Advancing sustainability: The impact of emerging technologies in agriculture

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Advancing sustainability: The impact of emerging technologies in agriculture

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ABSTRACT

The need to ensure food security and promote environmental sustainability has led to a transformative period in agriculture. This period is characterized by the use of novel technology, which provides solutions that effectively address ecological concerns while also ensuring economic viability. Emerging technologies, such as precision farming enabled by drones, sensor-based monitoring systems and genetic editing techniques that result in drought-resistant crops, are significantly changing the agricultural sector. The integration of data analytics and machine learning algorithms is transforming supply chain management and enhancing the capabilities of predictive analytics in the context of crop diseases. Technological interventions serve to optimize efficiency and minimize the adverse ecological effects associated with farming, promoting the goals of sustainable agriculture. However, it is important to carefully address ethical and socio-economic considerations, including accessibility and data privacy, to manage these effects effectively. Therefore, the objective of this study is to examine the contributions of emerging technology to sustainable agriculture, evaluate its constraints, and suggest a comprehensive framework for its ethical and equitable integration. Communication technology has also impacted the agricultural sector, particularly with the increased use of connected devices. Artificial intelligence and deep learning advancements make processing collected data faster and more efficient, leading to more sustainable agricultural production using free, open-source software and sensor technology solutions. This technology enhances land optimization and boosts agricultural productivity, making sustainable farming practices more viable for both large and small-scale farmers. Our bibliometric analysis indicates a notable increase in interest in integrating sustainable agricultural methods with new technologies, particularly since 2018. It also revealed a strong link between precision agriculture, smart farming, machine learning, and the Internet of Things. However, awareness of technology is not very prevalent in the Asian region, especially among small-scale farmers. As a result, excessive usage of agricultural resources and wastage bring many adverse repercussions, and it's a high constraint to sustainable agricultural practices in the region.

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1. Introduction

1.1. What is sustainable agriculture?

Agriculture has undergone some significant changes in the years following World War II. Advancements in technology and favourable government policies aimed at enhancing production and minimizing food costs have led to a significant increase in food and agricultural productivity. Increased usage of chemicals and specialization in the agriculture sector have been key mechanisms in achieving this growth. Additionally, the government has implemented policies that have further aided in maximizing production and reducing food prices. [1–5]. Some farmers have been able to increase their food production while keeping prices low due to certain changes. Even though the idea of the excessive utilization of resources for high yield in agriculture has been debated over the years [1,6]. As a result of humans becoming more involved in natural habitats, various types of environmental imbalances have occurred. These include pollution, loss of soil through erosion, shifts in wildlife populations, and changes in the natural flora and fauna due to human intervention [7]. Furthermore, in response to the exponential population growth, the demand for food also increased rapidly for population survival and skill diversification [8]. The early trends of biological and chemical sciences led to the gradual reduction of engaging individuals in food processing or production, encouraging society to diversify, which does not directly blend with survival; instead, it promotes increased quality of life [5]. However, negligence or inappropriate chemical and biological technology use in agriculture can negatively affect the ecosystem and threaten its sustainability [9]. Therefore, it is necessary to create sustainable innovation and technology in the agriculture industry. In light of the challenges posed by limited resources, we must accept the importance of new technology in enhancing agricultural productivity.

Sustainable agriculture primarily targets site-specific applications and aims to curtail human needs such as food and fibre. It also ensures the environmental safety and the natural resource base of a particular economy [10]. Sustainable agriculture mainly lies on three primary goals: (1) The environmental health, (2) the financial viability, and (3) the Social equity are all important factors to consider in sustainable agriculture. Above all, implementing sustainable agriculture practices can ensure that the needs of future generations are met while also fulfilling current needs [11]. It is worth noting that sustainable agriculture can balance economic feasibility with environmental conservation [12]. Therefore, a long-term relationship is needed between natural and human interaction and vice versa for achieving short-term economic targets, which includes considering social responsibilities such as welfare of labourers consumer health, safety, etc. [11]. Thus, Proper planning of land use can effectively accomplish the production of food, preservation of habitat, conservation of resources, and farm business. By conducting extensive analyses, it is possible to optimize land use to achieve high yields while also maintaining significant areas for wildlife conservation within the same land [13].

A constantly evolving and location-specific field, agriculture requires a broad and adaptive knowledge to ensure sustainable practices. This involves utilizing both formal and experimental science, as well as incorporating the insight of farmers on the ground [14]. To achieve the objective above, it would be beneficial to adopt a system that holistically connects local farmers, ranging from individual farmers to the local ecosystem and communities that are affected by the farming system, both locally and globally. This approach enables one to identify the interconnectedness between farming and the wider environment and encourages cross-disciplinary collaboration in research and education to ensure fairness in society. As population engagement in food production diminishes, there is a growing shift toward intensive and large-scale agricultural practices, which often undermine sustainability. This trend results in a less resilient food system, characterized by greater environmental impact and reduced local involvement. Technology can play a pivotal role in transforming agriculture, but its effectiveness is contingent upon accessibility and the broader economic and political context. For technology to truly drive sustainable change, it must be widely available and supported by favorable policies and economic conditions. Only then can it bridge the gap between industrial-scale production and the need for more sustainable, localized farming practices. A systems perspective necessitates the involvement of researchers from diverse fields, farmers, farmworkers, consumers, policymakers, and other stakeholders. In conclusion, a systems perspective towards food systems and agroecosystems may provide us with the tools to examine the effects of agriculture on environmental sustainability and human society.

2. Benefits of sustainable agriculture

Compared to intensive industrial agriculture, sustainable agriculture can preserve resources, benefitting both the natural environment and social welfare. Sustainable agriculture prevents eutrophication and the pollution of large bodies of water by reducing agricultural runoff. It conserves water and naturally maintains soil fertility by recycling nutrients on the farm by promoting closed nutrient cycles. By using specific agricultural techniques, it enhances carbon sequestration by soil and perennial vegetation. It also promotes energy efficiency, thus reducing energy consumption and decreasing emissions of air pollutants and greenhouse gases. Sustainable agriculture creates habitats for pollinators and beneficial insects, encouraging biodiversity and ensuring the welfare of farm animals while also providing space for respectful coexistence with native wildlife [15–17]. These environmental benefits also contribute to our social well-being since our well-being is intrinsically connected to the health of our natural surroundings. Moreover, sustainable agriculture produces safe and nutritious food, and it goes without saying that "We are what we eat" [18]. Currently, the nutritional content of foods is declining. Some experts speculate that the reason for this is that popular high-yielding strains of crops have weaker root systems, which makes it difficult for them to absorb nutrients from the soil. Due to this, they produce less nutritious food. To solve this problem, reducing the use of pesticides and increasing food diversity could be helpful. Sustainable farms do not concentrate solely on growing cash crops like wheat or corn. Instead, they cultivate local varieties in highly diversified farming systems [19]. Using precise appropriate technology in sustainable agriculture can also increase worker safety. In addition, sustainable agriculture aids rural areas' socio-economic development by providing jobs to young people in these areas.

Furthermore, sustainable agriculture has the potential to support food security by incorporating home gardens, utilizing locally sourced farm products in school meal programs, and establishing local food cooperatives. These initiatives can foster a sense of community and belonging while also promoting the sustainability of food systems [20,21]. In many developed nations, the compensation offered to workers for their labour is inadequate, and as a result, farmers rely heavily on migrant labour from economically less developed countries. This puts farmers in the position of having to deal with immigration policies and creates a burden on social welfare programs provided by the government. The legal status of these workers also contributes to their low wages, substandard living conditions, lack of job security and opportunities, and their exclusion from safety regulations that are considered standard in other industries [22]. A sustainable agriculture approach that adopts a systems perspective would involve combining resources among farmers to enhance housing facilities, sharing labour across farms with various crops to reduce seasonal unemployment, sharing the profits from farm production, training workers to manage their farms, and developing innovative ways to provide healthcare and educational opportunities to workers, thereby promoting social equity and sustainability [22].

The transformation to sustainable agriculture will be a distinct process requiring small, realistic steps for farmers. Household economic situations and personal inspirations will significantly influence how fast or how far the transition progresses. Even so, we are collectively responsible for nurturing the transition towards sustainable agriculture. To ensure the long-term sustainability of agroecosystems, technical competence, skilled labour, and knowledge are essential. In order to achieve agricultural productivity and sustainability, social institutions must encourage innovation, promote the education of farmers and scientists, and establish partnerships between farmers and researchers.

3. The role of new technology in sustainable agriculture

The rapid pace of advancement and innovation in future technologies is poised to significantly influence the stability and productivity of agriculture. Emerging technologies are expected to provide farmers and other stakeholders with crucial insights and tools that will enhance decision-making throughout the entire food production process. From precision agriculture to advanced data analytics, these innovations will enable more informed choices, optimizing resource use and improving crop yields. For instance, real-time data on soil health, weather conditions, and crop growth can help farmers make timely interventions, thereby increasing efficiency and reducing waste [23].

