

Review

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Review

Sustainable Advances in Agroecosystems and the Impact on Crop Production

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Abstract: Agroecosystems support food production through ecosystem services, agricultural activities and socio-aspects such as traditional knowledge and technology. These agroecological practices benefit the agroecosystem such as biodiversity, pest control and soil conservation, water conservation and climate change mitigation. The review aims to investigate the recent advances in sustainable crop production that have emerged over the years such as agroecological practices and precision agriculture. Some agroecological practices reviewed include cover crops, intercropping, crop rotations and agroforestry. The practices that were found to have advanced than others were intercropping followed by crop rotation and agroforestry. Factors influencing farmers' adoption or non-adoption of these practices such as farm or land size, age, sex, skills and knowledge are also explained. The farm size followed age, skills, and knowledge followed by age and sex were the dominant factors that were responsible for adoption and non-adoption. The various types of crop diversification had an impact on the environment, crop growth and yield.

Keywords: agroecosystems; agroecology; crop production; crop diversification; pest management; soil health; water resource management

1. Introduction

Agroecosystems are defined as ecosystems that support food production directly through human activities in systems such as farms or gardens. They are socio-ecological systems characterised by three interacting components such as the managed fields characterised by agricultural activities, the semi-natural or natural habitats of the ecosystem, and the human-derived capital which is characterised by knowledge, cultural traditions, technologies, settlements, and infrastructures [1]. Biodiversity supports the agroecosystem functioning by providing food, feed, timber, fibres, and other products. Currently, agroecosystem sustainability is mainly challenged by unsustainable agricultural practices that lead to land degradation and climate change [2].

The growth in human population led to increased agricultural production to improve food security and resulted in agricultural intensification [3]. As the demand for food resources increased it resulted in the Green Revolution. The Green Revolution brought a lot of agricultural intensification to alleviate hunger and improve food security. Intensive agriculture also regarded as conventional agriculture is characterised by higher levels of inputs such as labour and agrochemicals, and outputs which are higher crop yields. However, conventional agriculture and food systems that came along with the Green Revolution succeeded in markedly increasing the production of staple crops, but this came with a lot of costs to human health and the environment [4–7]. The environmental challenges include biodiversity loss, greenhouse gas emissions, excessive pesticide and fertiliser usage, soil degradation, water logging, erosion, water pollution, air pollution, heavy metal pollution, and the outbreak of pests and diseases [Sudarshan et al., 2024]. Therefore, there was a need to address these challenges.

Agroecosystems must be protected through sustainable agricultural and agroecological practices, whereby agricultural systems are designed and managed for productivity whilst conserving natural resources such as soil and water. Sustainable agriculture can help to protect our agroecosystems by integrating appropriate natural biological cycles to sustain the economic viability of farm operations whilst enhancing the quality of life for farmers and society [9]. Sustainable agriculture is

encompassed by three main dimensions which are environmental, economic, and social aspects. Sustainability in agriculture is achieved when a balance of these 3 dimensions is in tandem [10]. A sustainable farm produces adequate amounts of high-quality food, protects its resources and is both environmentally safe and profitable [9]. Agroecological practices include agricultural landscaping which is the altering of existing designs of gardens and farms by planting or adding different trees or plants. Other agroecological practices include farm diversification, intercropping, crop pasture rotation, organic farming, silvopasture, integrated aquaculture, the planting of cover crops, and avoiding the use of synthetic inputs like fertilizers and pesticides [11,12].

However, with the rise in demand for food production due to increasing human population, agricultural technologies for better food production have been introduced. The Internet of Things (IoT) has emerged as one of the most vital components of modern information technology that makes farming systems possible [13]. The Internet of Things includes the use of artificial intelligence brilliance, precision agriculture, the wonders of Agri biotechnology, the power of robotics, the agility of drones, remote sensing, Big Data Artificial Intelligence and technology connectivity [6,13]. Agricultural technology innovation speeds up the agro-industries, mitigating risks, tracking real-time progress, and optimising costs while preserving food quality [6].

Solving the problem of agricultural food production and environmental protection has become the main concern of sustainable agriculture. The current review aims to identify the recent methods and technologies that have been applied or developed to mitigate the effects of agricultural intensification and climate change.

