Transforming Food and Agriculture for Sustainable Development Goals: Achieving Climate Resilience and Global Food Security

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Abstract

Climate-smart agriculture is a package of integrated innovation approaches to promote sustainable agriculture, using modern resource management practices for agroecological improvement to enhance food security and combat climate change. Techniques like agroforestry, biochar, and precision irrigation have improved Soil Organic Carbon (SOC) by up to 15 units ha^{-1}, and water evaporation in arid areas is now a 40 million cubic meters reduction per annum. All these strategies lead to increased productivity rates, reduced greenhouse gas effects, and promote sustainable growth. However, some challenges affecting implementation include high costs of ownership, limited technology access, and insufficient policies to support full integration. These systems call for crop productivity in the face of climate change and bode well for ecosystems in terms of soil health and conservation, carbon stocks, and dependency on inorganic fertilizers. From an economic point of view, those practices improve farmers' revenues by reducing waste and diversifying resource utilization, such as biogas and bio-products. To address the existing barriers, new targeted investment, capacity-building undertakings, and aligned policy including the Green Deal of EU and national level programs of SDG alignment become imperative for fostering the scale of adoption at a higher pace. When scientific innovations are integrated with principles of the sustainable developmental agenda, climate-smart agriculture portrays an integrated wicked solution to establishing food system security for future generations.

Keywords: agroecology, Climate-resilient agriculture, Circular economy, Food security, Sustainable practices

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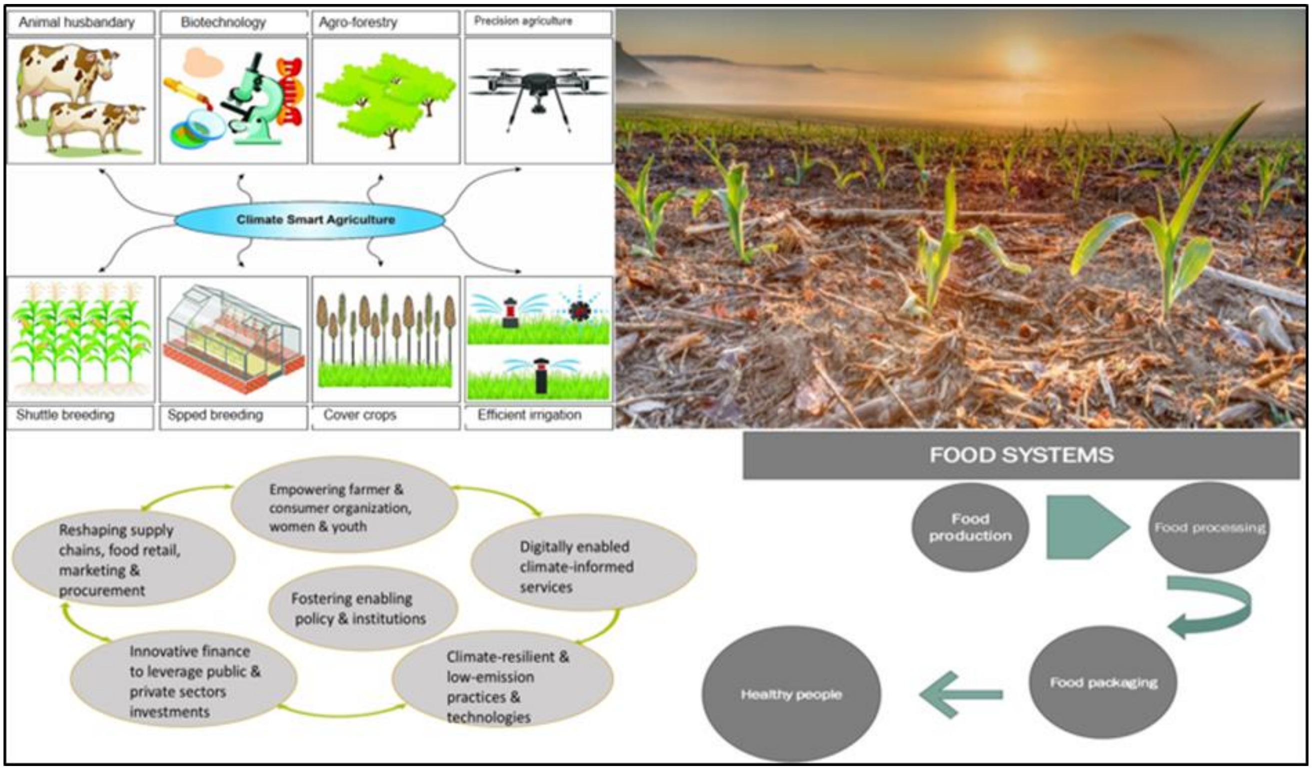
Introduction

