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Review

Multidimensional Perspective of Sustainable Agroecosystems and the Impact on Crop Production: A Review

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Abstract: Agroecosystems form a natural ecosystem component, allowing the proper classification of a regional biome at a global scale. It is important to view agroecosystems from a micro-environmental perspective given that they are characterised by a combination of factors, including the interaction of soil–plant–atmosphere conditions, which are largely responsive to human management practices. The published literature generally provides a limited explanation of the multidimensional nature of agroecosystems. In combination, agroecosystem practices promote efficient water use and nutrient cycling in defence of regenerative agriculture ethos. Sustainable agroecosystem practices can be combined to explain how to mitigate the risks to biodiversity. This study aims to present a review of predominant advances in sustainable crop production from the perspective of the agroecosystem. A hybrid methodology of data mining and interpretation was used to establish the meaning and relationships of the major research areas that have emerged over time and dominate the narrative of sustainable agroecosystem definition and practices. Crop diversification, sustainable soil management, integrated pest management, sustainable water resource management, and precision agriculture were selected using document summarisation and entity relation modelling to generate and explain relationships between various components of sustainable agroecosystems based on the existing literature. A major finding is the confirmation of comparable applications in different regions, whose explanation is enhanced by recent advances in data summation. This review concludes that sustainable agroecosystems are separable in meaning and impact. However, it is reasonable to recommend the need for future research into their integration for implementation and interpretation.

Keywords: sustainable agriculture; agroecology; crop diversification; pest management; soil health; water resource management; precision agriculture

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1. Introduction

Agroecosystems are socio-ecological systems characterised by three interacting components, namely soil–plant–atmosphere interactions, the natural ecosystem which represents the stability of a biome for global classification in the context of natural systems, and the human-derived capital, which is characterised by knowledge, cultural traditions, technologies, settlements, and infrastructures [1]. Agroecosystems characterised by high levels of biodiversity better support their functioning due to resilience to challenges associated with providing food, feed, timber, fibres, and other products. The vulnerability of agroecosystem sustainability can be associated with challenges arising from inadequate agricultural practices in response to climate change [2].

The factors which compromise agroecosystem sustainability vary. For this review, the focus is on agricultural management practices in the context of food security [3]. It is imperative to acknowledge the positive contribution of intensive or conventional agriculture to food security and socioeconomic advancement at the national, regional, and global levels [4–7]. However, it is important to analyse environmental challenges to the sustainability of agroecosystems in the context of biodiversity, soil health, water use efficiency, and mitigation of vulnerability factors such as environmental degradation, diseases and pests, and the consequent reduction in crop productivity and quality [3].

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 agroecosystems by integrating appropriate natural biological cycles to sustain the economic viability of farm operations [8]. 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 three dimensions is in tandem [9]. A sustainable farm produces adequate amounts of high-quality food, protects its resources, and is both environmentally safe and profitable [10]. Agroecological practices may be characterised by monoculture or diversified farming practices, e.g., intercropping, crop and pasture rotation, organic farming, silvopasture, integrated aquaculture, the planting of cover crops, and reducing the use of synthetic inputs [11,12].

It is important to explore existing and prospects for sustainable agroecosystems. This requires the recognition of current practices and identification of modern information technology options [6,13]. For example, technological innovations optimise farming practices [6]. This study aims to provide a consolidated agroecosystem perspective based on the existing literature and use that information to propose a future theoretical model for future research.

2. Methodology

The approach adopted in this review is based on semi-structured data analysis. Text Mining and Natural Language Processing (NLP) have been applied to extract meaningful information from text-heavy semi-structured data [14]. For this study, document summarisation and entity relation modelling were combined to generate and explain relationships between various components of sustainable agroecosystems based on the existing literature. Therefore, this study does not generate new research. Instead, it establishes a new dimension of understanding. Selected knowledge areas of sustainable agroecosystems are listed in Table 1, where justification for selection is indicated based on data mining evidence. An illustration of the research model framework, which was developed using data in Table 1, is shown in Figure 1.

Table 1. Selected areas of sustainable agroecosystem justification. Resource base: 1. agronomy; 2. crop science; 3. pathology; 4. ecology; 5. hydrology; 6. food security; 7. agricultural extension. (Number of mined resources is shown in parentheses).

Knowledge Area	Justification	Applicable Predominant Resource Base (References)
A. Crop Diversification	Stabilisation of biodiversity at a farm level	1, 3, 4, 6, 7 [15]
B. Sustainable Soil Management	Soil carbon sequestration and health	1, 3, 4, 6, 7 [16]

Table 1. *Cont.*

Knowledge Area	Justification	Applicable Predominant Resource Base (References)
C. Integrated Pest Management	Minimising vulnerability of the biosphere	1, 2, 3, 4, 6, 7 [17]
D. Sustainable Water Resource Management	Optimisation of resilient crop productivity	1, 2, 5, 6, 7 [18]
E. Precision Agriculture in Agroecosystem Management	Confirmation of existing basis for future advanced technologies	1, 2, 4, 5, 6, 7 [19]