The development and dissemination of new agricultural technologies are particularly impactful for the world's 475 million small farms. These farms, which constitute a significant portion of global agriculture, stand to benefit immensely from technological advancements. Innovations such as affordable sensors, mobile applications, and automated systems can help smallholders manage their operations more effectively, leading to enhanced productivity and profitability. Technology can also facilitate access to market information and supply chain management tools, further empowering small-scale farmers to compete in global markets [24].

Adopting a systems perspective is crucial for maximizing the potential of these technological advancements. By viewing agriculture as an interconnected system, we can better understand how technological innovations can be integrated to promote sustainability. This approach encourages the use of technology to address multiple aspects of farming, such as improving soil health, optimizing water use, and reducing environmental impact. For example, integrating data from various sources can help develop more precise irrigation strategies, reduce chemical inputs, and support biodiversity [25].

4. Sustainable farming methods and practices

4.1. *Permaculture*

Permaculture is a holistic design philosophy that seeks to create sustainable and self-sufficient ecosystems by mirroring the principles and processes of natural ecosystems. This methodology is rooted in principles that promote environmental stewardship, resource efficiency, and resilience. A key element in a well-structured permaculture system is the integration of perennial crops—such as fruit trees, nut trees, and various shrubs—into the landscape. These plants are integral because they provide long-term yields and contribute to the stability and health of the ecosystem. Unlike annual crops, which require replanting each year, perennials establish themselves over time, reducing soil disturbance and enhancing soil fertility [26].

The incorporation of perennial crops into permaculture systems offers several benefits. These plants help build and maintain soil health through deep root systems that improve soil structure and nutrient cycling. They also support biodiversity by providing habitat and food sources for a variety of organisms, from insects to birds. Additionally, perennials contribute to a more stable and productive food system, as they require less input and management once established compared to annual crops [26].

4.2. *Polycultures/companion planting and crop rotations*

Cultivating diverse crop species in the same area can result in a more productive and sustainable outcome. There are two methods to consider when mimicking natural principles: polyculture and crop rotation. Polyculture involves growing complementary crops in the same plot to make the most of available resources and provide a wider range of products. This method enhances biodiversity, improves soil fertility, and encourages a balanced diet, all of which contribute to a more resilient system that can cope with weather changes [27].

Crop rotation is the practice of cultivating different types of crops in the same area during consecutive seasons. The frequency of crop rotation varies and can occur annually, every few years, or over more extended periods. Crop rotation is an effective agricultural technique for preventing soil fertility depletion. Interrupting the development cycles of diseases and pests through crop rotation reduces their occurrence. This technique also lessens the need for fertilizers and pesticides in farming.

4.3. *Biodynamic farming*

Biodynamic farming, rooted in the principles of anthroposophy developed by Rudolf Steiner, embraces an ecological and holistic approach to agriculture, viewing the farm as a cohesive, self-sustaining organism where plants, animals, and soil interact in a mutually beneficial manner. This method prioritizes enhancing soil fertility and plant health through natural means, such as integrating livestock to provide manure for composting, which enriches the soil and supports healthy plant growth [28]. Biodynamic practices also emphasize minimizing reliance on external inputs by reducing or eliminating synthetic fertilizers and pesticides. Instead, farmers employ techniques like cover cropping and crop rotations to maintain soil fertility and prevent erosion. The approach values biodiversity by fostering a diverse ecosystem that includes a variety of plants, animals, and beneficial insects, all of which contribute to a balanced and resilient agricultural system. Additionally, biodynamic farming incorporates lunar and cosmic rhythms into its practices, aligning agricultural activities with these natural cycles to optimize plant growth and farm productivity. Versatile and adaptable, biodynamic principles can be effectively applied across different types of farming operations, including vegetable gardens, orchards, vineyards, and more, creating sustainable and productive agricultural environments [28].

4.4. *Hydroponics and aquaponics*

Growing plants without soil can be achieved through hydroponics and aquaponics. The plants in these systems are nourished through water that has been enriched with special nutrients. In hydroponic systems, the roots can be directly positioned in mineral solutions or placed in an inert medium like gravel or perlite. On the other hand, aquaponic systems involve the cultivation of hydroponic crops alongside aquatic animals. The water that is used to nourish the crops contains waste material from the fish raised in aquaculture, which in turn nourishes the plants. The fish then reuse the water as it is recirculated back into the system. Both hydroponic and aquaponic systems can be used for commercial or personal purposes [25,28,29].

4.5. *Urban agriculture*

Ensuring that our food sources are nearby is crucial as our cities expand. The majority of people are expected to live in urban areas in the coming years, which means that we need to modify our food systems to suit these environments [29]. There are several ways to accomplish this goal, including backyard farms or gardens, community gardens, rooftop farms, urban greenhouses, indoor hydroponic farms, and vertical urban farm towers. Given the limited space in urban areas, it is essential to find creative solutions to transform our food systems and address this challenge.

4.6. Vertical farming

Vertical farming is an eco-friendly approach to crop cultivation where plants are grown in layers above each other rather than on the ground, like traditional farming methods. By using this method, farmers can maximize the productivity of the same area of land. Hydroponics and aquaponics are frequently employed to create a tightly controlled environment. As the crops grow in a regulated climate, the necessity for pesticides is greatly reduced and the occurrence of diseases is considerably diminished. Vertical farming can reduce carbon footprints and the demand for labour by introducing robots for harvesting, planting and logistics. Using this technology can be an option for farming in urban areas, but it consumes more energy than traditional farming [30]. Therefore, it is recommended to use it reasonably and with careful consideration.

4.7. Agroforestry and food forests

Agroforestry and food forests are farming methods that promote the growth of trees and shrubs among crops or grazing land, encouraging the combination of agriculture and forestry. Trees create a microclimate that maintains temperatures and soil moisture, protecting crops from wind or heavy rain. They also stabilize soil, minimizing nutrient runoff, improving soil structure, promoting healthy food crop growth, and maintaining soil fertility. Trees provide wood and fruit as an additional income source for farmers. As trees improve soil stability, agroforestry and food forests are becoming increasingly popular in dry regions susceptible to desertification [28,31].

Food forests, which are also known as forest gardens, are designed using permaculture principles. These systems consist of a multi-layered edible 'forest' made up primarily of perennial food plants. The forest canopy comprises tall and short fruit and nut trees, followed by a layer of fruit shrubs, perennial herbs, mushrooms, and vegetables on the ground level. In addition, climbing plants and root vegetables grow underground [28,31].

4.8. Growth of heirloom and older varieties

The problem of reduced genetic variety and biodiversity is pressing. This reduction signifies a decrease in species' ability to adapt to changes in climate, diseases, and pests in the environment. It is essential to conserve the biodiversity of seeds to prevent the loss of some food plant varieties forever. We will retain crucial genetic information if we preserve these plant varieties. These varieties have adapted precisely to make the most of local conditions, and our ancestors have selected the best seeds that provide the most nutritious and flavoured food.

4.9. Natural animal raising

When raised naturally, animals live on pastures or their preferred environment, making them less stressed, cleaner, and smell better. This leads to the production of more nutritious products. Animals and grasslands rely on each other: manure returns nutrients to the soil while hoof action aerates the soil, suppressing dominant species and providing rarer plants the opportunity to grow, promoting biodiversity. Strong root systems and plentiful tufts are created by grazing and trampling, which serve to prevent erosion, build soil, sequester carbon emissions in soil, and preserve grassland habitats that support other forms of wildlife and insects. Encouraging this symbiotic relationship between animals and grasslands is crucial to natural animal raising [32].

4.10. Natural pest management or Integrated Pest Management (IPM)

Integrated Pest Management prioritizes natural pest control mechanisms while growing crops. This method avoids using synthetic pesticides and other harmful chemicals that suppress pest infestations and pathogens, minimizing environmental and ecosystem harm [33]. Instead, integrated Pest Management doesn't rely on harmful pesticides but instead employs techniques that enhance the natural resilience of crops and interrupt pest cycles. These techniques include intercropping, crop rotations, and growing a diverse range of crops that disrupt preferred food sources of pests. This attracts various insects, including natural predators of pests, and helps maintain a balance in population sizes. Furthermore, these practices create an environment for populations of beneficial insects such as ladybugs, lacewings, fly parasites, birds, and bats that act as predators of crop-eating pests [34].

4.11. Mulching, groundcovers and manual weed control

Different techniques can be employed to minimize the proliferation of undesirable plants and maintain soil moisture. These methods may include the application of mulch, using groundcovers, and manual weeding. This approach can even eliminate the need for herbicides, as any persistent weeds can be easily handled by hand due to their minimal numbers. Using organic materials like wood chips, straw, and grass clippings for mulching can improve soil quality, reducing the need for tilling [35].

4.12. Zero tillage/no-till farming

A technique, known as zero tillage or no-till farming, can be used to avoid ploughing soil and reduce the requirement for heavy farm machinery. The approach can help to minimize the level of soil disturbance, thus leading to a reduction in greenhouse gas emissions, erosion, and runoff. It also improves soil carbon sequestration, utilises crop residue and conserves both soil and water. Zero tillage requires little investment before results can be observed. The biggest challenge restricting the implementation of this method is educating farmers [36].