2. Crop Diversification

One way to improve the agroecosystems is to minimize or stop the loss of biodiversity from intensive farming. Increasing agrobiodiversity is essential for productivity and adaptability of species, global food production, food security and sustainable agricultural development. For instance, more crop diversity enhances microbial populations, which can promote plant growth and increase agricultural output [14].

Many of the ecosystem functions provided by biodiversity, like pollination, nutrient retention, weed control, or disease suppression, are important for agricultural crop production and hence can be classified as agroecosystem services [15]. A higher diversity is beneficial to crops and the surrounding environment. Crop diversification entails planting cover crops after harvest of the main crop, crop rotations, multiple cropping, intercropping, cultivar mixtures, and agroforestry. All these practices have been shown to enhance ecosystem functioning such as increased yield and stability, increased resource-use efficiency, enhanced soil fertility, reduced crop disease, and minimized environmental costs [16–18].

2.1. Cover crops

Cover crops are any plant species grown for purposes beyond primary grain or forage production and are generally classified as leguminous broadleaves, non-leguminous broadleaves, brassicas or grasses [19,20]. They protect and improve the soil between regular annual crop production or between trees in orchards and vines in vineyards [19]. Cover crops are planted with or after the main crop and are usually removed before the next crop is planted. Winter-planted cover crops are considered an in-field best management practice, which does not typically require taking land out of cash crop production. They are usually planted after the harvesting of cash crops, with planting generally occurring in the fall and followed by mechanical or chemical termination before planting a summer cash crop [21]. Cover crops are also green manures, catch crops, or living mulch. Cover crops provide in-field benefits such as erosion prevention, improvements in soil quality and nutrient retention, improved water quality by reducing soil and nutrient losses, increase biodiversity in an agroecosystem, and contribute to landscape scale environmental benefits such as decreasing sediment run-off [18,21,22]. Besides providing ground protection, cover crops can provide weed and pest suppression [20]. Cover crops can also assist farmers in fighting against climate change as they offer carbon sequestration [20,23,24].

Moreover, cover crop biomass also contributes to waste material that enters the soil, leading to increased carbon and nitrogen content in the soil. A study conducted by McClelland et al. [25] found that cover crops in temperate climates can help to increase the storage of soil organic matter and carbon. The stored carbon and nitrogen could become available for the next crops [16,26]. Integration of livestock is also an important factor in driving cover crops as cover crops enhance forage opportunities for many livestock [21].

Some farmers adopted cover crops whilst some did not due to several reasons such as skills, knowledge, socio-influence and risk fear [20,21,27]. Some farmers may choose not to practice cover cropping due to production costs and fear of taking risks. Knowledge of how to use cover crops and the skills required have a huge influence on adoption.

2.2. Intercropping

Intercropping is the practice of planting two or more crops in the same field during the same growing season with the primary goal of increasing production on a specific piece of land by making use of resources that would otherwise go unused by a single crop [28]. It is a diverse type of cropping system where two or more crops are planted. It involves planting annual plants with annual plants, annual plants with perennial plants and perennial plants with perennial plants. Planting may take two forms, row-intercropping where two or more crops are planted simultaneously in regular rows, and mixed-intercropping which involves growing two or more crops simultaneously with no distinct row arrangement.

Strip-intercropping involves growing two or more crops simultaneously in different strips wide enough to permit independent cultivation but narrow enough for the crops to interact ergonomically and relay-intercropping is where two or more crops are planted simultaneously during part of the life cycle of each [29–31]. Alternate intercropping, or transposition intercropping, is a new intercropping pattern in which two crops are intercropped in a wide strip with planting positions rotated annually on the same land [36]. Alternate intercropping combines rotation with intercropping to effectively benefit yield increases and the efficiency is further enhanced by the rotation [34]. Annual rotations of the adjacent maize- and soybean-strips intercropped increased the grain yield of the next seasonal maize whilst improving the absorption of nitrogen, phosphorus, and potassium of the maize [33].

A study conducted by [32] found that strip intercropping enhanced biodiversity and controlled insect pests. Rotational strip intercropping is a compound planting system involving annual intercropping and interannual rotation of intercropped strips and has been shown to offer better crop productivity than monoculture [38,39].



Figure 1. Strip intercropping of maize, soybean and oat crops [35].