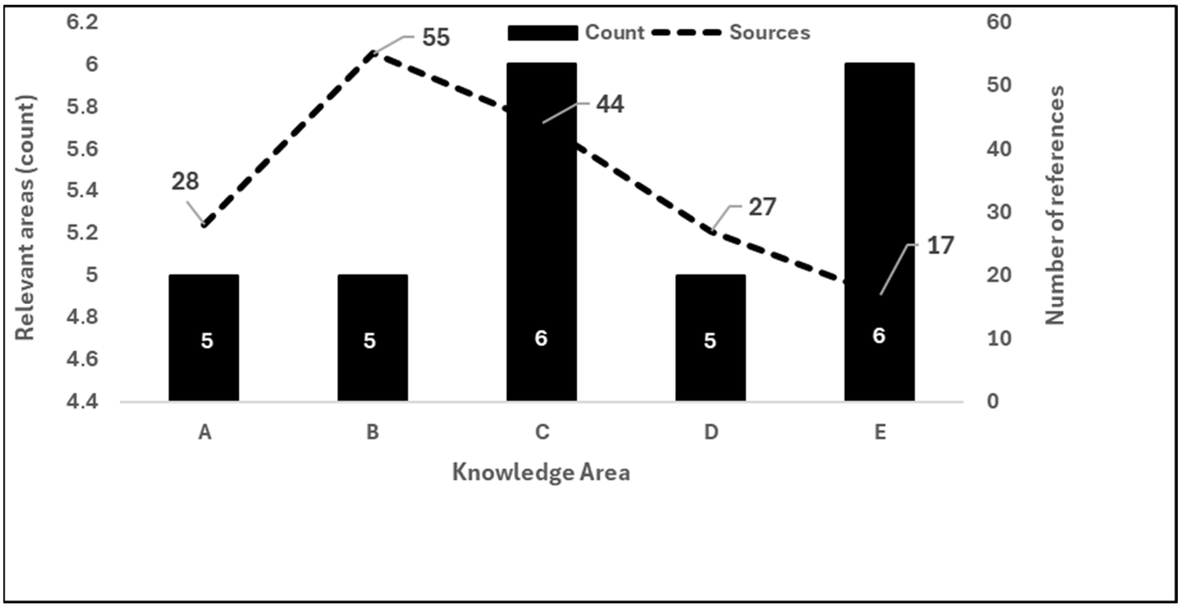

Figure 1. Theoretical research model data resource framework based on selective data area identification.

3. Crop Diversification

One way to improve the agroecosystems is to minimise or stop the loss of biodiversity from intensive farming. Increasing agrobiodiversity is essential for the productivity and adaptability of species, global food production, food security, and sustainable agricultural development. For instance, greater crop diversity enhances microbial populations, which can promote plant growth and increase agricultural output [20].

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 [21]. A higher diversity is beneficial to crops and the surrounding environment. Crop diversification entails planting cover crops after harvesting the main crop, crop rotations, multiple cropping, intercropping, cultivar mixtures, and agroforestry. All these practices have been shown to enhance ecosystem functioning, leading to increased yield and stability, increased resource-use efficiency, enhanced soil fertility, reduced crop disease, and minimised environmental costs [22–24].

3.1. 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 [25,26]. They protect and improve the soil between regular annual crop production or between trees in orchards and vines in vineyards [25]. 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 [27]. 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, and increased biodiversity in an agroecosystem, and contribute to landscape-scale environmental benefits such as decreasing sediment run-off [24,27,28]. Besides providing ground protection, cover crops can provide weed and pest suppression [26]. Cover crops can also assist farmers in fighting against climate change as they offer carbon sequestration [26,29,30].

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. [31] 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 [22,32]. Integration of livestock is also an important factor in driving cover crops, as cover crops enhance forage opportunities for many livestock [27].

Some farmers adopted cover crops whilst some did not due to several reasons such as lack of skills, knowledge, or socio-influence, or fear of risk [26,27,33]. Some farmers may choose not to practise 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.

Farmers will choose cover crops depending on their knowledge and experience. Most farmers should cover crops based on their growth performance and avoid those that are associated with production risks. Cover crops assist in increasing species diversity and come with several environmental benefits such as controlling the growth of weeds. Government programmes are needed that can assist in educating farmers about which types of cover crops can be used regionally, while taking into consideration the climatic patterns of different geographical areas.

Also, the use of indigenous knowledge about which cover crops are most used will assist them in making better choices in crop selection. The planting of winter crops as winter cover in late summer to early fall can assist in soil conservation. Farmers can also take into consideration the use of cover crops that can also be cash crops and explore how to diversify them.

3.2. 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 [15]. 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. Intercropping was found to increase yield as an intercropping system of oat and sunflower was 28–32% and 18–47% higher for oat and sunflower respectively compared with monocultures [34].

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 each crop's life cycle [35,36]. A study conducted by [37] found that strip intercropping enhanced biodiversity and controlled insect pests. Annual rotations of the adjacent maize and soybean strip intercrops increased the grain yield of the next seasonal maize whilst improving the absorption of nitrogen, phosphorus, and potassium of the maize [38].

Alternate intercropping combines rotation with intercropping to effectively benefit yield increases, and the efficiency is further enhanced by the rotation [39]. 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 [40]. Figure 2 shows a strip intercropping model.

