Perdomo, 2023)

Integration of conservation or NT along with cover crops testified to boost SOC, SOM, WSA, and nutrient availability under various agro-climatic situations. A comparative study on the influence of NT cover crops on CT in northern Italy resulted in a substantial increase in SOM, TN, and phosphorus under NT cover crops (Boselli et al., 2020). Rye and hairy vetch cover crops increased SOM (30% and 20%, respectively) and TN (28% and 21%, respectively) more than CT. The various legume cover crops were reported to increase the TN content of soil (10-80%) and WSA (6-24%) depending on the soil and agro-climatic conditions (Koudahe et al., 2022).

Besides, hairy vetch and rye were found to increase the water infiltration rate (26-102%) in subtropical, continental, and semi-arid climates of the USA (Koudahe et al., 2022).

Legume cover crops considerably increase soil fertility by fixing atmospheric nitrogen and enhancing soil microflora, besides adding large biomass to the soil (Clark, 2012). The nitrogen-fixing ability of various legume cover crops of tropical and temperate regions, along with their seed rate and growing season, is illustrated in Table 5. Most of the tropical cover crops can also be sown as summer season crops in temperate regions. Most tropical countries prefer to grow cover crops as pure single crops and green manure crops. In contrast, in temperate regions, cover crops are also sown as mixtures (Mndzebele et al., 2020). In cocktail mixes, depending on the number of mixtures, half or one-third of the recommended seed rate can be taken (Clark, 2012; Hybner et al., 2019). However, cocktail mixes present challenges in seeding and management, generate large amounts of biomass, and complicate their integration into existing crop rotations. Hence, careful planning, species selection based on regional needs and goals, or proper biomass management techniques may be helpful to manage multiple cover crops. Among the different cover crops, berseem clover (summer season), hairy vetch (winter season), and lucerne (summer/winter) have been found to be suitable for temperate regions and fix maximum nitrogen, whereas cowpea has been found to be the best tropical cover crop (Table 5).

Some non-legume cover crops, such as broad-leaf crops and grasses, have been reported to add huge biomass into the soil (Table 6). Forage sorghum, oats, rye, barley and ryegrass have been reported to produce maximum biomass compared to other cereal cover crops (Clark, 2012).

Though the cover crops have numerous benefits, sometimes they may become invasive and compete for water and nutrients with the main crop, and they may become host to some insect pests (Dabney et al., 2001; Kasper et al., 2022; Lu et al., 2000). Especially under tropical conditions, where three to four cropping seasons per year are planned, it may be hard for a farmer to plan a cover crop in between as well as in long-duration crops. It may demand extra cost and labor, in addition to machinery for cultivating and harvesting cover crops effectively (Sharma et al., 2018). Hence, a well-designed five-year cropping plan that includes carefully selected cover crops would be economically beneficial for ecosystem stability and soil health as well.

Table 6. Non-legume cover crops with their seed rate, growing season, and biomass production

Non-Legume Cover Crop	Seed Rate ($kg \cdot ha^{-1}$)	Season	Biomass Production ($t \cdot ha^{-1}$)	References
Broadleaf crop				
Buckwheat (*Fagopyrum esculentum)*	68-102	Summer	5.0-7.5	(Clark, 2012)
Flax (*Linum usitatissimum)*	22-39	Summer	4.2-4.7	(Lloveras et al., 2006; Bilenky et al., 2022)
Phacelia (*Phacelia tenacetifolia)*	2-5	Summer	4.0-4.5	(Hybner et al., 2019)
Radish (*Raphanus sativus*)	9-14	Winter	45-80	(Clark, 2012)
Rapeseed (*Brassica napus*)	9-16	Winter	22-56	(Clark, 2012)
Safflower (*Carthamus tinctorius*)	15-20	Summer	5.2-5.6	(Wolf & Tilley, 2021)
Sunflower (*Helianthus annuus*)	11-12	Summer	9-18	(Wolf & Tilley, 2021)
Turnip (*Brassica rapa*)	9-16	Winter	34-102	(Clark, 2012)
Grass				
Barley (*Hordeum vulgare*)	55-102	Winter	22-112	(Clark, 2012)
Forage sorghum (*Sorghum bicolor*)	45-55	Summer	90-112	(Clark, 2012)
Millet (*Pennisetum glaucum*)	15-20	Summer	2.5-2.8	(Wolf & Tilley, 2021)
Oats (*Avena sativa*)	79-125	Winter	22-112	(Clark, 2012)
Rye (*Secale cereal*)	68-112	Winter	34-112	(Clark, 2012)
Ryegrass (*Lolium perenne*)	22-34	Winter	22-102	(Clark, 2012)
Triticale (*Triticosecale*)	60-70	Spring/ winter	7.3	(Glaze-Corcoran et al., 2023)
Winter wheat (*Triticum aestivum*)	68-112	Winter	34-90	(Clark, 2012)