A study by Baker et al. [37] examined the growth of sorghum intercropped with a legume under weeding and no weeding conditions and concluded that the intercropping pattern significantly affects plant height and chlorophyll content with weeding having a significant effect on the agronomic indicators. Moreover, intercropping not only improves crop yield but also reduces competition for major soil /nutrients, increases beneficial soil microorganisms, improves N status and N use efficiency and reduces pathogenic microorganisms [31,40,42]. It assists in reducing the attack of insect pests, checks the incidence of diseases, restricts weed population and thus minimises the use of protection plant chemicals [45].

Push-pull intercropping is an advanced agroecological technique which involves the use of repellent properties of an intercrop (push) and attractive properties of a border crop (pull) surrounding the field for pest control. The focal crop is usually maize, or sorghum planted with a legume of the *Desmodium* genus which helps to reduce herbivore attacks and suppresses the growth of the parasitic weeds [46–49].



Figure 2. Push-pull intercropping with brachia grass as a border crop [50].

Regarding soil nutrients, intercropping was shown to increase the contents of soil labile phosphorous, stable phosphorous, solution phosphorous, hydrolysable phosphorous and exchangeable phosphorous [43]. The legume Cowpea is a crop used mostly for intercropping by farmers in African countries. Legume-cereal rotations are commonly adopted in sub-Saharan Africa to maintain soil fertility to compensate for the limited access to inorganic fertilizers [44]. Furthermore, intercropping systems have the potential to ensure the regulation of climatic factors, maintain efficient soil moisture utilisation, maximise the use of solar radiation, reduce greenhouse gas emissions and promote more carbon sequestration [51]. Intercrops have an impact on the gross income of the crops, and they promote land use efficiency [52].

Some farmers adopt intercropping systems as they improve yield quality [53–55]. Compared with traditional intercropping or rotation, transposition intercropping may lead to an increase in yield [36]. Intercropping improves weed and disease reduction, conserves water and improves N content in the soil [56–59]. The adoption of intercropping practice is influenced by farm characteristics, such as farm size and income, which might shape intercropping intervention [58,60]. Although intercropping is regarded to be good and beneficial, some farmers have not adopted it and still practice monocropping practice. Monocropping is simple, with less landscaping requirements, and less

financial burdens. Other farmers believe it has no contribution to yield gain in cash crops. Another challenge in intercropping relates to incorporating more than two crops in a field where irrigation is required but the underground water needs for each crop are different. Though it may not offer the benefits that come with intercropping and crop rotation systems, some commercial farmers still practice monocropping yield and use some herbicides and pesticides to manage weeds and pests.

2.3. Crop rotation

Crop rotation involves growing different crops in consecutive planting seasons in the same field. Two types of crop rotations are commonly encountered. Exhaustive rotation involves more exhaustive crops which take up a lot of nutrients and leave the soil poor in fertility, e.g., wheat, cotton, and maize among others, while restorative rotation includes leguminous crops which improve soil fertility [61]. Crop rotation ensures crops are planted in a regular order one after the other on the same piece of land keeping in view that the fertility of land may not be adversely affected. Studies have shown that crop rotation increases N availability. Smith et al. [62] reported increasing crop rotational diversity can increase cereal yields and found that the deeper roots of winter wheat are better at reducing N leaching and provide better yield benefits to subsequent crops. Other studies have also reported that crop rotation has the potential to increase crop yields without increasing overreliance on chemical fertilizers [63–65].

An advancement such as multiple crop rotation generator models is a diversified type of crop rotation devised to explore alternative rotations. The model generates agronomically feasible rotations based on a list of candidate crops and a set of agronomic rules [66,67]. Diversifying crop rotations increases food production such as planting traditional cereal monoculture with cash crops and legumes, increasing yield and reducing N₂O emissions [68]. Diversified crop rotations also improve soil health and microbial diversity [68]. The advancements in crop rotation are very important for sustainable food production. Crop rotation is also beneficial as it breaks the life cycle of pests thereby reducing pest infestations [67,69]. Rotating the crops disrupts insect and pathogen reproduction and therefore disrupts their life cycle [70,71].