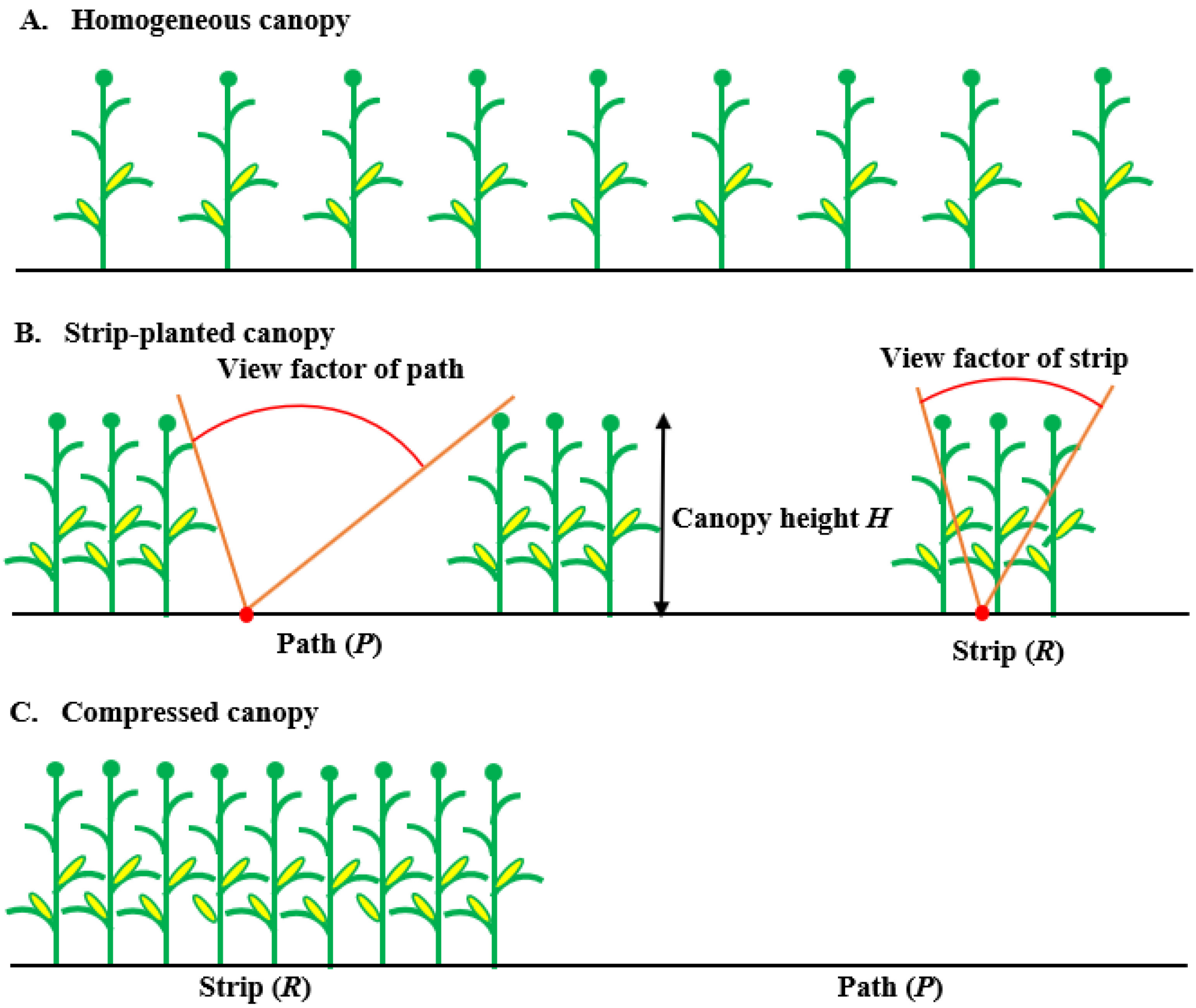

Figure 2. Strip intercropping model [40].

Compared with traditional intercropping, strip intercropping may lead to an increase in yield as adequate radiation interception of the crop aboveground is an advantage [41]. A study by Baker et al. [42] 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. 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 [43,44].

Moreover, intercropping not only improves crop yield but also improves soil nutrients such as phosphorous, reduces competition for major soil nutrients, increases beneficial soil microorganisms, improves N status and N use efficiency, and reduces pathogenic microorganisms [45–48]. The legume Cowpea is a crop used mostly for intercropping by farmers in African countries. Legume-cereal intercropping improves the resilience to environmental stressors and increases yield stability which are critical for sustainability under ongoing climate change conditions [49]. The use of agrochemicals is reduced as leguminous plants are capable of fixing atmospheric nitrogen [50,51].

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 [17,52–54]. Figure 3 [55] shows push-pull intercropping of maize, faba bean and wheat.