3.1.3.2 Green manure crops

Green manure crops are cultivated and plowed down into the soil when they are still green before reaching maturity to enhance soil fertility (Fageria, 2007). Cover crops are often used as green manure crops, i.e., turning the young cover crops into the soil has been found to increase SOC stocks in agricultural soils (Poeplau & Don, 2015). Cover crops are grown to protect the soil, improve soil health, and suppress weeds. Green manure, on the other hand, specifically refers to cover crops that are incorporated into the soil to release nutrients and organic matter. Most cover crops can act as green manure crops as they produce a huge biomass, increase soil fertility, and add all the benefits of cover cropping (Dong et al., 2021; Islam et al., 2019). Some *Sesbania* species, *Sesbania bispinosa*, *Sesbania sesban*, *Sesbania rostrata*, cowpea, sun hemp, and *Mucuna* are some of the tropical green manure crops that decompose faster, and add a large quantity of organic matter into the soil (Maitra et al., 2018;

Ramanjaneyulu et al., 2021). All cover crops can be used as green manure crops if they are added to the soil before flowering or fiber development with the objective of adding organic matter and nutrients to the soil (Fageria, 2007). However, green manure crops are plowed into the soil well before the crop is sown, allowing the organic matter to decompose slowly and become available to the crop (Sandhya Rani et al., 2021). Other than in-situ green manure crops, some ex-situ green leaf manure can also be used to add nutrients to the soil (Ramanjaneyulu et al., 2021). For example, perennial crops such as neem (*Azadirachta indica*), mahua (*Madhuca longifolia*), *Gliricidia sepium*, karanja (*Millettia pinnata*), crown flower (*Calotropis gigantea*), agathi (*Sesbania grandiflora*), subabul (*Leucaena leucocephala*) and golden shower (*Cassia fistula*) are the tropical green leaf manure crops grown all along the bunds or at the corner of the field. They are pruned regularly, and the green biomass is either added directly to the field or pre-decomposed with cow manure or compost culture before being incorporated into the soil to enhance fertility (Gatsios et al., 2021; Sandhya Rani et al., 2021).

3.1.3.3 Mulching

Covering the soil around plants with organic or synthetic materials to create favorable conditions for crop growth, especially to reduce weed growth and soil moisture loss, is known as mulching. From time immemorial, natural mulches such as crop residues, straw, hay, dry grasses, sawdust, green leaves, and cover crops have been used to cover the ground to reduce soil erosion and smother weeds (Fogliatto et al., 2020). Mulching conserves soil moisture by reducing evaporation and surface runoff and by checking soil erosion (Ranjan et al., 2017). In addition, it prevents soil compaction and regulates soil temperature, thereby enhancing soil microflora (Iqbal et al., 2020). Some of the legume cover crops such as cowpea, velvet beans, clover, and alfalfa act as not only soil mulches to cover the ground surface but also green manure crops to fix atmospheric nitrogen and increase SOM.

But sometimes, it may harbor insect pests, and dry crop residues or straws in dry weather may catch fire easily. An ideal mulch should be cost-effective and locally available and should not decompose quickly, and have better aeration (Thakur & Kumar, 2021). Naturally, wood chips are a more ideal organic mulching material than crop residues. Even though organic mulches add organic matter to the soil and enhance soil biota, they have been reported to be less effective in controlling weeds and not as durable as synthetic plastic mulches (El-Beltagi et al., 2022; Hammermeister, 2016). Hence, biodegradable plastic films or recyclable mulch films can be used as an alternate option for mulching. Mulching is expected to be the best alternative for cover crops to suppress the weed population and conserve soil without much cost, labor, time, and space (Ray & Biswasi, 2016). In regenerative farming, cover crops, green manuring, and mulching should be carried out simultaneously, and all are complementary to each other, or the integration of any two components of the above would be more profitable.