Climate-smart agriculture has emerged as a crucial approach to addressing food security and climate change concerns. It is a broad system that focuses on the application of the recent advances in factors affecting soil performance, complex and optimal use of technology, and both farm and natural resource productivity, for enhancing agricultural systems that are stable and can break climatic shocks (Agrimonti et al., 2021; Sarma et al., 2024). Drought frequencies, unpredictable rainfall, and floods have resulted in low crop production, hence food insecurity and loss of living standards. Climate-smart agriculture is not only focused on food production for food security but also ensures that small-scale producers reduce their exposure to the effects of climate change. It recommends sustainable production of food, and this is because it encourages crop introduction and the efficient control of pests, which help make ecosystems stable (Hellin et al., 2023). Further, precision agriculture and digital technologies help farmers so that they will reduce the effects of exhaustion of natural resources, environmental degradation, and global issues such as climate change and population explosion.

The United Nations and its member countries are working toward the 2030 goals of individuals and communities with sustainable development goals (Krannich & Reiser, 2023). In this context, SDG 2 (Zero Hunger) and SDG 13 (Climate Action) arrange a significant part of sustainable agriculture by their focus on hunger eradication and climate change, respectively (Hansen et al., 2022; Lile et al., 2023). They're also compartmentalized with other goals, like for instance the abolition of poverty (SDG 1) and sustainable consumption and production (SDG 12). Conservation practices like agroforestry systems, conservation agriculture, and water management help to bring in rich nutrient foods and concurrently act as carbon sinks (Atapattu et al., 2024). Climate-smart agriculture is therefore used as an approach to implementing a sustainable climate-smart food system that is sustainable and humane on the planet. It is beneficial for addressing current and future climate change barriers and enhancing sustainable food systems in the future.

1.1 Climate-Smart Agriculture for Food Security: Principles and Operational Indicators

Climate-smart agriculture (CSA) is a promising approach to achieving food security and reducing climate variability footprints simultaneously. This approach covers better practice activities that indicate precision irrigation and crop and livestock production diversification to improve adaptations to climate volatility, raise input productivity, and decrease total GHG emission rates (Ariom et al., 2022). For instance, Kenyan drought-stressed maize has provided a 24% yield increase when drought-tolerant varieties are used and integrated crop-livestock systems in Brazil have been proven to reduce GHG emissions by 20% ha^{-1} (Rao, 2021). Further, CSA practices as; no-tillage and biochar application through CSA can sequester up to 0.5 t C ha^{-1} per annum in the pilot African and Latin American farms (Ondrasek & Zhang, 2023). These efforts have shown how CSA can revolutionize the current agricultural production inputs to continue feeding the world with food in the emerging deepening climate reality.



Graphical Abstract

Technology has greatly boosted the effectiveness of CSA implementation. With technologically advanced devices like GIS and IoT, a farmer can now assess the nature of the soil, and its characteristics and even work on the conservation and utilization of resources in the presence of climate risks. For example, SCADA-based irrigation systems in Nepal have lowered water usage to 35%, and precision farming using UAV in Europe has reached 95% accuracy thus decreasing pesticide application to 30% (Rehman et al., 2024). In addition to technological interventions, CSA includes region-specific practices such as agroforestry practised in Asia where SOR has increased to 50% within 15 years and Agro terracing in Nepalese hills where it helps to reduce soil erosion and increase productivity (Joshi, 2022). Case studies including India, Tanzania, and Nepal illustrate that CSA has a great capability to solve multiple environmental and socioeconomic issues (Acharyya, 2022). These examples therefore support the position that CSA plays an important role in advancing sustainable agriculture by showing aspects of gains in production, better use of input resources, and moving to better coping mechanisms with climate change in different world regions.