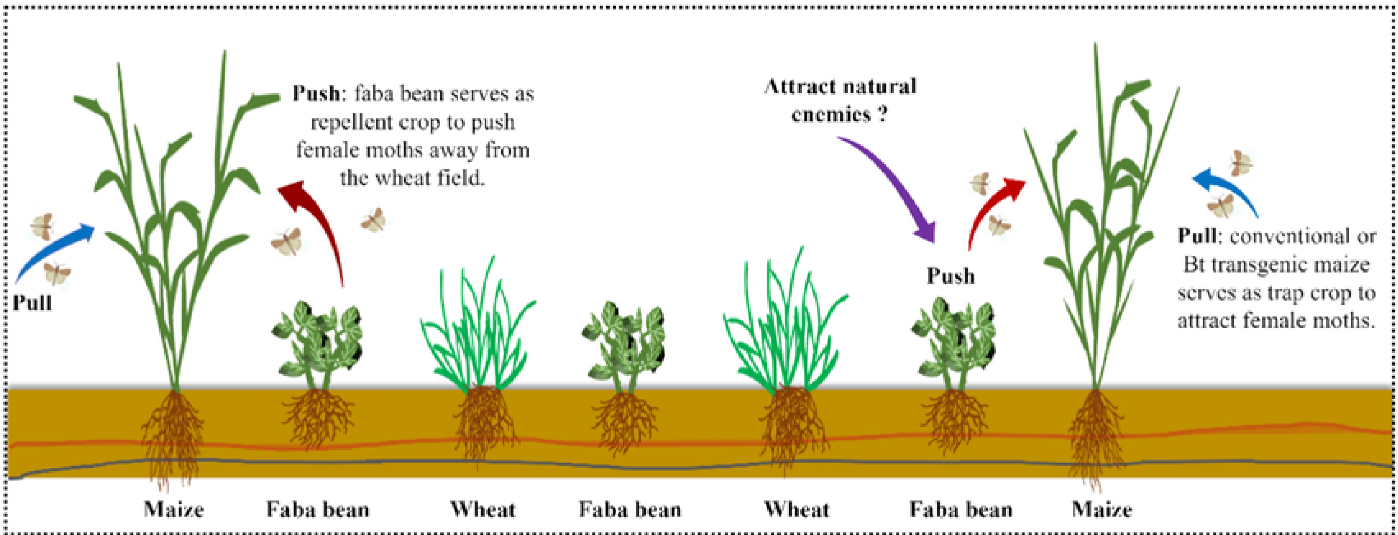

Figure 3. Push–pull intercropping [55].

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 [56]. Intercrops have an impact on the gross income of the crops, and they promote land use efficiency [56].

Some farmers adopt intercropping systems as they improve yield quality and economic returns [57,58]. Intercropping improves weed and disease reduction, conserves water and increases N content in the soil [59–62]. The adoption of the intercropping practice is influenced by farm characteristics, such as farm size and income, which might shape intercropping interventions [63–65]. Although intercropping is regarded as good and beneficial, some farmers have not adopted it and still practise monocropping. Monocropping is simple, with fewer landscaping requirements, and fewer financial burdens. Other farmers believe it has no contribution to yield gains in cash crops. Another challenge in intercropping relates to incorporating more than two crops in a field where irrigation is required, but each crop's underground water needs differ. Though it may not offer the benefits that come with intercropping and crop rotation systems, some commercial farmers still practise monocropping and use some herbicides and pesticides to manage weeds and pests. Monocropping is simple, with fewer landscaping requirements, and fewer financial burdens. Other farmers believe intercropping has no contribution to yield gains in cash crops.

Most importantly, this section highlighted how intercropping can improve the overall productivity of farming systems. Intercrops can assist in increasing soil moisture in arid regions and help to fix more N in the soil, which results in enhanced crop performance compared to monocultures. Farmers need to intercrop crops that will exhibit less interspecific competition, whilst taking into consideration the local agricultural crop productivity. Two- or three-crop species intercropping could perform well, such as planting wheat/maize/local herbs, wheat/maize, or wheat/legume.

Strategically planting crops and optimising intercropping patterns can help to promote crop interactions below and above ground. Planting intercropping patterns known to demonstrate reduced root competition must be considered, as root competition can inhibit growth in some intercropping systems. The literature showed that planting cereals like wheat and legumes shows early dominance of wheat through increased biomass whilst not hindering the growth of legumes. This means farmers can be incorporated into research studies so that they can learn and understand crop growth dynamics in intercropping systems, such as which crops tend to show dominance at an early stage and how to manage crop competition and plan for crop productivity.

3.3. 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 [66]. Crop rotation ensures crops are planted in a regular order, one after another 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. [67] 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 fertilisers [68–70].

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 [71,72]. Diversifying crop rotations increases food production, such as planting traditional cereal monoculture with cash crops and legumes, increasing yield and reducing N_2O emissions [73]. Diversified crop rotations also improve soil health and microbial diversity [73]. 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 [72,74]. Rotating the crops disrupts insect and pathogen reproduction and therefore disrupts their life cycle [75,76].

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 practise restorative rotation and when to use crop rotation as a method of integrated pest management.

Crop rotation is also highly beneficial as it offers crop climate resilience as it contributes to carbon sequestration. Studies have demonstrated that diverse crop rotations can increase crop yields over time, whilst assisting in reduced water loss in the soil. This means crop rotations can assist farmers during drought periods, thereby reducing the loss in crop yields compared to monocultures. Therefore, a crop rotation system will be beneficial in promoting the environment whilst promoting crop productivity.

3.4. Agroforestry

Agroforestry is a diverse type of farming method where woody perennials are grown with arable crops, livestock, or fodder on the same piece of land, promoting the efficient use of resources. The integration of trees provides several soil-related ecological services such as soil fertility improvement and climate change mitigation [77,78]. 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 [79].