4.13. Use of green manure

The term "green manure" refers to un-decomposed green material that is utilized as manure. This can be obtained by cultivating green manure crops or gathering green leaves from plants grown in wastelands or forests. Green manure crops include cowpeas and cluster beans, whereas green leaf manure crops include Gliricidia (*Gliricidia sepium*) and Neem (*Azadirachta indica*). Green manure serves as an organic alternative to synthetic fertilisers.

4.14. Organic farming

Organic farming bans the usage of chemicals for fertilization and pest control. Instead, it relies on organic substances such as compost, green manure, and bone meal [37]. This approach also focuses on using techniques such as crop rotation and polycultures to manage pests, weeds, and diseases. Organic farming emerged in the 20th century as a response to the Green Revolution, which introduced new agricultural practices and innovations, including genetically modified high-yielding crop varieties that responded well to synthetic fertilizers [20,38]. While organic farming has the potential to enrich the soil's carbon sequestration, it typically produces lower yields. This implies that greater land areas are required to generate an equivalent amount of food. [39]. This has sparked a debate about whether to prioritize land-sharing or land-sparing, leading to controversy about the sustainability of organic farming. One possible solution to reduce land use in organic farming could be vertical farming [40].

4.14.1. *Traditional farming practices*

Sri Lankan farmers, with their rich agricultural heritage spanning centuries, have honed indigenous farming practices that are both sustainable and eco-friendly. These traditional techniques encompass a variety of methods for pest control and crop health management, which rely on biological practices rather than harmful chemicals. The knowledge of these methods, passed down through generations, includes specific agricultural protection techniques, rituals, and beliefs deeply rooted in the community's cultural fabric. These practices not only ensure effective pest management but also maintain the ecological balance, reflecting a profound understanding of sustainable agriculture and environmental stewardship. An overview of these techniques, including their technical details and efficacy, can be found in Table 1.

5. Technologies and techniques in sustainable agriculture

5.1. *Renewable energy*

Renewable energy is an excellent alternative to non-renewable fossil fuels because it can replenish itself, which means we can rely on it for a long time without completely depleting it. Using renewable energy sources is also better for the environment because they don't release harmful emissions into the atmosphere. Solar power can be used to operate farm machinery, lighting, and water pumps. Additionally, solar thermal technology is effective for water heating and can be used in solar greenhouses and for underground soil heating. Wind turbines require minimal land and can be used to pump water for irrigation purposes. Biomass, which includes plant materials and animal waste, can be burned to produce energy and generate heat for heating buildings, crop drying, and dairy operations. It can also be used to generate electricity and steam.

5.2. *Biotechnology*

Biotechnology encompasses the development of genetically modified (GM) crops with enhanced traits, such as increased resistance to drought and pests, improved yield, and greater tolerance to environmental stresses. These advances can lead to the creation of high-yielding varieties that require less water, fewer inputs, and reduced ploughing, thereby boosting agricultural efficiency and sustainability. Furthermore, biotechnology facilitates the production of bio-pesticides and other beneficial agricultural products, contributing to resource conservation and enhanced resilience to climate change [49].

Despite these advantages, biotechnology is accompanied by significant controversy and debate. Concerns often center around the safety of GM crops for human health, animal welfare, and environmental impact. The potential for misuse, such as creating crops with unintended consequences or contributing to ecological imbalances, further complicates the discourse. Rigorous safety assessments and regulatory frameworks are essential to address these issues and ensure that biotechnology is applied responsibly and ethically. As biotechnology continues to evolve, it is crucial to balance its potential benefits with careful consideration of its risks and implications [49]. [49].

5.3. *Precision technology/precision agriculture*

Using the appropriate technology to enhance efficiency, productivity, crop yield, and profitability is the essence of precision agriculture [50]. The utilization of computational technology coupled with geographical location devices and remote sensing advancements is employed to address the vagueness of the environment. Using environmental modeling and risk management algorithms will result in the most efficient utilization of resources. Precision technology can be used to evaluate crop conditions much faster, and input application or harvesting technology can respond swiftly to varying environmental conditions, thereby reducing wastes relative to traditional technology.

Table 1
Review of Indigenous farming practices in Sri Lanka.

No	Traditional Agricultural techniques	Descriptions	References
01	**Rice Devotion (Bath Pay Kiriima):**	In response to a pest infestation, a farmer collects small portions of uncooked rice from the village. They then cook this rice with coconut milk near the main water source. During the cooking process, specific prayers are recited, and flowers are offered to God. The cooked rice is placed in an open traditional basket called "Kuruniya" and scattered around the rice field. Finally, In the middle of the paddy field, a branch of a thorny plant is placed. After that, three claps are made, which are believed to prevent insect infestations.	[41,42]
02	**The arrangement of Coconut Husks and Tree Branches.:**	Short poles with coconut husks attached to them are spread throughout the field, accompanied by scattered branches from different trees.	[43]
03	**Burying of Oranges:**	In the morning, a farmer heads to the field without engaging in any conversation. Once there, the farmer buries oranges in various locations throughout the paddy field.	[44]
04	**Daluk (Euphorbia Antiquorum) Treatment:**	The Daluk plant's branches are crushed and combined with water from the higher end of the field. Euphorbia Antiquorum is a tiny tree.	[44]
05	**Neem (Azadirachta indica) Seed Oil or Crushed Seed Application:**	Farmers usually crush neem seeds and spread them in the field when they detect a pest infestation. Another common practice is applying neem seed oil in the field.	[41]
06	**Five Latex Treatment:**	Latex is gathered from five different types of plants, namely Alstonia scholaris, Pagiantha dichotoma, Artocarpus altilis, Artocarpus heterophyllus, and Cocos nucifera. Bamboo trees, coconut leaves, and a panicle of rice from the affected field are also needed to complete the process. The field is set up by placing a bamboo trunk in the center and surrounding it with eight more bamboo trunks. Coconut leaves are then tied to the bamboo trees, and the collected latex from the five plants is poured into a cut coconut. The coconut is then securely attached to the central bamboo tree, and the panicle from the affected field is placed on top.	[41,42]
07	**Oil Lamp Treatment:**	Farmers use four coconuts to create four oil lamps to combat stem borer infestation. These lamps are placed in the four corners of the field during the evening. Following this, a small quantity of sand is spread over the field.	[45,46]
08	**Wood Ash Treatment:**	Farmers spread wood ash from a traditional hearth around the perimeter to protect the field	[46]

(*continued on next page*)

Table 1 (*continued*)

No	Traditional Agricultural techniques	Descriptions	References
		from insect pests. The application begins at a specific point and continues in a circular motion, concluding at the starting point. This is done in the evenings, and it is crucial not to speak during the process or step over the ash circle	
09	**Cycas circinalis Treatment:**	When a pest attack is detected, the water in the field is combined with the crushed reproductive parts of the Cycas circinalis plant.	[43]
10	**Shorea Zeylanica or Vateria Copallifera Resin Treatment:**	Strips of used cloth are soaked in resin extracted from Shorea Zeylanica or Vateria Copallifera. The soaked strips are then tied at even intervals along a rope. Next, two farmers hold the rope from opposite ends and pull it across the field.	[46]
11	**Crop Protection from Animals:**	**Using Banana Trunks and Leaves:** o Instructions involving a 7-foot banana trunk and leaves to create a protective barrier. **Flies Control:** o Method for repelling flies using branches and a specific chant. **Rat Infestation:** o Techniques for dealing with rat infestations, involving natural materials like cat dung and leaves. **Elephant Deterrent:** o Using Madara wood to deter elephants from crops.	[43]
12	**Pest Control and Insect Management:**	● **Insect Repellent Plants:** o Cultivating specific plants to naturally deter insects. ● **Bird Deterrent:** o Planting bamboo tree roots in the field to deter birds. ● **Leaf-Eating Worms:** o Using Kappitiya leaves to control leaf-eating worms. ● **Mite Infestation:** o Method for dealing with mite infestations using specific techniques and chants. ● **Bees Management:** o Techniques involving flowers, water, and the use of ash.	[47]
13	**Miscellaneous Crop Protection Methods:**	● **Fruit Crop Protection:** o Techniques for protecting fruit crops from damage. ● **Coconut Tree Protection:** o Methods for safeguarding coconut trees from pests. ● **Cobra Image Method:** o Using copper plates with cobra images to deter rats.	[48]
14	**Rituals and Superstitions:**	● **Rice Farming Rituals:** o Performing specific rituals related to rice farming for protection against diseases. ● **Protection in Forests:** o Rituals and practices for safety in forest environments. ● **Journey Protection:** o Superstitious practices before embarking on a journey. ● **Insect Bites and Stings:** o Traditional methods for treating insect bites and stings. ● **Ant Control:** o Using vinegar to repel ants.	[47]
15	**Unique Practices for Crop Protection:**	● **Rice Plantation with Coconut:** o Using coconuts in rice farming activities for protection. ● **Black Drawing for Protection:** o A ritual involving drawing lines for protection. ● **Mawi Seed for Safety:** o Superstitious practice for safety during machine operation. ● **Insect Removal from Eyes:** o Technique for removing insects from eyes. ● **Rat Control with Crushed Rice:** o Using crushed rice and an unmarried girl for rat control.	[41]

Farmers can access scientific data for better crop understanding and plan accordingly to maximize their harvests [51].