However, several challenges hinder the adoption of CSA. The challenges include the Lack of capital is one of the biggest issues with smallholder farmers; they lack the capital to put proper measures into use. For instance, though the 'zero tillage farming' practice is practised now by many farmers in India, the percentage is pulling not more than 40%, whereas 60% of farmers avoid this technique due to its high cost – both initial investments in equipment and machinery (Dinesh et al., 2022). Likewise, in Tanzania and other SSA countries, rain farming remains the most popular type, and irrigation structures are available to only 30% of the interviewed producers (Njeru, 2020). These barriers need to be addressed through deliberate resources to build up the physical enablers, human capital, and institutions to close the equity chasm on CSA technology adoption.

Evaluating and monitoring CSA appears to be vital in amplifying the results of CSA and some investigators seem to be very emphatic regarding this matter. Of these, yields, greenhouse gas emissions, and efficiency in the use of resources must be used to assess the sustainability of CSA techniques. For instance, Ojha and Hall (2023) and Birla et al. (2024), working at Developing Nations Show organizers in Nepal, have found monitoring systems in communities to be advantageous for metrics that capture the worth of agroforestry, enhancing the farmer uptake and in turn associated rates. From these examples, using the NASW research findings to strengthen CSA programs is most likely to yield maximum effectiveness and sustainability.

As presented in Table 1, key CSA practices, their regional applicability, and evidence-supported outcomes are presented. In sub-Saharan Africa and India, agroforestry has led to a 20%-30% increase in soil organic carbon stocks, subsequently enhancing soil health and species diversity (Fahad et al., 2022). Precision Agriculture, widely adopted in Europe and Australia, has reduced fertilizer use by half and water consumption by three-quarters without significantly impacting crop yields (McMillan, 2023). Crop diversification in South Asia and Latin America has helped maintain stable crop yields and increased pest and disease resistance by 25% (Hollósy et al., 2023). CSA strategies, such as emphasizing drought-resistant crops and rainwater management, have boosted productivity in arid regions. Furthermore, implementing viable Integrated Climate Smart Agriculture can foster sustainable and productive farming systems.

Table 1: Climate-Resilient Practices in Agriculture

Practice	Description	Region/Case Study	Impact/Outcome	References
Agroforestry	Integration of trees and shrubs into agricultural landscapes for enhanced biodiversity and soil health.	Sub-Saharan Africa, India	Increased soil organic carbon by 20–30% and improved water retention in arid areas.	(Muthee et al., 2022)
Precision Agriculture	Use of advanced tools like GIS, sensors, and drones for optimizing resource applications.	Europe, Australia	Reduced fertilizer use by 15% and water usage by 30%, maintaining yield stability.	(Raj et al., 2022)
Crop Diversification	Planting multiple crops enhances ecosystem services and reduces dependency on a single crop.	South Asia, Latin America	Improved resilience to pests and diseases with a 25% increase in yield stability.	(Laub et al., 2023)
Soil Carbon Sequestration	Practices such as no-till farming and cover cropping enhance carbon storage in soils.	North America, Europe	Sequestered 0.3%–0.5% tons of CO2 per hectare annually, reducing GHG emissions significantly.	(Zomer et al., 2017)
Drought-Resistant Crops	Development and adoption of crops bred for higher resilience to water stress.	Sub-Saharan Africa, Asia	Yield increases of 20%–40% in drought-prone regions.	(Raj et al., 2022)
Integrated Pest Management (IPM)	Combination of biological, cultural, and chemical tools to control pests sustainably.	Asia, Latin America	Reduced pesticide use by 30%, with better long-term pest control and reduced resistance.	(Sanyaolu & Sadowski, 2024)
Rainwater Harvesting	Techniques to collect and store rainwater for agricultural use during dry periods.	India, Tanzania	Increased water availability by 50%, improving crop yields by 15%–25% in water-scarce regions.	(Lakhiar et al., 2024)

1. Soil Health and Sustainable Resource Management

It is an essential natural resource in food production, maintaining ecological integrity, and is important for climatic change adaptation through its functions in nutrient cycling, water, and food production. But there are holes in these as increased cases of food production and harsh weather such as droughts and floods due to climate change have exposed the vulnerability of the soil systems. For example, due to overuse and soil erosion productivity in sub-Saharan Africa has declined by 25% to 40%, hence the importance of sustainable soil management (Mbow, 2020). Those states implementing climate-smart technologies suggest evidence of enhanced performance. Conservation agriculture in South Asia yields better; and shows improved water infiltration of 30% hence reducing soil surface runoff when there is heavy rainfall (Somasundaram et al., 2020). Likewise, no-till farming in North America has built SOC stocks by 0.5 to 1.0 per year in addition to increasing production to counteract climate risks (Sorenson et al., 2024). Figure 1 mentions that regenerative agriculture also enhances the aspect of soil by decreasing its water needs owing to increased soil infiltration in dry areas.

