



Impact of environmental technology on sustainable agriculture and food production

Pranabesh Ghosh¹, Abhishek Konar^{1*}, Tahsina Tabia¹, Pallabi Banerjee²

¹ School of Life Sciences, Seacom Skills University, Santiniketan, Bolpur, Birbhum, West Bengal, India

² Department of Chemistry, Seacom Skills University, Santiniketan, Bolpur, Birbhum, West Bengal, India

Corresponding Author: Abhishek Konar

DOI: <https://doi.org/10.66856/ijaps.2026.8.2.8115>

Abstract

Today, Agricultural systems worldwide are facing unprecedented pressures from climate change, natural resource depletion, and increasing food demand. Environmental technologies have emerged as critical enablers of sustainable intensification by enhancing productivity while minimizing ecological degradation. This review synthesizes recent advancements in digital agriculture, smart irrigation systems, controlled-environment agriculture, and biotechnology-driven climate-resilient crops. Digital agriculture, through remote sensing, geospatial analytics, artificial intelligence, and smart sensor devices, enables data-driven decision-making that optimizes resource use and reduces environmental footprints. Smart irrigation technologies integrating satellite-based monitoring, automated controllers, and solar-powered systems significantly improve water-use efficiency and mitigate groundwater depletion. Controlled-environment agriculture enhances productivity per unit area while reducing pesticide dependence and water consumption, though energy requirements remain a critical consideration.

Advances in molecular breeding, genomic selection, microbiome engineering, and biofertilizers contribute to the development of stress-tolerant crops and improved nutrient-use efficiency. Collectively, these innovations demonstrate substantial potential to reduce greenhouse gas emissions, enhance resilience to climatic variability, and promote sustainable resource management. However, lifecycle trade-offs, technological accessibility, and governance challenges must be addressed to ensure equitable and environmentally sound implementation. Future research should prioritize integrative system approaches, renewable energy integration, digital inclusivity, and ecological sustainability metrics to strengthen global food system resilience.

Keywords: Precision agriculture, remote sensing, controlled-environment agriculture, renewable energy, sensors, biotechnology

Introduction

Today's challenges in agriculture stem from climate change, the increasing global population, and the depletion of natural resources. The United Nations projects that the global population will reach almost 9.7 billion by 2050, applying even more pressure to the food production system. This challenge of feeding a growing population also contributes to climate change^[1]. However, Climate change and food production will globally impact for food production. Positive changes to global agriculture will be required to be implement with both of these challenges in mind. A major component of "digital agriculture" is the collection and analysis of data in real-time, which is used to improve both the productivity of the farm and productivity of the farm's use of inputs (such as fertilizers, pesticides, and water) in a way that minimizes the impact on the environment. Also, other digital components of agriculture that improve the efficiency of farm operations and reduce the chemicals fertilizer uses and prevent soil and water pollution from chemical substances is the use of satellite images, unmanned aerial vehicles (UAVs) and even improved farming implements that utilize "smart" technologies like the Internet of Things (IoT) to optimize the use of inputs^[2-4].

In dry places, sustainable practices in farming are strongly affected by a lack of fresh water. In farming fresh water used is seventy percent of all freshwater used. Smart irrigation consists of soil moisture sensors, automatic controllers, and climate-based scheduling, is one of the best

ways to save water and reduce the ground water use for irrigation along with the energy costs of irrigation^[5-7]. Another way for low carbon practices to become widespread in developing nations is the integration of solar powered pumps. Vertical farming and other greenhouse methods, are examples of Controlled Environment Agriculture (CEA) and are yet another innovation. CEA allows farming to occur year-round, while the farmer can decide to use no or low pesticides.

However, CEA has a significant role for energy demand, making the use of renewable energy imperative to ensure the practice is sustainable^[8-10]. Biotechnology Improvements will be crucial for increased resilience and sustainability. There is a growing of tools available to molecular breeding, genomic selection, gene editing and microbiome engineering. These tools have enabled the crops development with enhanced traits like stress tolerance, improved nutrient use efficiency, and increased resistance to pests and diseases. The use of biofertilizer and plant growth promoting rhizobacteria are examples of ways to reduce the use of synthetic fertilizers and therefore, nitrous oxide emissions while also improving soil health^[11, 2, 7].