Crop rotation is an old farming practice which farmers continue to apply. However, farmers need the knowledge and skills on how to best practice diverse crop rotations and which types of crops to plant seasonally. The skills and knowledge will inform farmers when to practice restorative rotation and when to use crop rotation as a method of integrated pest management.

2.4. Agroforestry

Agroforestry is a diverse type of farming method where woody perennials are grown with arable crops, livestock, or fodder in the same piece of land resulting in the promotion of the efficient use of resources. The integration of trees provides several soil-related ecological services such as soil fertility improvement and climate change mitigation [72,73]. Due to environmental and climatic challenges, agroforestry stands out as a promising approach that enhances agricultural production while promoting the sustainable management of natural resources [74].

Agroforestry minimises soil erosion, and N loss due to soil erosion, boosts crop productivity, increases crop diversity, assists in pest control, improves water content in the soil, assists in crop pollination, improves forage, controls crop destruction by winds and assists in climate change mitigation [74–76]. A study that was conducted in some rural areas of Nepal by Ghimire et al. [77] on agroforestry practices amongst family farming found that agroforestry increases food production, environmental conservation, and economic returns. On the contrary, a review of the economic benefits of agroforestry in Europe and North America by Thiesmeier & Zander [79] found that conventional farming provided the highest economic benefits for farmers whilst agroforestry could offer more benefits in ecosystem services. Some farmers in Europe had adopted agroforestry systems such as traditional silvopastoral in Mediterranean regions [79]. Other agroforestry practices include Agrisilviculture, Agrosilvopastoral, and Hortiagriculture [77].

Although agroforestry systems have emerged as promising alternative measures for addressing major environmental issues, their use, especially in Africa, remains below anticipated levels [74]. Some farmers in Malawi adopted agroforestry by planting fertilizer trees known as *G. sepium* and *F. albida* with their crops [80].

A study conducted by Ahmad et al. [81] found that socio-economic factors such as family size, land ownership and age had either a positive or negative influence on the choice to adopt or not to

adopt agroforestry. The study found that families with large farm sizes, old family members, and large families were likely to adopt agroforestry [81,82].



Figure 3. Agroforestry practice of coffee shrub trees and trees [78].

Greater knowledge of agroforestry practices or higher incomes were significantly more willing to adopt agroforestry practices, while participants with larger farms were less likely to adopt agroforestry [83]. A study on the adoption of agroforestry practices among rural households in Kwazulu-Natal South Africa by Zaca et al. [84] found that non-adoption choices were due to time constraints, financial constraints and the lack of technical skills required.

Some advancements in agroforestry, such as agrisilviculture, which integrates trees and crops, are used as a land management strategy, and an agrosilvopastoral system that incorporates trees, livestock, and crops offers economic and ecological benefits [85]. Table 1 provides a list of various crop diversification studies from different geographical areas found in the literature, their impact on the agroecosystem and crop production and how the practices have contributed to the fight against climate change

Table 1. Crop diversification practices from different geographical areas.

Practices	Countries	Impact on agroecosystem	Impact on crop production	Contribution to climate change mitigation	References
Cover cropping potatoes and tomatoes with Brassicaceae plants such as oil seed radish and rocket salad	S. Africa	Reduced population densities of the root-knot nematodes <i>M. incognita</i> and <i>M. javanica</i>	Increase in crop biomass	Not specified	Daneel et al. [86]
Cover cropping legume or oat crops incomplete	Australia	N cycling and fixation, C cycling, water conservation, pest reduction	Cover crop biomass production and food production profitability	Reduced pesticides	Garba et al. [87] Torun [88]
Cover cropping wheat with legume	S. Africa	Soil quality was improved and N fixation	Increased wheat grain quality	Decreased use of N fertilizers after improved N fixation	Smit et al. [89]