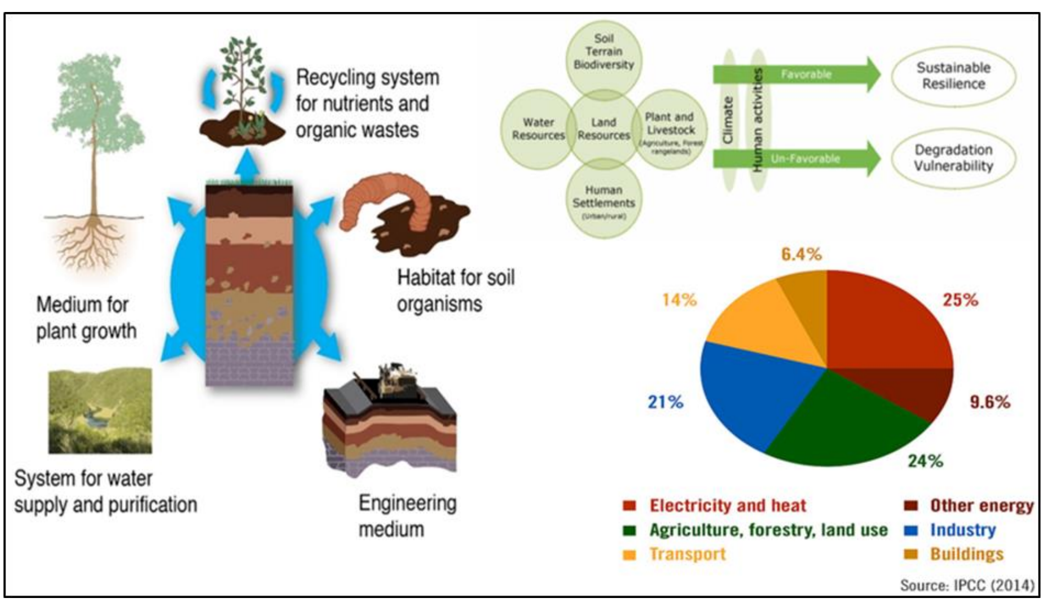


Fig. 1: Soil Health and Sustainable Resource Management

2. Carbon Sequestration in Soils

Carbon sequestration in the soil is one way through which climate change can be tackled and soil productivity improved. The next mechanism stabilizes the carbon in the soil as an organic matter and helps mitigate greenhouse gas emissions while enhancing the soil's physical and chemical characteristics. Knowledge also suggests that practices such as the use of covers, trees within farming fields, and the application of biochar boost the level of carbon dioxide in the atmosphere by approximately 0.3-0.5 tons ha^{-1} every year (Kopakkala, 2022). National and international practices for agriculture with trees including European Integrated Agroforestry Research (AgroFor) have established that SOC has risen by 25% in the last 20 years coupled with improved crop production by 15% (Báder et al., 2023). Likewise, in the Australian environment characterized by a dry and warm climate, the use of biochar has increased SOC by between 10% and 15% in five years and the water retention capacity by 20%. On the other hand, conventional tilling practices in Asian regions have led to soil carbon loss, thus the call for sustainable farming. These results confirm that soil carbon sequestration and SOC increase are critical for easing climate change consequences, agricultural productivity, and crop yield steadiness.

Carbon Sequestration

$C_s = A \times S \times R$

This formula estimates the capacity to stock carbon in the soil as; Cs=A*S*R; Cs=Total carbon stored in tons; A=Area of land in hectares; S=Rate of sequestration in tons of C/ha/year; R=Retention factor which is the proportion of Carbon that is retained over some time. This applies mainly to the application of agroforestry and biochar as witnessed in some parts of sub-Saharan Africa where rates of sequestration can be up to 0.5 tons per hectare per year.