New technological innovations in environmental science have the strong to transform numerous fields. However, they need to be assessed in regard to the related socio-economic issues, including governance. Different Factors related to cost, digital illiteracy, the lack of infrastructure, and environmental impacts during the various phases of the product life cycle can hinder the equitable adoption of

innovations. Thus, a combination of policy initiatives addressing equitable social inclusion, technological advancement, and ecological sustainability will be required in the future for better resilience in food systems. In this regard, the review focusses on the current state of environmental technologies in sustainable agriculture and food production, highlighting the current trends and future research needs for a socially equitable and environmentally sustainable approach [11].

Digital Agriculture: Toward Data-Driven Sustainability:

Digital agriculture is the incorporation of state-of-the-art Information and Communication Technology (ICT), automation, and data analysis within agricultural processes. The world’s agricultural supply system faces climate change, natural resource depletions, and increasing demand of food supply, digital agriculture provides the necessary tools for the world’s farmers to manage the environment and supply system. With the combination of real-time data and the ability to analyse farm inputs with digital tools, climate-smart agriculture becomes possible. Artificial intelligence and sensor integration most practical common examples of remote sensing and smart sensing systems. These systems enable farmers to measure their conditions with unprecedented levels of accuracy and timeliness [2].

1. Different Technologies in Digital Agriculture

Digital agriculture compresses broad area, including global positioning systems (GPS), geographic information systems (GIS), remote sensing device, unmanned aerial vehicles (UAVs), Internet of Things (IoT) devices, machine learning algorithms, robotics, and cloud computing. These modern tools facilitate site-specific crop management, predictive analytics, and automated interventions. This modern tool reduces waste, lowers production costs, and minimizes environmental contamination. According to Wolfert et al. (2017), big data and smart farming technologies have the potential to significantly promote agricultural proficiency and sustainability by integrating field-level data with advanced analytics. Digital platforms also enable improved supply chain transparency, market forecasting, and traceability. Blockchain technology and farm management

software systems contribute to food safety and logistical optimization. Thus, digital agriculture extends beyond field operations and supports the entire agri-food value chain [2, 12].

1.1 Remote Sensing and Geospatial Technologies

In agriculture, remote sensing and geospatial technologies are crucial, they provide information about the crop and soil condition and environmental factors that exist. Satellite images and drone sensors, as well as airborne sensors, collect and analyse multispectral and hyperspectral data. This analysis is used to identify and assess certain vegetation indices, including the Normalized Difference Vegetation Index (NDVI), where plant vigour, biomass, and stress levels can be determined. Remote sensing data, combined with topographic, soil, and climatic information, is used in Geographic Information Systems (GIS) to develop detailed maps of agricultural fields as management units. These maps are used to develop and guide variable-rate technologies (VRT) in agricultural fields. For instance, a GIS field map of an agricultural unit (field) can determine the location of a zone with a nitrogen scarcity in a field and can prescribe the precise application of nitrogen fertiliser to the field, thereby minimising the potential for nitrogen pollution of surface water and groundwater from agricultural return water [14, 15].

Remote sensing is beneficial to irrigation management through estimating soil moisture. Farmers can easily calculate how much water their crops will need and how to time their irrigation using a combination of satellite and weather data. The Food and Agriculture Organisation states that digital tools in water management is an important aspect in sustainably managing water use in a growing economy (2017). Drones (Unmanned Aerial Vehicles) have the ability to monitor crops and provide high resolution images of the agriculture fields. Drones can see pests, disease, and nutrient deficiencies. When remote sensing is used with ground-based practices, the result is better decisions, i.e. better use of climate and reduction of unfavourable impacts from climate change [14]. Figure 1, shows Remote Sensing and GIS Workflow and its benefits in Agriculture.