Cover cropping sorghum and maize with annual ryegrass, winter triticale, turnip, daikon radish and pea	Mexico	Improved organic carbon and nitrogen in the soil and increased soil fertility	Improved crop yields	Increased carbon sequestration	Singh et al. [90]
Cover crops such as soybean, sudangrass and soybean-sudangrass mixture before wheat planting each year.	China	Improved soil minerals, soil carbon stabilisation and enhanced soil aggregation	Not specified	Increased carbon sequestration	Zhu et al. [91]
Bananas grown with goosegrass and siratro cover crops	China	Soil organic increase, total nitrogen and total phosphorus increase and increased phosphatase, catalase, invertase and urease activities from soil bacteria communities	Not specified	Not specified	Xu et al. [92]
Wheat and chickpea intercropping	Pakistan	N and P increase in the soil	Wheat and chickpea grain quality improved and biomass increased	Not specified	Raza et al. [93]
Intercropping rubber, timber fruit, and shrub trees	Thailand	Improved the soil quality	Higher fruit production	Reduced temperature (lowered light intensity) and increased humidity	Buakong et al. [94]
Cowpea and wheat intercropping	Tanzania	Improved soil fertility, weed control, decrease in pests and crop diseases	Improved crop yield	Higher radiation interception	Kinyua et al. [95]
<i>Desmodium</i> spp. employed as intercrop and Brachiaria or Napier grass employed as border crops with maize	Kenya, Rwanda, Uganda	Increased maize resistance to herbivore attacks, insect and weed pests' control and increased N fixation by <i>Desmodium</i>	Improved maize yields	Not specified	Lang et al. [96]
Intercropping olive with <i>Crocus sativus</i> , <i>Vicia sativa</i> , <i>Avena sativa</i> in and <i>Lavandula intermedia</i> with olive orchards	Spain	Soil-improved carbon storage, N fixation	No effects on crop yield detected	Increased carbon sequestration in the soil	Aguilera-Huerts et al. [97]
Sorghum-cowpea intercropping in a no-tillage system	S. Africa	Reduced carbon emissions and improved carbon storage in the soil	N-fixation in the soil, C storage in the soil	Less CO ₂ emissions in the atmosphere	Mogale et al. [98]
Maize and Cowpea intercropping	Burkina Faso, Mozambique	Weed reduction increased N fixation, increased phosphorous in the soil	Increased maize production, increased maize and fodder production	Not specified	Sanfo et al. [99] Dimande et al. [100]
Maize and faba bean intercropping	Ethiopia	Not specified	Maize grain yield increase and biomass increase	Not specified	Nurgi et al. [101]
Wolfberry intercropped with alfalfa	China	Improved water use efficiency (WUE) by the tree leaves, reduced soil water loss	Increase in Wolfberry biomass	Not specified	Wang et al. [102]
Relay intercropping of winter durum wheat with lentil	Italy	Weed suppression, increased nutrient availability and improved soil microbial matter	Increase in wheat and lentil yields	Not specified	Leoni et al. [103]
Tomato and alfalfa crop rotation	America	Enhanced soil nutrient availability, pest suppression	Improved quality yield of tomato crops	N and C soil fixation reducing atmospheric N and C	Samaddar et al. [104]
Crop rotation of potato cultivars with dry bean cultivars	South Africa	Reduced levels of <i>Meloidogyne pest</i>	Increase in yields Reduced infestation by <i>Meloidogyne</i> spp in one cultivar	Not specified	Pofu et al. [105]
Rubber dandelion and sugar beet crop rotation	China	Enhanced soil microbiome and	Increased sugar beet biomass, increased	Not specified	Guo et al. [106]

		increased abundance of <i>Actinobacteria</i> and <i>Streptomyces</i> .	urease activity in the soil, N fixation, phosphorous and potassium increase		
Agroforestry practice of planting rubber trees with different types of trees and fruit trees	China	Water and soil conservation increased light-use efficiency	Increase in the fruit yield in fruit trees	Not specified	Qi et al. [107]
Agrosilvopastoral system of trees, crops, and livestock and a syntropic agroforestry system of trees, shrub species, and forage crops.	Germany	Improved soil microbiome and a reduction in plant diseases	Not specified	Soil organic carbon storage increases under syntropic agroforestry	Vaupel et al. [108]
Homegarden agroforestry	Ethiopia	Improved soil properties such as pH and improved soil density	Fruit yield not specified but improvement in stem density and tree height	The home gardens act as carbon sinks	Tilinti et al. [109]
Ginger and mixed spices agroforestry	Tanzania	Improved soil fertility		Soil organic carbon sequestration	Kimaro et al. [110]
Coffee agroforestry systems	Brazil	Improved soil microfauna and improved organic matter	Not specified	Soil organic carbon storage	dos Santos Nascimento et al. [111]

3. Sustainable soil management

Soil is important for many ecological processes such as maintaining biodiversity and sustaining life. Soil health management is important for protecting biodiversity and safeguarding sustainable agriculture, and if the soil is compromised the production of plants and crops will be compromised [112]. Soil health may be affected in several ways. Soil health parameters include soil organic carbon content (SOC), soil nutrient status (total nitrogen available forms of phosphorus, potassium, and magnesium), soil acidification and soil microelements [113].