Drones are an example of equipment use in precision agriculture. They can gather an overview of the farm faster than in traditional ways, so farmers will better understand their crops' health and water and nutrient requirements. They will also be able to save money by identifying problems that are difficult to locate otherwise and take action at the right time to prevent pest infestations or disease outbreaks. Drones have many uses in agriculture, but their primary use is approaching detailed data through different sensors, an example of using remote sensing technology. Micro-climate data, pH levels, and animal movements can be monitored using sensors. The data collected can be utilized to generate 3D models and maps of an area, which can be further analyzed to identify crop health, detect disease stress in crops, and pinpoint irrigation issues. Drones are capable of spreading mulch, planting seeds, and spraying agrochemicals. [52]. Drones have a wide range of applications, including livestock management and irrigation mapping. Two types of drones are available: fixed-wing and multi-copter drones. Fixed-wing drones are designed to withstand harsh weather conditions and can stay in the air for longer. However, they are more costly and require significant space for take-off and landing. Multi-copter drones are more flexible, easier to fly, less expensive, and can be used for precision spraying of pesticides, fertilizers, and seedings, as well as photogrammetry. Farmers also use satellite technology to gain a better understanding of their farms' condition [53].

5.4. *Automation with robots*

Innovation in robotics is being utilized to create self-driving tractors, robotic harvesters, and automatic seeding and watering robots. Although these technologies are relatively new, a significant number of conventional agricultural companies have integrated them at a decent pace. Automated machines can be used to apply pesticides in a focused manner, instead of haphazardly spraying them from a tractor. This will not only improve human health as workers are not as exposed to pesticides but also reduce soil compaction and, therefore, less runoff as there is no human passenger, making the machinery lighter. Automation technology aims to cover easier, mundane and repetitive tasks to tackle problems such as farm labour shortages, changing consumer preferences, and even the environmental impact of farming [54].

5.5. *Livestock farming technology*

Managing livestock, such as poultry, dairy cows, or cattle, involves keeping accurate financial records, supervising workers, and ensuring proper care and feeding of the animals. However, nutritional, genetic, and digital technological advancements have made livestock management more accessible and more efficient. For instance, sensors, like electronic ear tags, can be used to track daily activity and health-related issues in cattle, providing valuable insights for the entire herd. Understanding genomics can help producers evaluate their herds' genetic risks and determine future profitability. Automated robotic milking systems have also led to more flexible working hours for workers and improved cow welfare. These technologies can enhance or even improve livestock productivity, welfare, and management [55].

5.6. *Water management/irrigation monitoring*

Technology can be used to capture, store and transmit water with minimum wastage and pollution. Farmers can grow native crops to reduce excessive water usage and prevent the depletion of rivers, dry land and soil degradation. Rainwater harvesting technology can store rainwater during droughts, and recycled wastewater can be used for irrigation. Other technologies to conserve water include precision technology such as drones, which promote more efficient use of resources, and wireless and remote monitoring systems, which help farmers gain better control of their operations [56].

The World Economic Forum identified the water crisis as one of the most significant economic and societal risks in the coming years. Therefore, it is crucial to use and manage water resources sustainably today and in the future, with a particular focus on agriculture, which is one of the largest water user sectors globally. Water management and monitoring in agricultural activities are essential to achieving secure water and increasing field yield while reducing costs using intelligent water management and monitoring techniques.

Traditional irrigation methods such as flood irrigation or overhead sprinklers can be wasteful and inefficient. They lead to water loss through evaporation, runoff, and deep percolation. Still, modern water management technologies have revolutionized how farmers use water by allowing for precise and optimized irrigation practices One of the most notable advancements in water management technology is using sensors and data analytics. Soil moisture sensors, weather stations, and other IoT devices can collect real-time data on soil moisture, temperature, humidity, and other factors [Fig. 1]. This data can be analyzed to provide valuable insights into crop water requirements, allowing farmers to make informed decisions about when, where, and how much to irrigate [57–59].

Water management technologies determine several parameters through monitoring devices to achieve water management using emerging technologies. These include soil moisture to determine water retention and moisture patterns, rainfall to avoid overwatering and conserve resources, evapotranspiration (ET) to calculate ET with temperature/RH, wind and solar radiation data, temperature and relative humidity, wind speed and direction to predict weather patterns or determine safe application of pesticides, solar radiation to understand the impact of light levels, site evaluation, plant growth, and water level to monitor water level in storage tanks and reservoirs [60].

Designing new irrigation water management and monitoring technologies has several benefits, such as higher crop yield and less risk of crop shortfalls. With better water management and monitoring, there is no need to irrigate too much against possible field flooding, saving on manual labour costs for water, and reducing nitrate levels in the groundwater. By applying only as much fertilizer as needed, such technologies contribute to water quality [59,61].

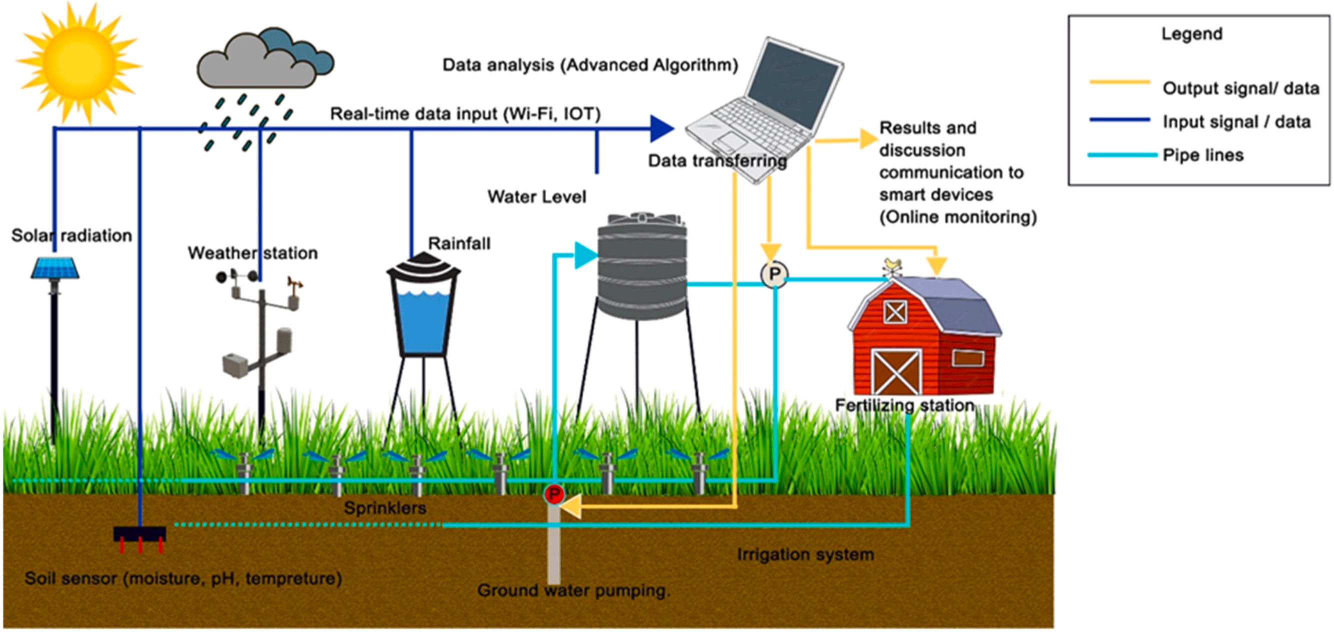

Fig. 1. Pictorial overview of the smart irrigation concept.

5.7. Information technology (IT)

Early warning systems and weather forecasting in Climate Risk Management (CRM) come in various scales and contribute significantly to determining relevant climate risks. Weather changes greatly affect agriculture, and open knowledge about weather changes aids in more accurate and effective decision-making and forecasting [62]. By monitoring or estimating the time and probability of fluctuations in rainfall patterns and environmental temperature fluctuations, farmers can receive weather forecasts for time scales of up to six weeks through strategic risk management. Mobile phones are another technology that improves farmers' understanding of weather changes. Mobile phones have supported farmers to communicate effectively with one another to share information and receive timely information about market dynamics, weather and responses to problems. Apps have enabled farmers to access every sector of their farming operations very easily as well. A better understanding of weather forecasts means that farmers can make better decisions about when to apply fertiliser and pesticides to minimise runoff [63].