3.1.4 Organic manures and bio-fertilizers

Decomposed plant or animal wastes used for supplying nutrients to crop plants are known as organic manures. Farmyard manure (FYM) can be prepared by mixing crop residues along with animal waste and sometimes with microbial culture. Animal wastes are a valuable source of energy and nutrients and are used for compost, fuel, and biogas generation. Organic manures include cattle manure, poultry waste, fish meal, slaughterhouse wastes, green manures, oil cakes, compost, vermicompost, wood ash, leaf litter, etc. (Green, 2015; Reddy, 2005; Veeresh, 2006). The nitrogen content in animal manures and vermicompost ranges from 0.5% to 2.5%, whereas oil cakes, fish, and bone meals contain slightly higher nitrogen levels (3-12%) (Chandra, 2005; Reddy, 2005). For compost or vermicompost preparation, raw materials with a carbon-to-nitrogen (C/N) ratio of 25:1-40:1 are needed, which is ideal for microbial decomposition (Rynk et al., 2022). However, crop residues have a higher C/N ratio (80:1-120:1) than manures (15:1-30:1) (Macias-Corral et al., 2019). Hence, both plant waste and animal manure have to be mixed in adequate quantity, and it takes at least 90 days to become compost. Vermicompost and vermiwash are more nutrient-rich than FYM and have been found to enhance crop yield and quality (Rehman et al., 2023). Composting of crop residues with a high C/N ratio with high cellulose and lignin content (sugarcane or corn straw) can be carried out by using compost cultures containing lignin-decomposing micro-organisms (Greff et al., 2022; Singh & Sharma, 2002). In organic farming, well-decomposed organic manures are added 15 days before planting, and the soil is always covered to maintain adequate moisture for microbial activity and to reduce denitrification (Reddy, 2005).

Biofertilizers are living or dormant microbial inoculants in liquid or solid formulations added to the soil directly or indirectly to enhance the nutrient availability to the plant. They are a low-cost source of plant nutrients, eco-friendly, and have a supplementary role with organic manures or any other nutrient sources. In a healthy rhizosphere soil, naturally, an enormous number of microbes is present, and these microbes are isolated. Single strains are cultured on nutrient media artificially and are finally mixed with different carriers to prepare biofertilizers (Bhardwaj et al., 2014; Daniel et al., 2022; Riaz et al., 2021). Root exudates of plants contain sugars, amino acids, and other metabolites to promote microbial growth and, in turn, mineralize the fixed nutrients in the soil (Canarini et al., 2019). Nitrogen fixers, phosphorous and potassium solubilizers, compost cultures, and plant growth-promoting rhizobacteria (PGPR) are the most popular among them (Bhattacharjee & Dey, 2014). *Rhizobium*, *Bradyrhizobium*, and *Azorhizobium* strains are used as symbiotic nitrogen-fixers in legumes and can fix 50-100 kg·N·ha^{-1}. Whereas, *Azospirillum*, *Azotobacter*, and blue-green algae are associative or free-living nitrogen-fixers up to 20-40 kg·N·ha^{-1} (Anuradha & Singh, 2021; Mishra et al., 2013). Vesicular-Arbuscular Mycorrhiza (VAM) is a mycorrhizal fungus used as a biofertilizer to help with phosphorous uptake from soil besides promoting root growth, drought tolerance, and water balance in annuals and perennials (Dar & Reshi, 2017; Srivastava et al., 1996). Biofertilizers can be directly applied to the soil by mixing with organic manures or through the seed treatment and seedling dip method before transplanting. However, the shelf life of biofertilizer is only 3-6 months based on the carriers, and some microbial strains may not be compatible with the native soil strains. In addition, some biofertilizer strains may be sensitive to specific environmental conditions and may not function optimally in all soil types. Hence, the native rhizosphere micro-organisms near the root zone of any healthy legumes or cereals can be multiplied in a liquid nutrient mixture containing cow dung (10%), cow urine (10%), sugar (1.5%) and chickpea flour (1.5%). The aerated mixture of not more than 48 hours can be applied to the root zone of the plant (diluted to 1:10), known as *Jeevamrut* (Saharan et al., 2023). The mixture used for seed dressing is called *Beejamrut*. Indiscriminate use of chemicals and synthetic fertilizers leaches harmful chemicals into the groundwater, causing soil acidification, eutrophication, and groundwater contamination (Daniel et al., 2022). Subsequently, organic manures and bio-fertilizers can be an alternative source of nutrients to enrich soil and ecological safety (Kumar et al., 2018).