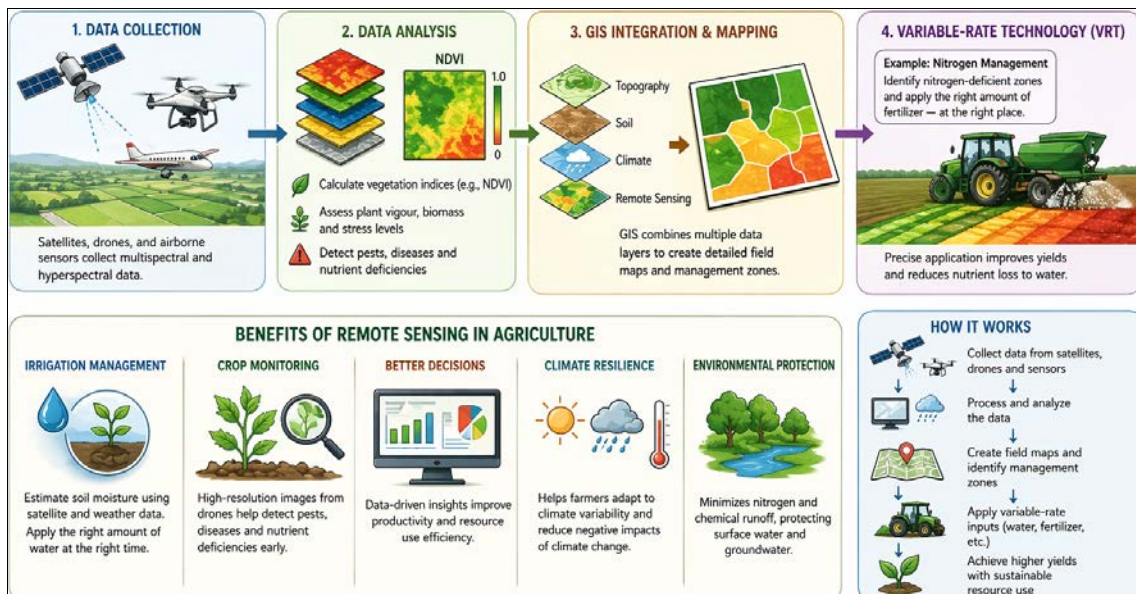


Fig 1: Remote Sensing and GIS Workflow and its benefits in Agriculture

1.2 Artificial Intelligence Applications (AI)

Some AI tools used in agriculture include predictive analytics and decision-support systems. These tools can analyse data from sensors and satellites. This allows the data to be used to predict patterns and outcomes. These shifts farming from responsive to proactive management. Based on an algorithm of a particular historical weather pattern and soil condition, AI can forecast crop yields, diseases, and the optimum time to plant. Image recognition AI can be used to health problems of plant and assess the health of crops. AI models can diagnose diseases more exactly and quickly than human who look at the plants.

AI can help recommend how and where to move fertiliser (also cutting down on the use of nitrate fertiliser, which is a greenhouse gas) to help plants use nutrients more efficiently. Sustainability can be improved using robotics with AI. For example, autonomous tractors, robotic harvesters, and smart spraying robots reduce dependency on human labour and increase operational efficiency and sustainability. AI tools can assess and provide data as to which fields to plant. This helps with a more efficient use of resources than methods based on intuition [2].

1.3 Smart Sensors device

Smart sensor devices allow effective data collection in digital agriculture. These devices include sensors that estimate moisture, temperature, humidity, pH, nutrients, and

atmospheric conditions in real time. These sensors are connected through IoT, and the sensor information is sent to the cloud for analysis and visualisation. Soil moisture sensors allow for effective water management by providing information on the water availability in the root zone. This means that under-irrigation or water wastage will not occur. Greenhouses, and controlled environment agriculture, benefit from temperature and humidity sensors, which enable microclimate management. This way, farmers can monitor and balance soil nutrients to avoid leaching. Rainfall, wind speed, and solar radiation sensors, which are part of weather stations, also enable effective crop modelling, and the prediction of crop diseases [2].

Sensor technology can track health, motion, and feeding behaviour and help farmers spot health issues before they become more serious. This saves money and increases productivity. IoT technology can automate the use of smart sensor networks and help with irrigation, smart fertilisation, and pest control. When combined with AI, these systems can help with smart, real-time guiding. Farmers can use a combination of sensors, mobile technology, and cloud computing to monitor their farms and have control of their farm's sensors. The systems can be costly, require great, and continuous power, and present cyber security vulnerabilities. However, the more cost-effective wireless and sensor technology has increased its availability to farmers, and also increased the potential for its use [2, 10].

Table 1: Application of Technologies in Digital Agriculture and Their Functions [2, 10].