Farmers can use AI technology in conjunction with remote sensors, satellites, and UAVs to better understand the data collected by these technologies. This is achieved through algorithms that process data and adapt based on the information received. As more data is collected, the algorithm becomes more accurate in its predictions, which farmers can leverage to maximize their crop yields [64].

Fleet management uses GIS technology to track fuel usage, engine speed, maintenance schedules, and more to improve farm vehicle efficiency and profitability [65]. The food industry can benefit from blockchain technology in addressing multiple issues, including fraud, safety recalls, supply chain inefficiencies, and traceability. By tracking ownership records and ensuring tamper resistance, blockchain promotes transparency and verified products and practices. Given the perishable nature of food, it is essential to quickly identify the source of foodborne illnesses to protect public health [66]. Blockchain enables real-time monitoring of the journey of food items, replacing the unreliable paper-based tracking system. Additionally, the establishment of a ledger network by blockchain creates market value by balancing pricing according to information provided by the entire value chain. With its potential to enhance transparency and safety, blockchain presents a hopeful prospect for a food marketplace that is more dependable and secure [66–68].

5.8. Nanotechnology

The field of nanotechnology involves the study and manipulation of matter ranging from 1 to 100 nm in size, and its impact on human well-being. Through nanotechnology, crops can be developed to withstand various environmental conditions, identify and manage plant diseases, and enhance their ability to absorb minerals from the soil, resulting in increased crop yield [69]. Nano-scale biomaterials could be combined with indigenous technologies to further its applications. Nanotechnology can be used to produce crops tolerant to high temperatures, develop specialised pesticides for specific insects called nano-pesticides, overcome problems of global warming and create nanotubes that store rainwater in the soil so plants can use it in droughts [70]. Nanoparticles may be used to effectively treat and monitor food crop diseases by targeting pathogens. This may be achieved using carbon, silver, silica and alumina silicate nano-forms [71]. Nano-fertilisers can be developed to control nutrient release into soils and prevent nutrient loss. Nanomaterials coated with a thin film can entrap nutrients, and they can also be delivered as emulsions. Nano-pesticides are created using various types of nanoparticles, including surfactants, organic polymers, and mineral nanoparticles. These nano-pesticides are designed to target certain insects while avoiding harm to other important insects [72]. Fast and sensitive sensors are necessary to identify plant pathogens, and nano-sensors can monitor agro-climatic conditions and integrate into a nano-system that triggers the release of fertilisers and pesticides as needed. Nanotechnology offers many applications for sustainable agriculture, and its cost-effectiveness makes it a promising technology [73].

5.9. Greenhouse technology

Small-scale greenhouses are adapting and becoming larger-scale facilities, utilizing advanced technologies like LED lights and automated control systems to tailor the cultivation environment based on individual needs. The popularity of urban greenhouses for local food production is increasing, leading to more capital investment in the industry [74]. Poinsettia is the main crop during November to December for Christmas. By artificially providing longer nights, the leaves gradually turn from green to red (Fig. 2(a),(b) and (c)). Further Gerbra grows throughout the year with changing environmental conditions (Fig. 2d). A hydroponic farm of leafy vegetables in green houses (Fig. 2(e),(f) and (g)) and some vegetable crops (Fig. 2(h) and (i)). Hydroponics typically uses more electricity compared to many other greenhouse production methods. Although it requires higher energy consumption than traditional vegetable and herb farming, it uses fewer limited resources like water, fertilizer, arable land, and pesticides [25.29]

5.10. Post-harvest technology

Advancing sustainability in agriculture heavily relies on post-harvest technologies, which are essential for minimizing waste and maintaining the physical and nutritional quality of produce. Emerging technologies in this field focus on enhancing storage, processing, and transportation methods to ensure that crops retain their freshness and nutritional value from the point of harvest to consumption. By incorporating innovations such as precision cooling systems, advanced packaging materials, and real-time monitoring tools, these technologies not only reduce spoilage and extend shelf life but also contribute to more sustainable agricultural practices, ultimately supporting a more efficient and eco-friendly food supply chain [25].

5.11. Soil spectroscopy

Soil spectroscopy techniques such as Fourier transform infrared spectroscopy (FTIR) gives farmers more insight and information about soil to make faster decisions and efficiently protect their soil through assessment, mapping and monitoring. This tool is fast, reliably accurate and cheap, so it can particularly benefit countries with limited funding for research. This library of information will improve evidence-based decision-making, allowing countries to sustainably manage their soil. Improved soil health will contribute to food security, nutrition, climate adaptation, carbon sequestration, and mitigation [20,75,76].

5.11.1. Smallholder farmers adopting digital agriculture in developing countries

Smallholder farmers in developing countries can benefit greatly from the digital transformation of agriculture. This emerging solution has a lot of promise [77]. Improved market transparency, increased farm productivity, and efficient logistics are some benefits of digitalization in agriculture. Digital transformation has facilitated farmers' access to technical information, real-time data, and other relevant resources, which has led to enhanced food traceability and increased competitiveness. Mobile technologies have been particularly effective in transmitting agricultural information, resulting in a 4 % boost in yields in sub-Saharan Africa and India. All in all, digital transformation presents an innovative solution to the current problems of the global food system [78–81].

Implementing digital agricultural technology may create a discrepancy between small- and large-scale farms, known as a "digital divide" [82]. Small farmers may find it difficult to access modern agricultural technology due to the commercialization of technology, which they may

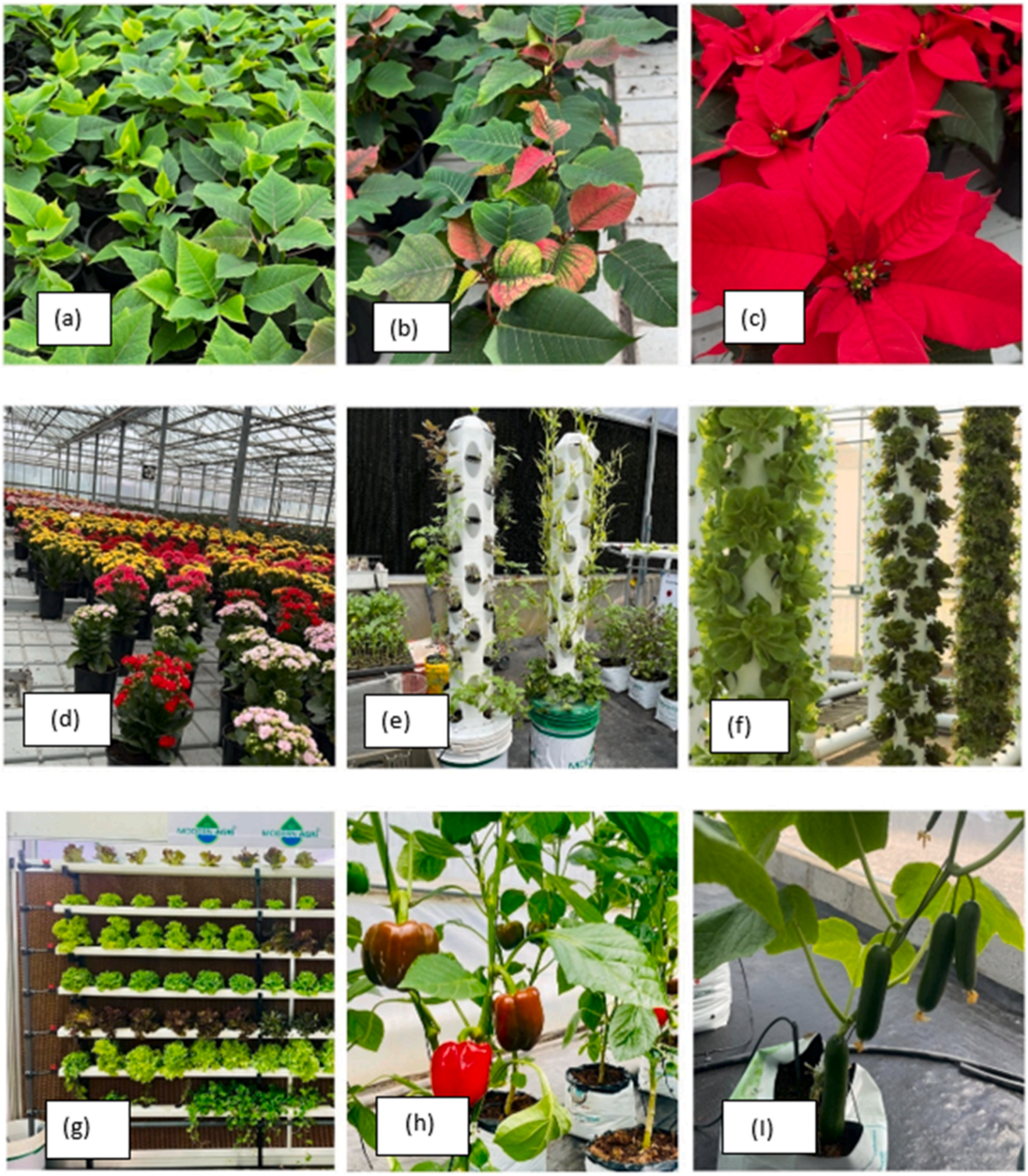

Fig. 2. Green house technology.

not have the financial resources to invest in. Developed countries are more advanced in digital agriculture while developing countries must catch up to keep pace [83]. Advanced digital technologies, including big data applications, are implemented mainly in North America and Europe. Small farmers face challenges in adopting digital technologies; evaluating whether they should be the primary users of such technology is crucial [84]. One potential resolution could be to engage small-scale farmers by dividing tasks within the agricultural sector to enable them to partake in the advantages of digital agriculture [85].