3.1.5 Soil and water conservation structures

In regenerative organic farming, soil and water conservation practices play a major role in preserving natural resources. Globally, 75 Gt of soil from arable land is eroded every year, with an estimated value of $400 billion (Borrelli et al., 2022). Changes in land use plans, deforestation, intensive cultivation practices, and climate change are the major causes of fertile soil loss. A report on soil erosion based on land use types estimated a soil loss of 12.7 Mg·ha^{-1}·yr^{-1} from cropland, which is 77 times higher than forest land (0.16 Mg·ha^{-1}·yr^{-1}) and seven times more than natural vegetation cover (1.84 Mg·ha^{-1}·yr^{-1}) (Borrelli et al., 2017). Some agronomic practices, such as conservation tillage, NT, cover crops, strip crops, pasture, perennial trees, shrubs, or mulching practices, can reduce soil erosion (Blanco-Canqui & Lal, 2008; Kumawat et al., 2021). Besides, there is a need for proper soil and water conservation structures on the land before crops are cultivated. Dividing land into small segments, creating contour bunds, establishing bench terraces, buffer strips, check dams, grassy waterways, diversion ditches around the field, windbreaks, and constructing micro- and macro-catchment water harvesting pits across the field are some of the soil conservation measures in regenerative agriculture (Kumawat et al., 2021; Mati, 2012; Otim et al., 2019).

A study on the effect of creating a micro-catchment basin and contour strips with Napier grass and *Lablab purpureus* was found to reduce soil erosion by 55-60% and increase the soil moisture by 58-65% with a land of 10% slope (Kizito et al., 2022). Furthermore, the implementation of soil conservation measures such as terracing and contour farming (slope of 6.1-29.6%) was found to reduce the TN and total phosphorus (TP) loss by 96.77% and 98.27%, respectively (Fang, 2021). Growing vetiver grass as a buffer strip across waterways, contour bunds and hill slopes are one of the cost-effective methods for reducing soil erosion besides water conservation due to the enormous fibrous root system of vetiver (Oshunsanya & Aliku, 2017; Welle et al., 2006).

3.2 Emphasis on Locally Available Inputs

In ROA, using locally available inputs makes the farm self-sufficient and more sustainable. On-farm-produced agriculture inputs like seeds, manures, tools, and small equipment make the farmer more independent and reduce input costs substantially (Kilcher, 2007). Self-saved quality seeds greatly influence the crop stand, diversity, and seed cost. Besides, buying seeds from local seed banks or community gene banks supports the socio-economic and cultural value of the society. Locally prepared organic manures, compost, vermicompost, leaf litter, and bio-fertilizer-enriched manures reduce the input cost in addition to the transport cost. Utilization of regional inputs is helpful for the proper recycling of nutrients and energy, making it eco-friendly and economically viable. On-site prepared bio-pesticides and bio-inoculants, in combination with cultural practices, have more potential to produce quality harvesting than readily available products in the market (Soytong et al., 2021). In regenerative farming, soil regeneration and ecosystem health are prioritized over crop productivity. Regenerative farms are planned in such a way that they should be self-reliant and energy-efficient. Hence, locally available inputs are used, such as heirloom seeds (which are preserved on the farm), composts, residue mulching, green leaf manures, solar or wind power, bio-inoculants, and specially designed equipment. All the available natural resources are used efficiently.

3.3 Multiple Cropping and Heirloom Varieties

Multiple cropping is growing two or more crop species on the same piece of land, overlapping some parts of their growth cycle with each other. It may be an integration of annuals, perennials, or both in the same geographical location (Azam-Ali, 2003). At the same time, a multi-layered cropping system is a combination of crops that intercept solar radiation at various levels and absorb moisture and nutrients at different soil depths (Pramanik, 2022; Shehrawat et al., 2023). In this system, crops with different heights and root systems are planted together to form multi-strata to avoid competition for light interception, water, and nutrients. For example, planting coconut, cocoa, and turmeric together forms a crop canopy at different levels and increases the number of harvests per unit area. Multiple cropping is ideal for efficient utilization of available natural resources, increasing cropping intensity besides enriching biological diversity (Gaba et al., 2015; Pramanik, 2022; Waha et al., 2020). Cultivating various agricultural crops together in the same field makes the farm more diverse, and the cultivation of various fruit trees along with cereals, vegetables, legumes, and fodder enhances farm economic stability by ensuring year-round income and reducing the risk of crop failure (Ojeda et al., 2018; Olasantan, 1999). In addition, multiple cropping has been reported to enhance microbial biomass and mycorrhizal associations, improve carbon and phosphorus cycling, and reduce the incidence of soil-borne pathogens (Trinchera et al., 2022).