Chemical fertilisers are applied in the soil to increase nitrogen, phosphate and potassium ultimately improving soil fertility [112]. However, these fertilisers negatively affect soil by altering its physicochemical and biological properties [112,114]. Herbicides and pesticides also contribute to the pollution of agricultural soil. Excessive use of pesticides to manage pests has detrimental effects on crop production as it pollutes and hardens the soil, reduces soil fertility and decreases soil nutrients and minerals [112,115,116].

To mitigate the negative effects of chemical fertilisers, enhanced efficiency fertilisers (EEFs) were developed to make fertilisers less problematic to the environment by reducing their solubility by reacting them with other chemical compounds to yield products with lower solubility or by coating them with hydrophobic materials [117]. Enhanced efficiency fertilisers generally increase soil nutrients, crop yield, and N use efficiency whilst reducing N leaching, and emissions of greenhouse gases and air pollutants [118].

As inorganic fertilisers pose a threat to the environment, biofertilisers and biopesticides are eco-friendly alternatives to inorganic fertilisers that are used in sustainable agriculture and offer beneficial effects on plant growth and crop yield [119]. Some examples of biofertilisers include rhizobium, azotobacter, azospirillum, blue-green algae, azolla, and mycorrhizae [115].

Bioremediation is an eco-friendly and cost-effective approach to remediate the environment using living organisms, including but not limited to, bacteria, fungi, plants, or enzymes [120]. Phytoremediation and vermiremediation are also bioremediation methods used to reduce or eliminate harmful contaminants in soil and water [121,122]. Physical and chemical remediation techniques such as soil replacement, soil isolation, vitrification, electrokinetic, immobilisation and soil washing are high-cost and destroy soil microorganisms [123,124].

The type of inventions such as enhanced efficiency fertilisers, biofertilisers, biopesticides and bioremediation have an impact on the environment and soil health and the health of the soil will result in safer and better crop production. These technologies have been widely adopted by farmers as they do not come with the problems of using chemical fertilisers and pesticides.

4. Integrated Pest and Management

Integrated pest management (IPM) is a sustainable strategy for managing pests with a primary focus on the evolutionary and ecological aspects of pest management [125]. IPM implementation depends on various factors including the level of education, economic and social conditions, environmental awareness, and government policies [125,126]. Pests have become a big agricultural challenge due to the resistance they have developed against herbicides and pesticides. Pesticides include herbicides, fungicides, insecticides, rodenticides, molluscicides, nematocides, and plant growth regulators [116].

Weeds have become resistant and affect crops such as wheat, rice, barley, maize, and chickpea. They have become resistant to herbicides and compete with the crops, affecting their growth [127]. The integration of sustainable weed control methods such as crop rotation, mulches, intercrops, planting date and pattern, tillage, herbicides, resistant crop cultivars and allelopathy can lead to their effective management [127,128]. With all these interventions, the control of weeds is still a challenge and recent developments in the management of weeds include strategies such as the Weed Surveillance Plan which assists in the early detection of invasive weeds in a new geographic area [128].

Insects have become resistant to insecticides, and they affect the production of crops resulting in lower yields. Some insects have grown resistant to some insecticides, and they include fall armyworms, potato beetles and oriental fruit flies which have become resistant to chlorantraniliprole, carbofuran and organophosphorus respectively [129]. Climate change conditions such as increased temperatures have made insect pests adapt to different climatic conditions and increased their populations rapidly [130,131].

The development of biopesticides from bacteria, fungi, plant exudates, essential oils, leaves, bark, and nanotechnology for the control of pests has helped to reduce the toxic effects of pesticides on agroecosystems and most have been registered commercially in arthropod pest control [133–135]. Moreover, the deliberate addition of natural enemies can help to regulate insect pest populations [132]. A study conducted by Ofuya et al. [136] on the management of pests found in vegetable crops reported that using a combination of IPM practices and the application of aqueous extracts of *A. Indica* and *P. guineense* seeds as a biopesticide protected the crop plants against several pest species.