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 [79–81]. Agroforestry practices include Agrisilvihorticulture, Agrosilvopastoral, and Hortiagriculture [82].

A study that was conducted in some rural areas of Nepal by Ghimire et al. [82] 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 and Zander [83] found that conventional farming provided the highest economic benefits for farmers whilst agroforestry could offer more benefits in ecosystem services. Some farmers in Europe have adopted agroforestry systems such as traditional silvopastoral in Mediterranean regions [83]. Although agroforestry systems have emerged as promising alternative measures for addressing major environmental issues, their use, especially in Africa, remains below anticipated levels [79]. Some farmers in Malawi adopted agroforestry by planting fertiliser trees known as *Gliricidia sepium* and *Faidherbia albida* with their crops [84].

A study conducted by Ahmad et al. [85] found that socioeconomic factors such as family size, land ownership, and age had either a positive or negative influence on the choice of whether to adopt agroforestry or not. Figure 4 [86] shows a multipurpose type of agroforestry system with a mixture of some trees, fruit trees, crops and herbs.

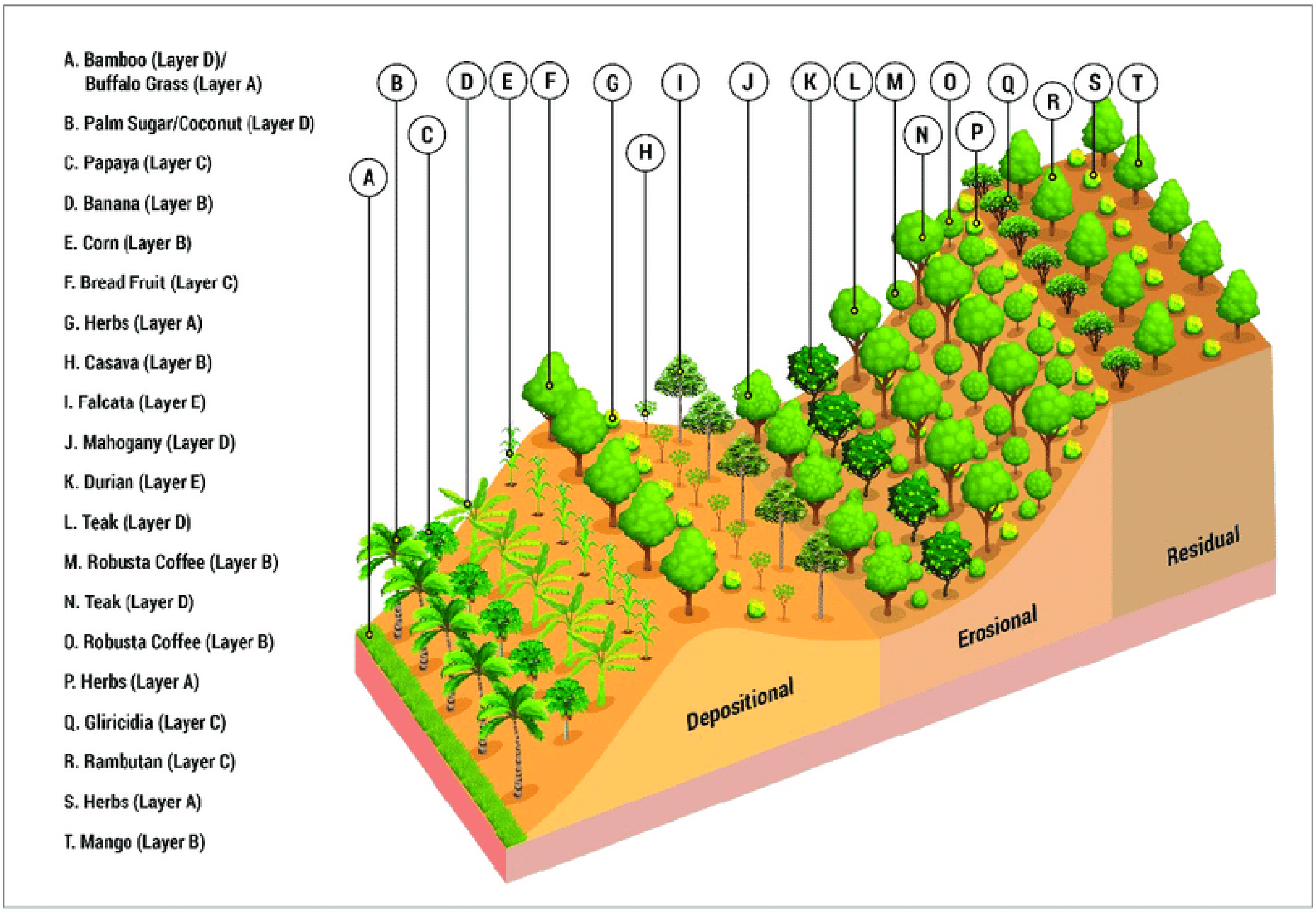

Figure 4. Multipurpose agroforestry layout [86].

Families with 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 [87,88]. A study on the adoption of agroforestry practices among rural households in Kwazulu–Natal South Africa by Zaca et al. [89] 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 [90].