Heirloom varieties are open-pollinated traditional cultivars with more genetic diversity and are comparatively resistant to pests and diseases. They have a unique flavor, color, taste, appearance, and cultural value preferred by the local community and fetch higher prices in the market than modern first filial generation (F_1) hybrids (Cleveland et al., 2014; Miles et al., 2015). Traditional landraces are developed and maintained by the farming community and naturally adapted to a particular locality. They sometimes outperform modern cultivars under stress conditions like drought, flood, salinity, etc. (Dwivedi et al., 2016). Quality seeds of open-pollinated cultivars can be saved easily by the farming community, reducing the seed input cost and seed dependency and drawing fewer nutrients from the soil. Community gene banks, heritage seed banks, and local custodian farming communities are the best sources for buying heirloom cultivars. Erosion of genetic diversity is a major global concern, with an estimated loss of 75% of plant diversity due to modern intensive and monoculture practices (Dwivedi et al., 2019). Cultivation of heirloom varieties attracts a lot of pollinators in the garden and produces a variety of products for the market. Hence, cultivation and conservation of traditional varieties not only improve the genetic diversity and cultural heritage but are also suitable for low-input organic agriculture practices (Chable, 2005).

3.4 Integration of Livestock and Perennials

The agro-silvopasture system is an integrated part of organic farming where the soil depends on nutrients from animals, and in turn, animals are fed with natural forage grasses and legumes. All components mutually benefit each other. Pastureland has been found to increase 60% more organic matter in the topsoil than row crops and enhance nitrogen content in the land (Heckman, 2015). In addition, organic pasture feeding can improve animal health and milk quality in dairy as well as egg color and nutritional quality in poultry (Karreman, 2011; Karsten & Baer, 2009). Integration of trees in agriculture not only conserves soil but also provides food, fodder, and timber and enhances ecosystem health and diversity; it has been found to be a powerful tool for carbon sequestration (Funk et al., 2011; Krug, 2023; Scott et al., 2022). Agroforestry systems were reported to produce huge above-ground and root biomass, contributing to a carbon sequestration of 30-300 $Mg \cdot C \cdot ha^{-1}$ up to 1 m soil depth (Lorenz & Lal, 2014). A study on the influence of silvopasture systems on carbon capture in Mexico reported a significant increase in SOC content (45-54%) under tree pasture systems than in open pasture (Aryal et al., 2022). In the same study, the maximum carbon density in primary forests (349.2 $Mg \cdot C \cdot ha^{-1}$) was reported, followed by the silvopasture system (192.9 $Mg \cdot C \cdot ha^{-1}$) and open pasture (132.7 $Mg \cdot C \cdot ha^{-1}$).

However, high-intensity grazing or overgrazing has been found to reduce the carbon stock and soil nitrogen content besides soil erosion. Heavy grazing results in fertility leaching and soil compaction and impairs soil structure over a period of time (Garcia-Franco et al., 2018; Hoffmann et al., 2008; Wiesmeier et al., 2012). Hence, the rejuvenation of degraded land can be promoted by sowing grass seeds, allowing rotational grazing and mowing for hay or silage production. Cultivation of fodder grasses or legumes in low-productive areas not only enhances carbon sequestration but also improves soil structure, aggregate stability, and SOM content (Baoyin et al., 2014; Ren et al., 2015; Xiong et al., 2016).

3.5 Optimum Use of Renewable Energy Sources

The agriculture and food sectors have been shown to consume 70% of fresh water and 30% of global energy, especially for manufacturing chemical fertilizers, pesticides, agriculture tools, equipment, transportation, storage, and processing (Majeed et al., 2023). Hence, regenerative organic farming could be an alternative farming system for sustainable food production. The use of renewable and natural energy sources such as solar, wind, biogas, and geothermal power directly in agriculture activities, irrigation, harvesting, drying, and storage reduces the production cost as well as the burden on finite energy sources (Ali et al., 2012; Majeed et al., 2023). Efficient conversion of solar energy alone can produce 10,000 times more energy than people currently use, which is eco-friendly and cheaper (Chel & Kaushik, 2011). Tropical countries are blessed with solar energy almost throughout the year, and it can be effectively used for greenhouse management, watering, drying, and refrigeration (Babatunde et al., 2019). Proficient use of renewable energy resources integrated with animal and plant biomass in organic agriculture could be more sustainable and environmentally friendly than conventional agriculture (Smith et al., 2015).