5.12. *The concept of Internet of Things (IoT)*

Over the last two decades, the Internet of Things (IoT) has progressed significantly. Nowadays, IoT-enabled devices can communicate, direct, and make choices autonomously through intelligent systems within their environment [86]. The implementation of IoT infrastructure has the potential to lower expenses, increase effectiveness, conserve energy, prevent losses and accidents, and open up new business prospects across diverse industries such as agriculture, healthcare, and manufacturing [87–89]. Although often overlooked, the remote nature of farming operations presents an opportunity to transform farming practices through IoT [90–92]. Smart farming involves in utilizing data and information technology to optimize complex farming systems; smart farming is on the brink of emerging as a major field of application in countries that rely on agriculture. With the help of IoT, cloud computing, and artificial intelligence, these technologies can be seamlessly integrated into agriculture to enhance its effectiveness and efficiency [93–95].

Due to the handling of livestock, operation of heavy machinery, exposure to hazardous chemicals, and working in open fields under direct sunlight or in enclosed spaces, the agricultural industry is widely known for being perilous for workers. Falls from high elevations are the most frequently occurring type of agricultural injury, which can lead to severe injuries, brain damage, and fractures [96–98] Wearable technology devices that utilize accelerometers and gyroscopes have become a hopeful solution to avoid the occurrence of such injuries. These devices can produce data capable of gathering and analysing vast amounts of information. Nevertheless, using Euler angles to represent 3D rotations has limitations, which can lead to rounding errors and distortion [99–102].

Despite this limitation, wearable technology exhibits potential in healthcare products, monitoring, personal health, and agriculture, despite its limitations. In the field of agriculture, it can be useful for preparing preventive measures for various types of casualties. IoT technology can benefit from the implementation of deep learning. Intelligent algorithms can analyse data from IoT sensors that provide input on farmers' positions and heart rates. The collected data can be combined with historical data and used to train models that identify patterns and predict the safety conditions of farmers in working environments [103,104].

5.13. Training in sustainable farming

Global demand for agricultural products is expected to double in the near future. This implies that the agriculture sector needs to increase its production while also adhering to sustainability standards, which is a growing concern [105]. The adverse impacts of intensive farming on biodiversity and climate change are well-known. As a result, there is a growing need for sustainable crop production. The objective of sustainable agriculture is to safeguard the environment, enhance the quality of life for farmers, and maintain or increase production levels. However, there are challenges in teaching the concept of sustainable agriculture, such as inadequate information management, on-farm trials, and demonstrations [106–109]. Despite these challenges, experiential learning methods that incorporate both experiential and information-centred teaching techniques have been successful in providing sustainable agricultural training, despite the challenges faced. Currently, most programs concentrate on teacher-centred techniques that are fact-heavy. However, the methods that are crucial in creating significant changes, as identified by behavioral and sustainability scholars, must also be highlighted [110].

Experiential learning is a highly effective way to apply knowledge in real-world settings, particularly in agriculture [111]. This is evidenced by the success of farmer field schools in India, which use participatory methods to foster autonomous learning and prepare students for future uncertainties and complexities [112]. However, it can be difficult to put these approaches into practice since it necessitates relinquishing control in the classroom and taking on a more prominent role as a facilitator of communal learning [113].

In order to advance sustainable agriculture, it is important to involve farmers in the development of educational programs through stakeholder engagement. This strategy empowers farmers to have a say in the program content, instruction, and evaluation, avoiding the pitfalls of past programs that deterred sustainable practices. Additionally, farmers and scientists must collaborate in order to create locally-tailored, sustainable knowledge [114,115].

Non-traditional curricula that are progressive, interdisciplinary, and system-based are necessary to ground theory in practice and promote sustainable practices that create change [116]. It is important to incorporate social and political sciences into the curriculum alongside environmental and economic sciences. Curricula which are based on real-world learning, critical problem-solving, experiential learning, behavior change, and sustainability competencies are the foundation for such subjects [117]. Farmers can learn a great deal from and with one another through peer learning. By sharing advice, feedback, and thoughtful questions, mutual learning and knowledge exchange are promoted. Peer learning fosters a valuable source of knowledge and ideas. Virtual reality technology is increasingly popular as an instructional medium in agricultural education [118]. Teachers believe it can effectively engage students in the learning process [119].

The production of food and management of agricultural resources has been transformed by digital agriculture. Advanced technologies such as big data, IoT, robotics, augmented reality, 3D printing, and sensors have enabled farmers to access state-of-the-art tools that optimize crop yields, reduce waste, and increase profits. However, a recent study conducted in Romania has found that many farmers find it challenging to keep up with technological change due to a shortage of qualified personnel and financial resources [120]. The complexity of these advanced systems requires specialized skills and training, posing a challenge for many farmers. Moreover, the cost of implementing and maintaining digital farming technologies is a significant obstacle for small and medium-sized farms. In order to overcome these challenges, it is necessary for governments, private organizations, and training institutions to invest in specialized training, offer financial assistance to farmers, and make digital farming programs more accessible and user-friendly. Such steps will help accelerate the adoption of these technologies and enable farmers to benefit from digital agriculture fully [120].

6. Sustainable agriculture and new technology bibliometric analysis

Our bibliomesttric analysis aimed to identify how the link between sustainable agriculture and new technology is being studied worldwide in current research. The main objective was to determine the research direction of this domain. We found that there are multiple linked words for both sustainable agriculture and new technology. In their bibliometric analysis, [121] used the following phrases: "sustainable agriculture," "sustainable and agriculture," "agricultural sustainability," "agricultural and sustainability," "agriculture and sustainability," "sustainable agricultural," "sustainable farming," "farm sustainability," "sustainable crop," "sustainable and cultivation," "sustainable agro," "agro. Sustainability," "Agri. Sustainable," "sustainability and cultivation," "sustainable agriculture and development," "sustainable tillage," "sustainable cultivation," "agriculture sustainability," "sustainable farm," "sustainable development and agriculture," "sustainable agroecology," "sustainable cropping," "sustainable agrarian," "sustainable sowing," and "sustainability and agricultural." For our analysis, we utilized the same set of keywords to represent sustainable agriculture. The following terms were used to represent modern technology: "new technology," "modern technology," "internet of things," "precision farming," "smart agriculture," "farm automation," "precision agriculture," "drone technology," "farm management software," "robotics," "sensor technology," "autonomous farming," "digital farming," "big data in agriculture," "artificial intelligence," and "machine learning." The data used in the analysis was obtained on February 14th, 2023.

We focused on collecting and analyzing journal articles while excluding conference papers, books, and book chapters. According to [122] journal articles hold the greatest scholarly value. We used two main databases, the Science Citation Index Expanded (SCI-E) and the Social Science Citation Index (SSCI), which cover more than 20,000 journals, books, and conferences in the Web of Science Core Collection (WoSCC). WoSCC is well-regarded among academics and researchers as a reliable and high-quality data source. We only considered articles written in English during the specified time period.

7. Results

The Fig. 3 Treemap chart showcases the ten most prominent Web of Science categories for research works in the agriculture and new technologies domain. The research works related to Environmental Sciences, Agronomy, Green Sustainable Science Technology, and Agriculture Multidisciplinary have been exhibiting exceptional performance.