3. Effects of LUCC

Global processes like deforestation, urbanization, and high-intensity agriculture have contributed to Soil Organic Carbon (SOC) through soil degradation. Recently cleared forests in South America in 40 years age group saw a 30% to 50% decline in SOC which was compounded by the loss of ecological services (Flores et al., 2024). Likewise, monoculture farming in Asia has reduced soil fertility in the past ten years by 15% which is evident in the poor land management practices. Furthermore, studies concerning methods aimed at reversing these negative approaches have positive results. For instance, the reforestation programs have noted the overall SOC content of Africa to range between 20% and 25% and boost resource supply and biodiversity. Fostering more biomass in a Southeast Asian setting has however improved the rates of biomass production by 30% and slashed erosion rates by 40% compared to conventional practices (Homeshwari-Devi et al., 2024). Additional activities are also active in urban agriculture; for instance, green roofs in Europe collect 30% more rainfall than any other ordinary surface reducing the effects of Urban Heat Island and boosting food production at the regional level (Mihalakakou et al., 2023). From these results, the need to enhance sound soil management policies to enhance the quality and availability of soil resources by promoting the efficient use of soil in a sustainable manner is evident represented in Figure 2.

4. Agro-Ecological Interventions

Biochar is proving to be an effective agroecological input improving soil structure, carbon stocks, and crop yields. Pyrolytic biochar obtained from organic waste enhances the physical characteristics, nutrient, and water-holding capacity of the soil. Research also indicates that in low-nutrient regions, the use of biochar in the degraded soil can lead to a 20%-25% increment in crop productivity (Kang et al., 2022). In Sub-Saharan Africa, applying biochar from crop residue increased the yields of available soil nitrogen and phosphorus by 18% and improved the nitrogen and phosphorus uptake by 30%, respectively (Mashamaite et al., 2024).

These are mostly hosted particularly in arid and semi-arid regions since the application of biochar greatly improves the fertility of the soil. When applied on the sandy soils in Australia, biochar enhanced inputs of moisture by 15%-20%, leading to the enhancement of wheat yields by 30% during the dry year. European temperate regions reveal 10%-15% yield gains, while the focus lies on the possibility of producing less emissions through biochar (Rodrigues et al., 2023). It has been proved that in Asian rice paddies, the use of biochar reduces methane emissions by up to 25%. Nonetheless, high production costs and the low perception of smallholder farmers about OCPs require more investment and favourable policies (Singh et al., 2022).

Integrating trees and shrubs into crop production systems or integrating crops with trees and shrubs (known as agroforestry) has been helpful in concerns about fertility, diversification, and water. One advantage of this strategy is the high impact in areas of low rainfall since tree roots help to bind the soil, prevent erosion, and improve its water-holding capacity. Speaking of Sub-Saharan Africa, the implementation of AF has raised crop productivity by 30%; millet and sorghum agriculturists benefitted from better drought tolerance. For instance, the integration of fruit trees in agroforestry systems of legume-based systems in India has resulted in increased 20% in soil organic carbon and a 25% improvement in the income of small farmers based on diversified productivity (Kumar et al., 2023). Figure 3 represents the critical interventions based on Agroecological behaviours.

5. Field and Risks Management

Sustainable agriculture is critical, and depending on the climatic volatilities, it has shifted towards the use of Agroforestry practices and most importantly efficient irrigation practices. For instance, small-scale irrigation such as drip irrigation and water conversation technology as well as water demand management techniques have proven to have the capacity to sustain water use rates and at the same time improve yields. Similarly, in Asia, the use of water-saving rice varieties reports up to a 40% cut in water use with yields 15% higher (Zhang et al., 2021). Further, rice farmers using alternating wet and dry techniques have brought down methane emissions by 30% without affecting crop production (Hossain & Islam, 2022). A study done by Mello et al. (2023) established that the application of agroforestry together with measures to conserve water yield sustainable gains that embrace reduced soil erosion by 40% in Brazil, and Latin America. These examples illustrate the potential for climate adaptation through sustainable water and land management in agriculture as shown in Table 2.