4. ROA for Sustainable Development and Limitations

Regenerative organic farming is a holistic approach to creating a healthy ecosystem. It is an integrated organic farming system combining annual row crops with legumes, cash crops, horticultural crops, tree species, and pasture, along with animal husbandry, aquaculture, and on-farm processing and value addition. It also focuses on organic pest management practices by using natural pest repellents or through cultural practices such as crop rotation, cover cropping, etc. Biopesticide formulations, neem oil, garlic and ginger mixture, rosemary oil, natural predators, etc., can be used for controlling various insects along with the use of light traps, sticky traps, water traps, and pheromone traps (IFOAM, 2015; Kumar & Topagi, 2014). Neem cake and biocontrol agents can be effectively used to control plant diseases, whereas mulching is the best practice to control weeds (Fogliatto et al., 2020; Srinivas & Ramakrishna, 2005; van Bruggen et al., 2016). The use of diversified crops, heirloom varieties, perennials, and natural pest control measures enriches the soil biology and ecological diversity by attracting more pollinators. Besides encouraging ecosystem diversity, regenerative farming was reported to have twice the net profit of conventional corn farming (LaCanne & Lundgren, 2018). Even though the corn yields were less (29%) in regenerative farming, it recorded higher profit (78%) than input-intensive traditional corn production systems, where the pest incidence was tenfold higher compared to pesticide-free regenerative farms. Ultimately, it helps the farmer as well as the whole society to meet the sustainable development goals by protecting the natural environment.

Since ROA is a holistic approach that integrates many components of agriculture, a farmer needs to prepare his crop planning well in advance, and at least a five-year crop rotation plan and a suitable crop calendar have to be formulated. Specialized skills and knowledge are required to prepare a crop calendar and to plan crop rotation, cover cropping, and mixed cropping (Khangura et al., 2023; Newton et al., 2020). Conversion of land from conventional agriculture to ROA is gradual because a huge amount of biomass needs to be added to the soil to compensate for the nutrient requirement of the crop. Hence, it may be difficult to do it on a large scale, especially in the management of livestock and multiple crops. Preliminary findings suggest that ROA can be more profitable due to lower input costs, enhanced soil fertility, and higher product costs. However, some future models suggest that these cost reductions may not be sufficient to offset potential yield decreases and increased labor demands associated with ROA practices (Colombi et al., 2025; Dudek & Rosa, 2023). The issues with complex and unpredictable regulation, as well as a lack of consistency among certification agencies, need to be addressed (Lemke et al., 2024). Currently, certification costs 0.2% of the gross regenerative organic product value, with an additional annual membership fee (Seidel, 2024). Thus, ROA requires careful study to determine its true financial advantages compared to conventional farming, particularly during the initial conversion period. A thorough analysis should encompass environmental, financial, and management factors, evaluating them in terms of both short- and long-term benefits. Future investigations should evaluate the capacity of regenerative practices to reduce agricultural operating expenses, particularly energy-related costs, and to enhance agriculture's contributions to both food and renewable energy production.

5. Conclusions

ROA boosts physical and chemical properties of the soil other than improving its microbial diversity. Conservation tillage practices, along with crop rotation, cover cropping, use of organic manures, biofertilizers, and soil and water conservation structures, make soil healthy, augment SOM and SOC, and improve soil aggregates and water infiltration rate besides reducing soil erosion. Incorporating animal components, perennials, local cultivars, renewable energy sources, self-saved seeds, and manures makes the farmer independent and self-sustainable. Readapting the ancient Vedic agriculture technology and integrating it with various farming practices could be the possible solution to address multiple issues like ecological imbalance, climate change, greenhouse gas emissions and increasing carbon stock. Even though ROA is considered a holistic approach to building healthy soil and biodiversity, long-term scientific studies are required to be carried out under various agro-climatic conditions to measure the quantitative benefits in comparison with conventional agriculture. Still, there is a lack of standardized cultural practices, certification procedures, and marketing strategies to promote ROA. In this regard, a special government policy based on carbon credits or other incentives needs to be initiated for the farmers who practice ROA. Overall, the ecological benefits of ROA need to be quantified alongside economic assessments.

Author Contributions

Idea of review, data collection, compilation and writing work was carried out by Yashaswini Sharma. The author has read and agreed to the published version of the manuscript.

Data Availability

All data generated or analyzed during this study are included in this published article and also available in the repository: https://paperpile.com/shared/IzwKCK.

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Conflicts of Interest

The author declares no conflict of interest.

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