By optimising crop productivity while reducing chemical inputs, agroforestry practices enhance climate resilience by promoting soil health, water conservation, and reducing greenhouse gases.

Furthermore, sustainable agronomic innovations can facilitate environmental restoration under agroforestry systems. Through the careful selection of tree species, types of crops, water management, and optimal spacing, these agronomic practices will support biodiversity, control soil erosion, and conserve water. This will assist in promoting an ecological balance and enhancing ecosystem services.

Table 2 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 2. 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 *M. incognita* and *M. javanica*	Increase in crop biomass	Not specified	Daneel et al. [91]
Cover cropping legume or oat crops	Australia	N cycling and fixation, C cycling, water conservation, pest reduction up to 75% and 51% for oats and legumes	Cover crop biomass production and food production profitability	Reduced pesticides	Garba et al. [92] Torun [93]
Cover cropping wheat with a legume	S. Africa	Soil quality was improved and N fixation	Wheat grain yield was between 2108 and 2580 kg ha^{-1}	Decreased use of N fertilisers after improved N fixation	Smit et al. [94]
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 stocks in the soil (0–80 cm) were up to 7–22% greater	Singh et al. [95]
Cover cropping sugar cane with millet	Brazil	Improved soil quality and soil carbon stabilisation	Maintenance of sugar cane yields at 100 Mg ha^{-1} over time	Increased carbon sequestration	Carneiro et al. [96]
Cover cropping maize with winter cover crops common vetch, fodder radish, and black oat	Brazil	Soil organic increase, total nitrogen, and total phosphorus	Vetch increased maize yield in conventional tillage and reduced tillage treatments by 10–38% and 26–34%, respectively	Soil carbon stocks increased under no-tillage system	Besen et al. [97]
Wheat/soybean, wheat/pea, and wheat/chickpea intercropping	Pakistan	N and P increase in the soil	Intercropped chickpea, soybean, and pea achieved 67–71%, 55–62%, and 62–70% of their sole system yield. Intercropped wheat with chickpea, soybean, and pea produced 66–69%, 57–62%, and 62–66% of sole wheat yield, respectively	Not specified	Raza et al. [98]
Intercropping rubber with timber trees, rubber with timber and fruit trees, rubber with timber, fruit, and shrub trees	Thailand	Improved the soil quality	The rubber, timber, fruit, and shrub tree intercropping model had the highest latex yield at 1866.31 kg/ha/year and dry rubber content at 40.11%	Reduced temperature (lowered light intensity) and increased humidity	Buakong et al. [99]

Table 2. *Cont.*

Practices	Countries	Impact on Agroecosystem	Impact on Crop Production	Contribution to Climate Change Mitigation	References
Legume–legume intercrop (doubled-up legume) and an innovation involving two maize rows intercropped with two legume species (Mbili-Mbili)	Tanzania	Improved soil fertility, weed control, decrease in pests and crop diseases	Doubled-up legume rotations were both the highest and lowest relative to other intercropping options, depending on the starting phase, and Mbili-Mbili intercropping system had a high net revenue of a mean of USD 623 per hectare	Higher radiation interception	Kinyua et al. [100]
Maize and cowpea intercropping	Somalia	Increased land equivalent ratio resulting in improved land use	Alternate intercropping produced the highest maize grain yield (3727.6 kg ha^{-1}) followed by within-row intercropping system (3670.3 kg ha^{-1}) where cowpea was planted within rows of maize.	Not specified	Farah et al. [101]
Intercropping olive with *Crocus sativus*, *Vicia sativa*, *Avena sativa* in, and *Lavandula intermedia* with olive orchards	Spain	Soil-improved carbon storage, N fixation	No effects on crop yield specifications	Increased carbon sequestration in the soil	Aguilera-Huerts et al. [102]
Intercropping maize and sunn hemp at different stand densities	S. Africa	Soil organic matter, nitrogen, potassium, and manganese were significantly enhanced by 39.7%, 19.0%, 21%, and 60.6%, respectively	Maize yields in the medium and high stand densities in the first season were significantly 15.3% and 34.3% higher than in the second season, respectively		Dzvene et al. [103]
Maize and cowpea intercropping	Burkina Faso, Mozambique	Weed reduction increased N fixation, increased phosphorous in the soil	Increased maize fodder biomass and grain yield in maize. Maize grain yield was 6.75 t ha^{-1} when intercropped, compared to 5.52 t ha^{-1} as a sole crop	Not specified	Sanfo et al. [104] Dimande et al. [105]