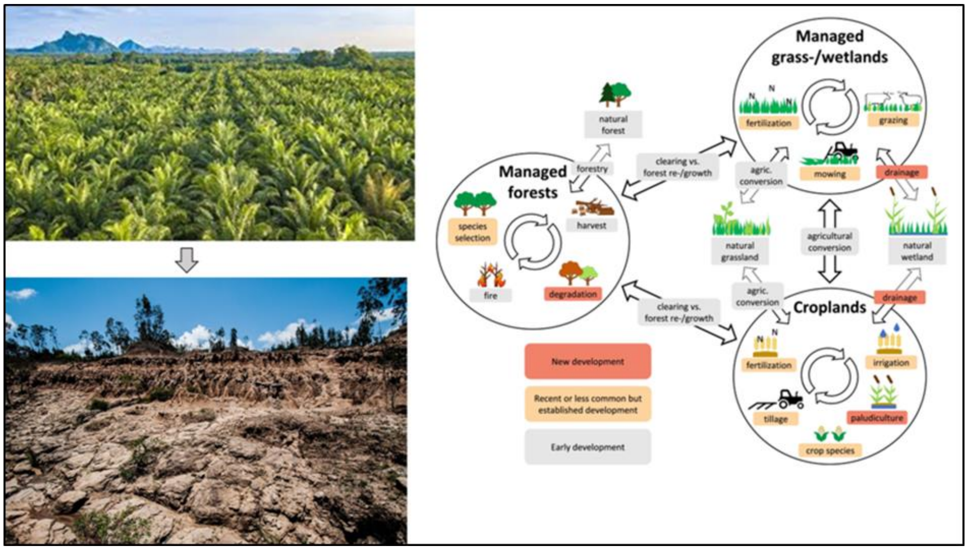


Fig. 2: Effects of LUCC

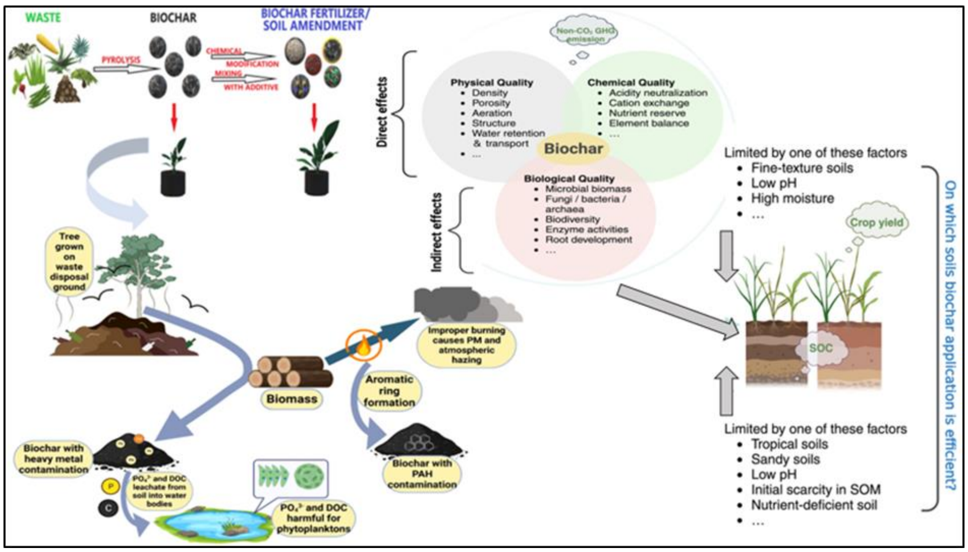


Fig. 3: Agro-Ecological Interventions

Table 2: Indicators for Sustainable Soil Health

Indicator	Description	Region/Case Study	Impact/Outcome	References
Soil Organic Carbon (SOC)	Measures the carbon stored in the soil, crucial for fertility, water retention, and nutrient cycling.	Sub-Saharan Africa, India	SOC increased by 15%-20% in conservation agriculture practices, enhancing yield stability by 25%.	(Knapp & van der Heijden, 2018)
Soil pH Levels	Indicates soil acidity or alkalinity, affecting nutrient availability and crop productivity.	Southeast Asia, Europe	Balanced pH through liming improved nitrogen efficiency by 30% in acidic soils.	(Knapp & van der Heijden, 2018)
Nutrient Retention	Refers to the soil's ability to hold nutrients like nitrogen and phosphorus for plant uptake.	Latin America, Australia	Reduced nutrient leaching by 20%-30% through biochar and organic amendments.	(Knapp & van der Heijden, 2018)
Water Holding Capacity	The soil's ability to retain water is critical for resilience during drought conditions.	Arid regions in Asia and Africa	Increased water retention by 20%-25% using cover crops and agroforestry systems.	(Knapp & van der Heijden, 2018)
Soil Microbial Biomass	Represents the living component of soil organic matter, essential for decomposition and nutrient cycling.	Europe, North America	Improved microbial biomass by 30% with reduced tillage, contributing to better soil health and fertility.	(Knapp & van der Heijden, 2018)
Erosion Rates	Indicates soil loss due to wind or water, affecting productivity and sustainability.	Sub-Saharan Africa, South America	Erosion was reduced by 40% through terracing and agroforestry practices in hilly regions.	(Knapp & van der Heijden, 2018)

Table 2 highlights challenges affecting the effectiveness of regional strategies in improving key soil health indicators. Conservation agriculture in Sub-Saharan Africa and India has shown a 15%-20% increase in Soil Organic Carbon (SOC), often through cycling, which helps stabilize crop yields. In Southeast Asia, living practices have boosted nitrogen use efficiency by approximately 30%, addressing soil acidity issues. African farmlands have seen a 25% increase in water storage capacity through agroforestry, offering a solution to drought in areas with limited rainfall. Microbial quantity has risen by 30% in Europe and North America due to conservation tillage implementation, enhancing ecosystem health. Additionally, agroforestry and terracing in hilly regions of Sub-Saharan Africa and South America have reduced soil erosion by 40%, demonstrating the impact of targeted sustainable farming interventions.

6. Innovative Approaches to Circular Economy in Food Systems