Integrated pest management can help to alleviate the environmental problems that have been caused by using herbicides and insecticides. It uses natural or biological methods to control the pests. Sustainable weed control can help to protect the crops from herbicides which can affect the growth of the crops.

5. Sustainable water resource management

The management of water resources for both rain-fed and irrigated agriculture is becoming a critical issue for sustainable agriculture worldwide due to water scarcity challenges that were caused by global warming and climate change [137]. Climate-smart water technologies such as drip irrigation and central pivot irrigation are some of the developments in agriculture that address the problem of water scarcity [137].

For farming to be sustainable, farmers need to know the water needs of their crops and how much water is being used or saved. Water use efficiency (WUE) calculations where hydrological variables serve as multiple WUE indicators are used to quantify agricultural water use in agroecosystem [138]. Research to determine the resilience of irrigated agriculture was conducted by Lankford et al. [139] by testing the WUE to drought by calculating variables such as irrigation area, irrigation efficiency and water storage in a semi-arid catchment in South Africa. The study found that irrigators have adapted to drought events through the construction of water storage and the adoption of more efficient irrigation practices.

Hydroponics is another smart-climate type of irrigation used in the sustainable management of water as it can save up to 90% of water [140]. The development of precision irrigation through the Internet of Things (IoT) plays an important environmental role in farming as it reduces water and electricity consumption whilst increasing food production [141]. Water Need Estimation (WNE) determines how much, when, and where to irrigate and WNE and it involves obtaining reliable data dealing with uncertainties caused by environmental and technical conditions whilst considering plant, soil, and water interactions [141].

The challenges that could be faced by farmers in determining WUE are climatic factors such as frost or snow in winter, inconsistent precipitation levels and extremely hot temperatures. For instance, an extremely hot or windy type of weather may result in lower water use efficiency.

6. Precision Agriculture in Agroecosystem Management

Precision agriculture (PA) is a framework that aims to make the most of the potential of natural, human, and mechanical resources with minimal disruption to the agroecosystem by assisting farmers to reduce costs and get more out of their land [142]. It is a crucial agricultural management system that requires the combined use of robotics and sensors, drones, advanced GPS and GNSS (Global Navigation Satellite Systems), IoT, weather modelling and how farmers can save water and reduce the use of chemicals on land [142]. The Internet of Things (IoT) and Wireless Sensor Networks (WSN) can be utilised to more effectively monitor crop fields and make quick choices for sustainable agriculture, leading to improved crop yields and economic return [143,144].

The integration of IoT devices and machine learning algorithms facilitates real-time data analysis which leads to improved resource use and reduced environmental impacts [145]. The integration of IoT devices and machine learning algorithms facilitates real-time data analysis which leads to improved resource use and reduced environmental impacts [145].

Wireless Sensor Network (WSN) technology has improved the use of motes and sensor nodes to monitor ecological occurrences across a vast geographic area [144]. The sensors in IoT are installed in crop fields and can gather data such as the occurrence of pests, a lack of water supply, and plant diseases [146,147]. Furthermore, in-situ sensors such as weather stations and soil moisture sensors provide information about the variability of weather and soil parameters whilst crop parameters can be measured with proximal and remote sensors [148]. Remote sensors can monitor parameters such as crop growth, health, and yield [148].

One of the latest advances recently in precision agriculture is Light Detection and Ranging (LiDAR) technology. LiDAR has been the most innovative subject in laser scanning, remote sensing, and object detection systems. This technology can pinpoint structures or zones of interest in millimeter detail and can highlight variations and irregularities such as surface degradation and vegetation growth [149]. Another technology is called the RGB colour model where the red, green, and blue primary colours of light are added together to reproduce a broad array of colours. The light or optical sensors detect specific wavelength bands of light and convert them into electrical signals and are applied for phenotyping such as moisture content, pigment content, photosynthesis rates, and morphological characteristics from the target by detecting the reflection of light [150].