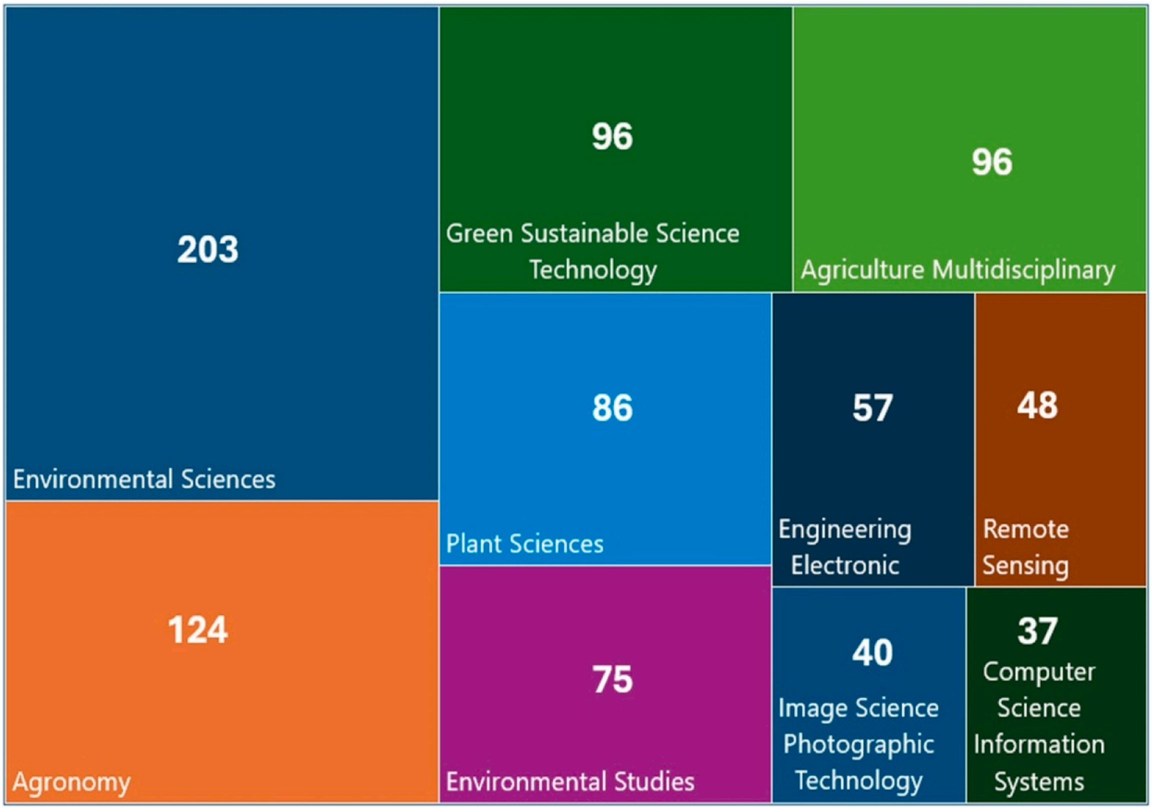

Fig. 3. The most prominent Web of Science categories for research works in the agriculture and new technologies domain.

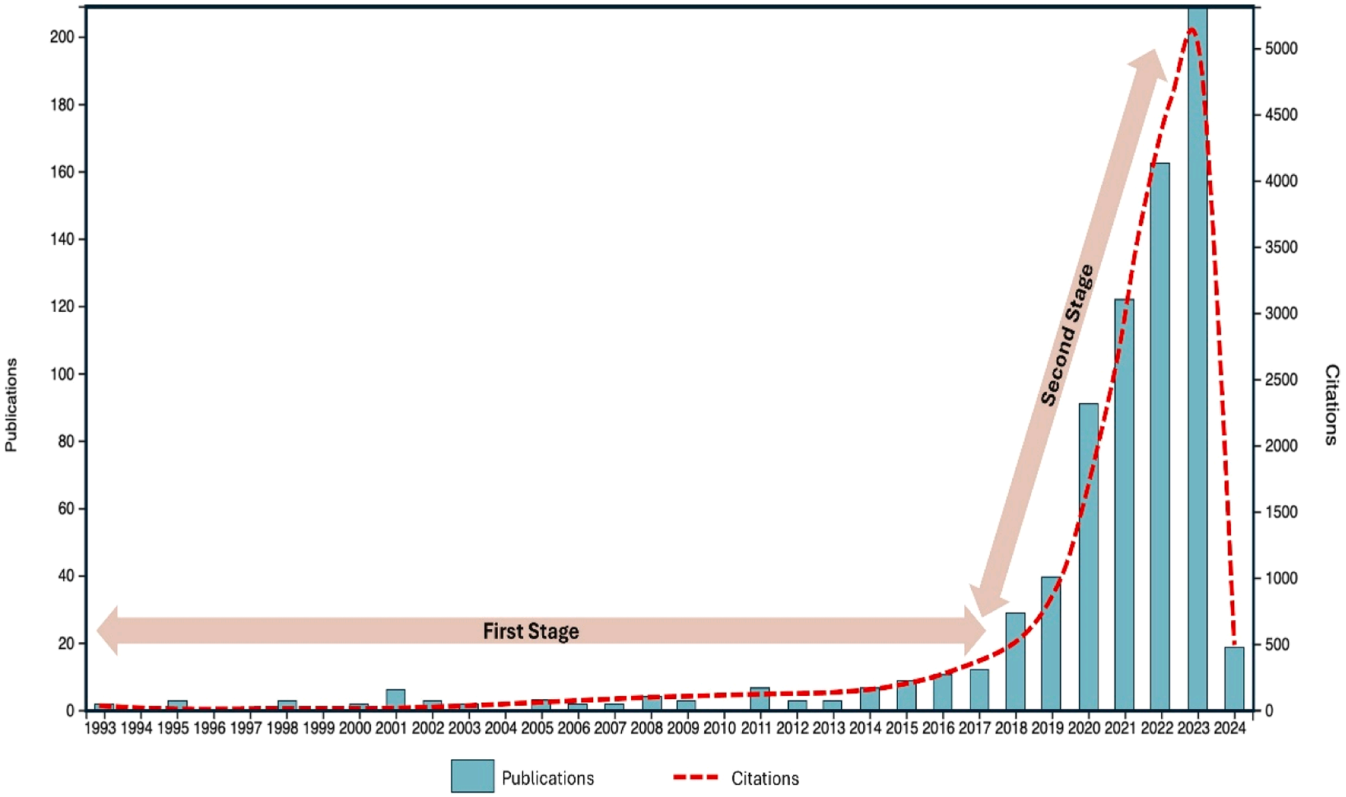

Fig. 4. Changes in the number of publications related to Sustainable Agriculture and New Technology from 1993 to 2024.

However, Computer Science Information Systems and Image Science Photographic Technology have been receiving comparatively less attention.

Fig. 4 displays the changes in the number of publications related to Sustainable Agriculture and New Technology from 1993 to 2024. The graph shows a consistent upward trend, with two distinct periods of publication growth. The first Stage (1993–2018) saw a slow increase in publications, while the second Stage (after 2018) showed a more rapid and steady rise.

Before 2018, this research area had a relatively small number of publications, with less than 40 published works and citation counts under 1000 per year. However, since 2018, there has been a significant increase in the number of publications, with 200 published works per year and citation counts reaching an impressive 5000 annually by 2023. The surge in publications related to Sustainable Agriculture and New Technology after 2018 can be attributed to several key factors, including heightened concerns about climate change, advancements in digital agriculture, and increased policy support for sustainable farming practices. Innovations such as precision agriculture, AI-driven tools, and IoT applications have significantly contributed to this rise, alongside global initiatives like the EU's Farm to Fork Strategy and the UN Sustainable Development Goals (SDGs). Adopted in 2015 as part of the 2030 Agenda for Sustainable Development, the SDGs consist of 17 goals designed to address critical environmental, social, and economic challenges, with several goals directly influencing sustainable agriculture. Key SDGs, such as SDG 2 (Zero Hunger), SDG 12 (Responsible Consumption and Production), SDG 13 (Climate Action), and SDG 9 (Industry, Innovation, and Infrastructure), have been pivotal in driving research and the adoption of new technologies in agriculture. The COVID-19 pandemic also highlighted vulnerabilities in global food systems, prompting a shift towards more resilient and sustainable agricultural models. A bibliometric analysis of this trend typically involves extracting data from academic databases, analyzing publication counts, citation metrics, and identifying key research themes, using tools like VOSviewer and Scopus to visualize growth and collaboration patterns.

Fig. 5 provides a comprehensive overview of the author keywords associated with sustainable agriculture and new technologies. This domain is closely linked with precision agriculture, smart farming, machine learning, and the Internet of Things. Moreover, the recent advancements in artificial intelligence have also been associated with sustainable agriculture.

Fig. 6 shows the simplified diagram outlining the role of new technology in sustainable agriculture.