The concept of circular economy transmits new opportunities for improving the efficiency of food chains that use agricultural and industrial residues as valuable resources, including bioenergy, animal feed, and organic fertilizers. For instance, Asian countries use rice husks and strew for biochar and biogas respectively, other than that European nations convert the brewery waste to cattle feed which increases resource utilization thus cutting down the costs (Ashokkumar et al., 2022). In the same way, Latin American smallholder farmers have reduced their chemical fertilizers with the use of organic compost. These practices demonstrate how circularity can be incorporated to contain environmental harm while at the same time spurring economic development.

Reduction and management of waste, and further utilization of the remaining waste are also clear strategies that positively contribute to change in the food system for sustainability. North American retailers rely on IoT technology to minimize fresh food waste at the retail and consumer point, and valorization helps convert surplus produce into new marketable goods. For instance, African cooperatives turned vegetables into dried snacks and Indian dairy farmers transformed excess milk into ghee, and powder. The enhancement of fishery byproducts into collagen and gelatin for medical utilization in Latin America is also evidence of forging a circular food system value chain. All these initiatives go to show that waste could be harnessed for the promotion of sustainable production and distribution of foods.

Water Use Efficiency

WUE=Y/W

WUE is expressed by an equation that quantifies the yield (kg ha^{-1}) around the amount of water used (mm or m^3). In this case, Y = Crop yield and W = Total water applied. This concept is relevant to precision irrigation techniques in Asia, where water consumption was decreased by 30% without compromising crop production levels.

Table 3: Food Waste Hierarchy in Circular Systems

Hierarchy Level	Description	Examples	Impacts	References
Prevention	Reducing food surplus at the source through better planning and demand forecasting.	Improved stock management in retail chains.	Minimized food waste at the retail level, improving efficiency and reducing emissions.	(Nikolicic et al., 2021)
Redistribution	Distributing edible food to those in need through food banks or similar organizations.	Surplus bakery items are redistributed to food banks.	Supported community food security, lowering overall food waste.	(Nikolicic et al., 2021)
Reprocessing	Transforming food waste into value-added products like animal feed, fertilizers, or bioplastics.	Use of spent grains for livestock feed in breweries.	Generated alternative revenue streams and reduced environmental burdens.	(Ashokkumar et al., 2022)
Recycling	Composting organic waste or using it for biogas production through anaerobic digestion.	Agricultural residues are converted into compost.	Improved soil fertility while reducing dependency on synthetic fertilizers.	(Sharma et al., 2019)
Disposal	Sending food waste to landfills or incineration as a last resort.	Food waste incineration with energy recovery.	Reduced landfill volumes but with environmental costs due to emissions during incineration.	(Sharma et al., 2019)