Table 2. *Cont.*

Practices	Countries	Impact on Agroecosystem	Impact on Crop Production	Contribution to Climate Change Mitigation	References
Maize and faba bean intercropping	Ethiopia	Not specified	Maize intercropped with 25% of sole faba bean produced a significantly higher grain yield than 50% and 75% plant density. Similarly, 75% plant density of sole faba bean intercropped with maize produced the highest grain	Not specified	Nurgi et al. [106]
Wolfberry intercropped with alfalfa	China	Improved water use efficiency (WUE) by the tree leaves, reduced soil water loss	Linear increase in Wolfberry growth in the rapid growth phase	Not specified	Wang et al. [107]
Relay intercropping of winter durum wheat with lentil	Italy	Weed suppression, increased nutrient availability, and improved soil microbial matter	Increases in wheat and lentil grain yields were 2.0, 1.7, and 1.8 t/ha, whereas for lentil, the dry grain yield was, respectively, 0.38, 0.56, and 1.3 t/ha	Not specified	Leoni et al. [108]
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. [109]
Crop rotation of potato cultivars with dry bean cultivars	South Africa	Reduced levels of *Meloidogyne* pest by the nematode-resistant legume crops	Increased potato yields and reduced infestation by *Meloidogyne* spp	Not specified	Pofu et al. [110]
Rubber dandelion and sugar beet crop rotation	China	Enhanced soil microbiome through increased abundance of *Actinobacteria* and *Streptomyces*, increased urease activity in the soil, N fixation, phosphorous and potassium increase	Increased sugar beet biomass	Not specified	Guo et al. [111]
Agroforestry practice of planting rubber trees with different types of trees and fruit trees	China	Water and soil conservation increased light-use efficiency	Young agroforestry systems yield an annual output value of USD 269 million, while mature agroforestry systems contribute USD 110 billion from dry rubber and USD 455 million from integrative crops	Not specified	Qi et al. [112]

Table 2. *Cont.*

Practices	Countries	Impact on Agroecosystem	Impact on Crop Production	Contribution to Climate Change Mitigation	References
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. [113]
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. [114]
Ginger and mixed spices agroforestry	Tanzania	Improved soil fertility		Soil organic carbon sequestration	Kimaro et al. [115]
Coffee agroforestry systems: coffee with *Grevillea robusta* and coffee with banana	Brazil	Improved soil microfauna and improved organic matter	Not specified	Soil organic carbon storage	dos Santos Nascimento et al. [116]

4. 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 [117]. Chemical fertilisers are applied in the soil to increase nitrogen, phosphate, and potassium, ultimately improving soil fertility [117]. 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 [118].

However, these fertilisers negatively affect soil by altering its physicochemical, biological properties and soil beneficial micro-organisms are lost [119,120]. 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 [120,121].

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 [122]. 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 [123].

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 [16].

Bioremediation is an eco-friendly and cost-effective approach to remediate the soil using living organisms, including but not limited to, bacteria, fungi, plants, or enzymes [124,125]. Biofertilisers were developed as alternatives to chemical fertilisers and examples include rhizobium, azotobacter, azospirillum, blue-green algae, azolla, and mycorrhizae [125].

Phytoremediation and vermiremediation are also bioremediation methods used to reduce or eliminate harmful contaminants in soil and water [125,126]. Physical and chemical remediation techniques such as soil replacement, soil isolation, vitrification, electrokinetic, immobilisation, and soil washing are high-cost and destroy soil microorganisms [127,128].

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.

5. 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 [129]. IPM implementation depends on various factors including the level of education, economic and social conditions, environmental awareness, and government policies [129,130]. Pests have become a big agricultural challenge due to the resistance they have developed against herbicides and pesticides.

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 [131]. 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 [131,132]. 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 [132].

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 (*Spodoptera frugiperda*), potato beetles (*Leptinotarsa decemlineata*), and oriental fruit flies (*Bactrocera dorsalis*), which have become resistant to chlorantraniliprole, carbofuran, and organophosphorus, respectively [133]. A study by Zhou [134] reported that a sustainable approach to integrated pest management includes prevention and cultural control methods, monitoring and decision-making, and biological control and chemical control.

Habitat manipulation techniques such as intercropping and crop rotation can significantly improve disease and pest management [135]. Moreover, the deliberate addition of natural enemies can help to regulate insect pest populations [136].

The development of biopesticides and nanopesticides is a part of sustainable chemical pest control methods that have helped to reduce the toxic effects of pesticides on agroecosystems, and most have been registered commercially in arthropod pest control [137–139]. A study conducted by Ofuya et al. [140] on the management of pests found in vegetable crops reported that using a combination of IPM practices and the application of aqueous extracts of *Azadirachta indica* and *Piper guineense* seeds as a biopesticide protected the crop plants against several pest species.

Moreover, there have been technological advancements in the field of integrated pest management. One such system is called the Intelligent and Integrated Pest and Disease Management (I^2PDM) computing device, which automatically detects and recognises major greenhouse insect pests such as thrips and whiteflies. It can measure environmental conditions including temperature, humidity, and light intensity, and send data to a remote server. The system was found to support farm managers in performing IPM-related tasks [141].

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.

6. 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 [142]. 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 [142].

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 agroecosystems [143].

Research to determine the resilience of irrigated agriculture was conducted by Lankford et al. [18] by testing the WUE in response 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 adapted to drought events through the construction of water storage facilities 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 [144]. 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 [145]. Water Need Estimation (WNE) determines how much, when, and where to irrigate, and it is reliable data dealing with uncertainties caused by environmental and technical conditions whilst considering plant, soil, and water interactions [145].

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.

7. 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 [146]. It is a crucial agricultural management system that requires the combined use of robotics and sensors, drones, advanced GPS and GNSSs (Global Navigation Satellite Systems), IoT, weather modelling, and how farmers can save water and reduce the use of chemicals on land [146]. The Internet of Things (IoT) and Wireless Sensor Networks (WSNs) can be utilised to more effectively monitor crop fields and make quick choices for sustainable agriculture, leading to improved crop yields and economic return [147,148]. Wireless Sensor Network (WSN) technology has improved the use of motes and sensor nodes to monitor ecological occurrences across a vast geographic area [148].