In terms of water management, Internet of Things (IoT) irrigation is an automatic irrigation system based on managing the pump for water storage of groundwater in the farmer’s field and tracking the soil humidity, pressure and temperature conditions on a field farm [151]. The Internet of Things also involves variable rate application (VRA), yield monitors, and remote sensing are examples of agricultural production practices or systems that use information technology to customise input utilisation to achieve desired outcomes.

Africa is one of the continents that has been affected by climate change and the farmers had to find strategies to help in the fight against climate change effects such as drought by managing water resources. Table 2 is a summary of some recent Internet of Things (IoTs), and Wireless Sensor Networks (WSN) technologies used in precision agriculture. A study by Erekaló et al. [152] focusing on the contribution of farming practices and technologies towards climate-smart agricultural outcomes in Europe found that agroecological farming practices involving precision fertilisation, precision irrigation and variable rate of irrigation contributed to higher crop production. Farmers use other precision agriculture technologies such as drones, machine learning and data management to improve their farming although there are still challenges for some farmers with issues like cost technology adoption and cost-effectiveness [153].

Table 2. Summary of some recent Internet of Things technologies.

Technological advancement	Application approach	Country	Contribution to agroecosystem	References
Data collection using sensors in the field using the Gaiasense system	Automatic field stations	Cyprus	Detection of soil moisture, temperature, humidity, wind, precipitation and atmospheric pressure	Adamides et al. [154]
Fuzzy logic (FL) controller, and long-range data transmission	Smart precision irrigation	Morocco	Saving water and energy	<u>Benzaouia</u> et al. [155]

and monitoring via the LoRa protocol Wireless Sensor Networks (WSN) using Arduino UNO WiFi Rev2 board server	Soil monitoring system	South Africa	Monitoring of soil conditions, weather patterns, and crop development	Dlamini et al. [156]
Data collection technology using Arduino ESP Wi-Fi technology	Automated irrigation	South Africa	Detects soil moisture and assists in water-use efficiency	Langa et al. [157]
GMP343 used with MI70 data logger	Measurement of CO ₂ emissions	South Africa	Determination of carbon stocks between intercropping and monocropping systems	Mogale et al. [158]
Ugunduzi Mobile App	To conduct field research	Tanzania	Monitoring maize and cassava crops through gathering, visualization & statistical analysis of soil fertility, conservation and biodiversity	Kihoma et al. [159]

7. Conclusions Remarks

This review study provided an in-depth picture of how sustainable management of agroecosystems influences crop production. The diversification of crops in agroecosystems has an impact on crop production. The most practised methods of crop diversification were discovered to be intercropping, cover cropping, crop rotation, row cropping and agroforestry. These methods benefit agroecosystems and the surrounding environment with processes such as weed control, disease and pest management, pollinator diversity, improved soil health and the conservation of available water. Most importantly, the review study found that crop diversity such as intercropping with legumes such as cowpeas helps in nitrogen fixation and assists in soil health by maintaining soil natural microbes and suppressing the growth of weeds, hence reducing the need for herbicide use. Planting trees, fruit trees, vegetables and shrubs which are agroforestry plays a huge role in mitigating the effects of climate change as more carbon from the atmosphere is eventually stored in the soil, roots, and plant biomass. Climate change mitigation is very important as this helps to improve food security.

Asia and Europe were found to have more agroforestry practices in literature as compared to other geographical areas. Agroforestry is a big and key component of sustainable agriculture since it uses sustainable farming approaches. It bridges the gap between agriculture and forestry by developing integrated systems that serve both environmental and economic aims. Since most literature describes agroforestry to be practised in family farming and that it is influenced by farm size, skills, knowledge and age, there needs to be further research on how agroecology can be incorporated into large-scale or commercial farming for sustainable crop production.

Furthermore, there needs to be research that focuses on distinguishing how agroforestry is similar or different according to geographic areas and the reasons that could account for those differences. If farmers were to be supported socio-economically to practice agroforestry, this would result in better environmental conditions.

Innovations like the Internet of Things such as the use of information technology and wireless technology have been a great advancement in agriculture. Wireless Sensor Networks (WSN) monitor environmental parameters like soil moisture content which is a good invention for drought-stricken areas. The less privileged farmers facing financial barriers could be assisted with the use of such technologies and they must be educated on how the technologies work so that they can also improve their farming conditions.

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