African national governments are collaborating with international organizations to improve food security. In Ethiopia, the Climate Resilient Green Economy Strategy has provided soil conservation training to 203,000 farmers, aligning with SDG15 (Life on Land) (Dey et al., 2022). Meanwhile, Brazil's Low Carbon Agriculture Plan promotes sustainable land management practices, resulting in the restoration of 2 million hectares of degraded pastures since its inception. These initiatives demonstrate a growing awareness of the importance of policy alignment in promoting sustainable development goals and fostering agricultural systems that support both environmental and economic sustainability.

Table 3 shows the structure of the food waste management systems which are aspects of circular economies. Actual prevention is considered the most effective approach, which focuses on improvements in inventory management and enhancing consumers' awareness. Redistribution helps in giving away surplus food to specific communities. On the other hand, reprocessing produces new valuable items from waste, examples being animal feed and bioplastics. Recycling schemes with a high emphasis on composting and heat energy entail nutrient cycling and energy recovery dimensions. Disposal, the last of the four methods, is the most unpopular because it leaves significant ecological impacts that necessitate searching for other forms of disposal. This hierarchy is indicative of the transition from waste-based to resource-based systems that pose value to both the environment and the economy.

Table 4 resource use efficiency between different global regions is also compared. This underpins the effectiveness of agroforestry in sub-Saharan Africa, as it enhances water and nutrient capture for important food crops. In Europe, sophisticated technologies such as IoT and precision agriculture apply extreme measures of discipline on inputs whilst ensuring steady yields. Asia's goal of attaining food production in the wake of the adverse climatic conditions is well-photographed in the case of drought-resistant varieties. North America focuses on the no-tillage method in farming, this has an effect of saving energy and water besides improving the soil quality. This shows Latin America's organic amendments and conservation practices effectively respond to soil degradation issues and long-term agricultural security. They used a strategy that is distinctive and suitable to the regions for improving the overall efficiency of resources internationally.

Table 4: Comparative Analysis of Resource Use Efficiency

Region	Practice	Input Optimization	Output Gains	References
Sub-Saharan Africa	Agroforestry and intercropping	Enhanced nutrient uptake and reduced water loss through integrated systems.	Improved resilience of millet and maize crops, increasing productivity under variable climatic conditions.	(Bado et al., 2021)
Europe	Precision agriculture and IoT integration	Reduced fertilizer application and efficient irrigation via sensor-based systems.	Maintained stable crop yields while lowering environmental footprint through optimized resource use.	(Laveglia et al., 2024)
Asia	Drought-tolerant crop varieties	Effective water management and climate adaptation with improved seed genetics.	Increased food security in water-stressed areas with higher yield stability despite adverse conditions.	(Nadeem et al., 2024)
North America	No-till farming and crop rotation	Retained soil moisture and reduced energy use through minimized soil disturbance.	Enhanced long-term soil health with stable productivity and lower operational costs.	(Jayaraman et al., 2024)
Latin America	Organic amendments and soil conservation	Improved organic matter content and reduced erosion through sustainable land practices.	Supported sustainable coffee and sugarcane farming while addressing soil degradation issues.	(Cherubin et al., 2021)

Conclusion

When definitions of agriculture in the context of climate change are expanded to include practices focused on sustainable resource use and innovative technologies, a powerful method for simultaneously advancing Global Sustainability Goals. Research has shown that current Agroecological approaches, such as agroforestry, biochar application, and no-tillage farming, have yielded positive outcomes. These include an estimated rise in soil organic carbon content of up to 15 units per hectare and a reduction in soil erosion across the globe. Cutting-edge technologies like AI-driven precision agriculture have led to a significant decrease in input usage, with annual fertilizer savings of millions of tons without compromising production efficiency. To date, no previous research has validated the policy acceleration of the EU Green Deal and Farm to Fork Strategy concerning circular economy principles and the annual utilization of millions of tons of agricultural byproducts for renewable energy and organic fertilizers. These advancements underscore the crucial role of multi-stakeholder collaboration, targeted investments, and location-specific approaches in disseminating sustainable agricultural practices.

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