The integration of IoT devices and machine learning algorithms facilitates real-time data analysis, which leads to improved resource use and reduced environmental impacts [149]. The integration of IoT devices and machine learning algorithms facilitates real-time data analysis, which leads to improved resource use and reduced environmental impacts [149].

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 [150,151]. 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 [19]. Remote sensors can monitor parameters such as crop growth, health, and yield [19].

One of the latest advances recently in precision agriculture is Light Detection and Ranging (LiDAR) technology. LiDAR has been the most innovative development in laser scanning, remote sensing, and object detection systems. This technology can pinpoint structures or zones of interest in millimetre detail and can highlight variations and irregularities such as surface degradation and vegetation growth [152]. Another technology is called the RGB (Red Green Blue) 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 [153].

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 [154]. The Internet of Things also encompasses variable rate application (VRA), yield monitors, and remote sensing, which 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 the effects of climate change, such as drought, by managing water resources. Table 3 is a summary of some recent Internet of Things (IoTs) and Wireless Sensor Networks (WSNs) technologies used in precision agriculture. A study by Erekalo et al. [155] 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 a 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 [156].

Table 3. 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. [157]
Fuzzy logic (FL) controller, and long-range data transmission and monitoring via the LoRa protocol	Smart precision irrigation	Morocco	Saving water and energy	Benzaouia et al. [158]
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. [159]
Data collection technology using Arduino ESP WiFi technology	Automated irrigation	South Africa	Detects soil moisture and assists in water use efficiency	Langa et al. [160]

Table 3. *Cont.*

Technological Advancement	Application Approach	Country	Contribution to Agroecosystem	References
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. [161]
Ugunduzi Mobile App	To conduct field research	Tanzania	Monitoring maize and cassava crops through gathering, visualisation, and statistical analysis of soil fertility, conservation, and biodiversity	Hilbeck et al. [162]

8. Comparative Aspects of Sustainable Agroecosystems

Based on the literature review, this study was able to identify major aspects of agroecosystem analysis and justify a comparative analysis.

8.1. Cover Cropping

Cover cropping involves growing leguminous broadleaves, non-leguminous broadleaves, brassicas, or grasses. Economic benefits include the following:

- Cost savings: natural pest control and improved soil health through water and nutrient retention, reducing the need for chemical inputs.
- Risk mitigation: diversifying crops helps to mitigate climate change and reduce crop losses.

8.2. Intercropping

Intercropping involves growing two or more crops together on the same piece of land. Its economic advantages are as follows:

- Higher yields: the combined yield of intercropped fields is often higher than that of monoculture fields.
- Risk mitigation: diversifying crops reduces the risk of total crop failure and stabilises income.
- Cost savings: natural pest control and improved soil health reduce the need for chemical inputs.

8.3. Crop Rotation

Crop rotation is the practice of growing different crops in succession on the same land. Its economic and environmental benefits are as follows:

- Improved soil health: rotating crops enhances soil fertility and structure, leading to better yields.
- Reduced input costs: lower reliance on chemical fertilisers and pesticides due to improved soil and pest management.
- Increased resilience: crop rotation helps manage environmental stresses and reduces the risk of pest and disease outbreaks.

8.4. Agroforestry

Agroforestry integrates trees and shrubs into crop and animal farming systems. This approach can provide multiple economic benefits:

- Increased productivity: trees can enhance soil fertility and water retention, leading to higher crop yields.

- Diversified income: farmers can earn additional income from timber, fruits, nuts, and other tree products.
- Reduced costs: agroforestry can reduce the need for chemical fertilisers and pesticides, lowering input costs.

8.5. Comparative Analysis

- Sustainability: agroforestry, intercropping, and crop rotation are more sustainable and environmentally friendly compared to conventional methods, which often lead to soil degradation and biodiversity loss.
- Long-term profitability: while conventional farming may offer higher short-term yields, sustainable practices like agroforestry, intercropping, and crop rotation can provide long-term economic benefits through improved soil health and reduced input costs.
- Risk management: diversified farming systems are generally more resilient to environmental and market fluctuations, reducing the risk of economic losses.

9. Concluding 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, this 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 constitute 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 the 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 studies describe 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 practise agroforestry, this would result in better environmental conditions.

The design and diversity of the different cropping systems require careful planning. This involves considering the types of crops that can grow well together whilst showing reduced competition on resources such as N. This will result in improved crop growth due to improved environmental conditions. The development of programmes by governments that can educate farmers about different cropping systems and how they contribute to crop growth will be effective for crop production. Extension services from the government can assist farmers in learning complex issues like how the surrounding environmental conditions affect the productivity of crops. There should be policies that are put in place to support farmers in the adoption of diverse cropping systems through training and incentives.

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 (WSNs) monitor environmental parameters like soil moisture content, which is a good invention for drought-stricken areas. Less-privileged farmers facing financial barriers could be assisted with the use of such technologies, and they must be educated on how these technologies work so that they can also improve their farming conditions.

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