8. The impact of emerging technologies on agriculture: opportunities, risks, and mitigation strategies

CRISPR, which stands for "clustered regularly interspaced short palindromic repeats," is a genome-editing technology that enables scientists to modify an organism's DNA. Genetic editing technologies like CRISPR have the potential to revolutionize crop disease resistance by facilitating the development of genetically modified crops that are more resilient to pathogens and pests. For instance, researchers have used CRISPR to enhance rice and wheat resistance to bacterial blight and powdery mildew, diseases that can lead to significant yield losses [123]. Beyond combating diseases, AI-driven solutions are transforming agricultural supply chain management by optimizing logistics, forecasting demand, and identifying inefficiencies. AI-powered systems, such as machine learning algorithms, can predict the onset of crop diseases, allowing farmers to take proactive measures and reduce post-harvest

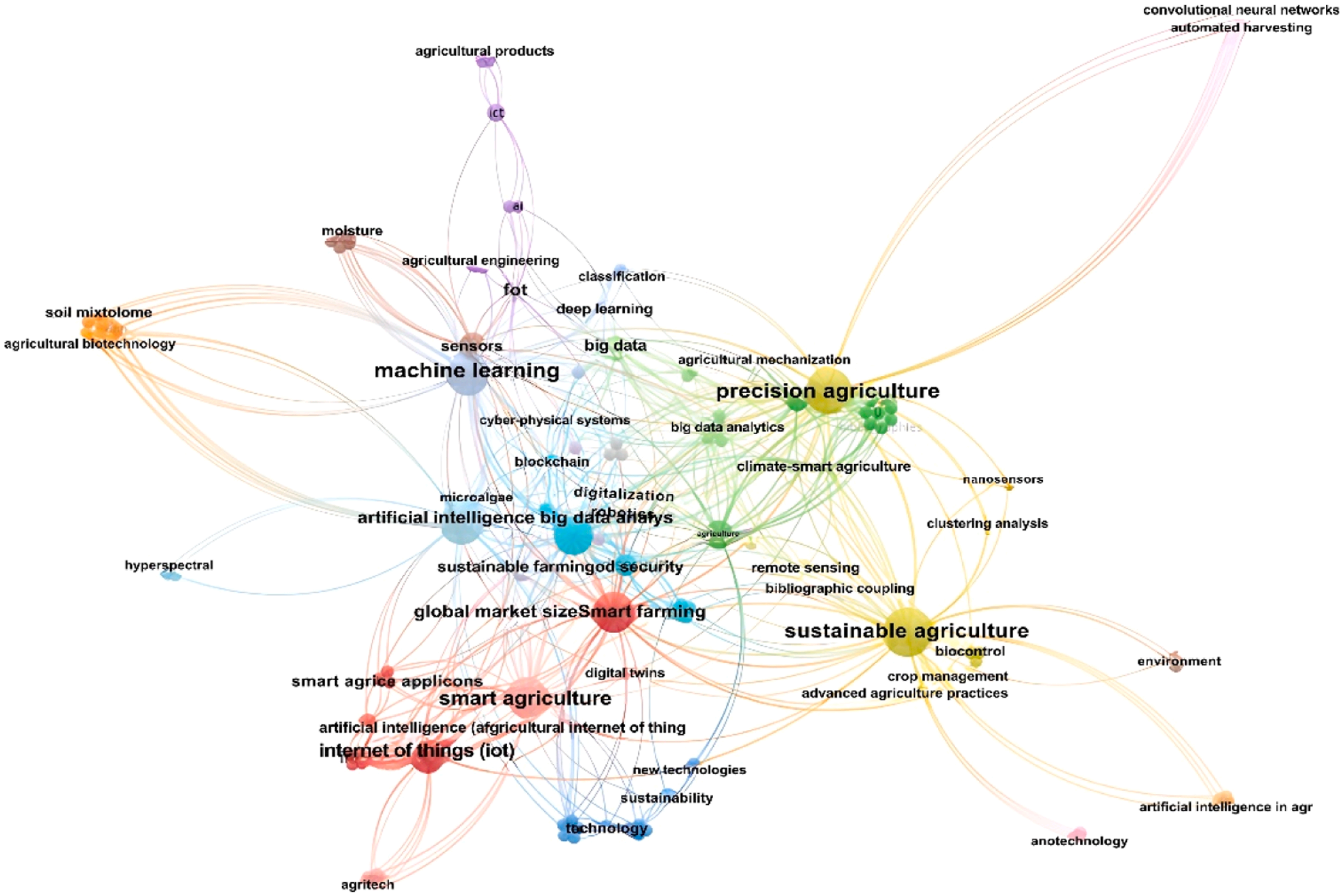

Fig. 5. A comprehensive overview of the author keywords associated with sustainable agriculture and new technologies.

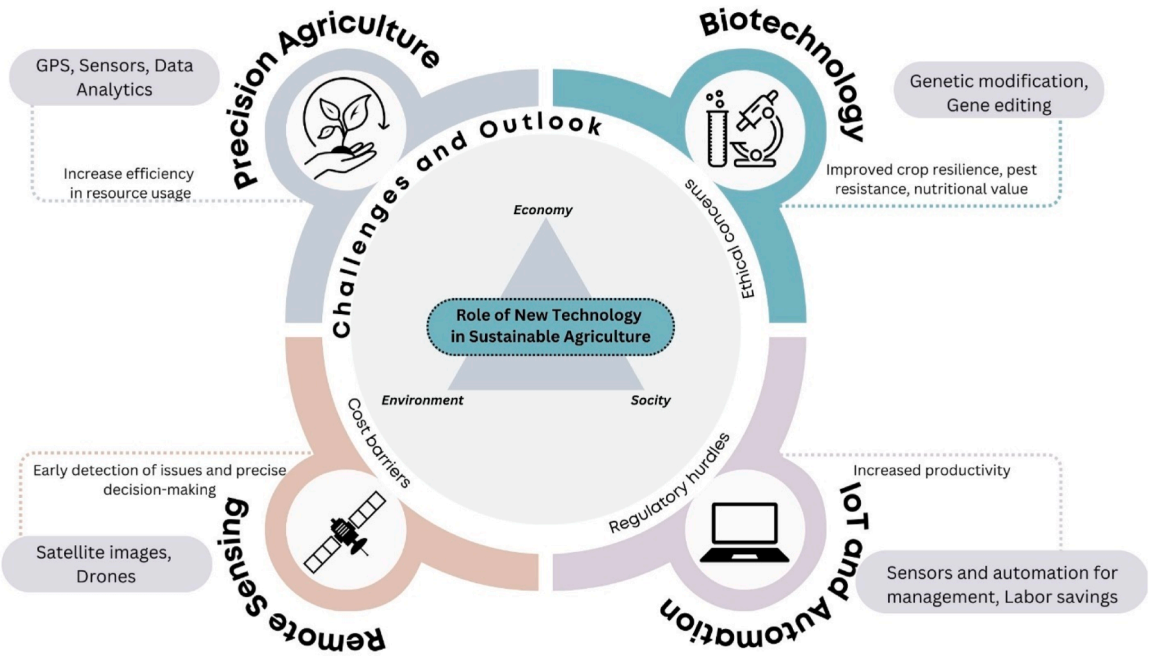

Fig. 6. A simplified diagram outlining the role of new technology in sustainable agriculture.

losses [124]. The integration of genetic editing with AI tools in agriculture holds the potential to produce more resilient crops and more efficient supply chains, both of which are crucial for addressing global food security challenges [125].

Small-scale farmers in Asia have increasingly adopted emerging agricultural technologies. For example, initiatives like the mobile-based precision farming platform mKrishi by Tata Consultancy Services in India have demonstrated how smallholder farmers can boost yields and reduce input costs through data-driven decision-making [126]. Similarly, low-cost sensors for soil health monitoring, implemented in the Philippines through projects supported by the International Rice Research Institute (IRRI), offer farmers valuable insights to optimize resource use [127].

However, the long-term consequences of these technological interventions on local economies, labor markets, and social structures in rural communities remain a concern. Research suggests that while agricultural technologies may boost productivity, they can also lead to labor displacement. This was evident in Southeast Asia, where the mechanization of farming led to challenges for small-scale farmers, particularly those lacking access to reskilling opportunities [128]. Additionally, the economic benefits of adopting such technologies often disproportionately favor wealthier farmers, exacerbating income inequality within rural areas unless accompanied by policies designed to ensure inclusive growth [129].

Technological failures in agriculture, such as equipment malfunctions, data breaches, and inaccurate weather predictions, can have significant consequences for farmers. To mitigate these risks, strategies like regular maintenance of machinery, robust cybersecurity for farm management systems, and diversifying weather data sources are crucial [130]. Additionally, using backup systems, redundant IoT devices, and continuously monitoring AI models can help minimize downtime and prevent errors [131]. Ensuring supply chain flexibility through diversified partnerships and leveraging technologies like blockchain for transparency can further protect against disruptions [132]. As technology evolves, ongoing investment in maintenance, training, and risk management will be vital to maintaining operational stability [133].

9. Conclusions

The agricultural sector stands poised for significant growth with the advent of novel technological advancements such as precision agriculture and enhanced supply chain management. These innovations are crucial for modernizing farming operations, yet their full potential remains largely untapped in developing regions, including parts of Africa and Asia. A bibliometric analysis underscores the interconnectedness of precision agriculture, smart farming, machine learning, and the Internet of Things, highlighting the need for future research to focus on adapting these technologies to the unique agronomic and socio-economic contexts of developing countries. Ensuring affordability and accessibility is vital to prevent smallholder farmers from being left behind in this technological revolution. Public-private partnerships can play a pivotal role in facilitating technology transfer and knowledge sharing. Additionally, targeted instructional programs are essential for equipping local farmers with the skills to leverage these emerging technologies effectively. Addressing ethical and governance concerns, such as data privacy and bioethics, is also crucial, especially in regions with less robust regulatory frameworks. A comprehensive approach that integrates technological, ethical, and socio-economic considerations is essential for advancing sustainable agriculture and achieving meaningful progress in developing countries.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Author contribution declaration

All authors contributed to writing and editing the manuscript.

Data availability

No data was used for the research described in the article.

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