Technology	Application in Agricultural field	Sustainability Contribution
GPS	Help in Field mapping	Accurate input positioning; less fuel and overlap
GIS	Analysis of field variability and management zoning	It Reduced nutrient leaching; targeted irrigation and fertiliser application
UAV	ET estimation and stress detection.	It improved irrigation system
Satellite	Crop health monitoring	It helps reduce the usage of chemicals and early illness detection
AI	Yield prediction and disease detection.	Farm management that is proactive
Robotics & Automation	Automated harvesting and precise spraying.	Decreased labour cost; reduced use of herbicides.
IoT	Monitoring soil pH and moisture.	Effective handling of nutrients and water; decreased waste

Smart Irrigation system and Water Management

Sustainable agriculture relies heavily on effective water resource management. Advanced irrigation technology integrates multiple soil, plant, and weather sensors, connectivity features such as wireless and satellite networking, and control mechanisms including valves, pumps, and controllers to automate water delivery based on timing and location. Overall, these technologies strive to improve water-use efficiency, sustain or enhance yield and quality, decrease energy and labour costs, and enhance farm and catchment scale planning data collection. Numerous field studies and meta-analyses demonstrate sensor and data irrigation technology to be effective on a range of crops from different climates, although not uniformly [15-17].

1. Remote Sensing and Satellite-Based Monitoring

Using remote sensing such as satellites, airborne sensors, or drones can provide repeated and synoptic measurements of crop and water-stress indicators (canopy temperature, vegetation indices, and evapotranspiration estimates). The two primary functions in irrigation management are (a) mapping and analysing spatial variability in and between fields so that irrigation can be zoned (defining management units), and (b) determining crop water demand through water-balance or evapotranspiration (ET) models. Satellites

(ex. Landsat, Sentinel, MODIS) provide images that allow users to derive vegetation indices (NDVI, NDWI) and surface temperature; these indices are related to biomass and water stress and can be converted into ET estimates using various energy balance or empirical methods. When integrated with local weather/ soil/ crop data, satellite ET will provide an estimation of actual water use, thus identifying areas that are both over- and under-irrigated. This is crucial not only for on-farm optimisation of irrigation systems, but also for accounting water use at the basin level. The satellite monitoring ET method is also scalable to close monitoring gaps, unlike sites that only have a few water meters and gauging stations [17].

These methods can be directly applied in a field environment as remote sensing products and field systems work together. For a given field, satellites delineate the irrigation zones or identify an irrigation anomaly, and then soil moisture sensors, NDVI sensors, or other field devices are used to refine the management for a given irrigation area or zone [18].

Drones are useful for conducting surveys when satellites aren't able to provide the information needed due to limitations with resolution or revisit, as well as the presence of cloud cover. However, there are challenges when operating with these devices, such as the remote sensing

outputs and how to best incorporate them into actionable twchs for the emitter or zone level (downscaling). As well, challenges remain with how to best handle the presence of cloud cover and the stage of vegetation, and finally, with how to integrate different and diverse streams of data into user-friendly farmer devices for decision making ^[18, 19].

2. Automated Irrigation Controllers system

Some controllers, which could be automated, incorporate sensing elements and logic to make decisions, and then tie those to an actuator such as valves and pumps. These can be rudimentary controllers like soil moisture threshold switches, to sophisticated ones that combine weather forecasting, crop coefficients, evapotranspiration, and machine learning predictive models. These controllers can be open loop or closed loop. Open loop controllers are model-based or scheduled controllers that don't have soil feedback. Closed loop controllers incorporate feedback from soil or plant sensors. Many of the modern systems use a combination of the two. Some of the most common sensors used are volumetric soil moisture sensors (capacitance, TDR), surface/soil moisture sensors, tensiometers, leaf wetness or plant water potential sensors, soil moisture controllers or flow, and pressure sensors. Communication layers can be short range radios such as LoRa, and Zigbee, cellular or GSM, or Wi-Fi. More recently, low power wide area networks (LPWAN) have been used as the communication method of choice for remote and rural sensing. From some of the studies previously done, soil moisture-based control systems have been shown to reduce rainfall events that are not needed. With the right configuration, water and energy can be saved. Good success requires proper placement of sensors, calibration of the sensors, and proper controller logic to be utilised. Automated timers or controllers that do not capture the local variable are poorly configured, and such systems will increase water use, thus requiring more calibration and adaptive algorithm systems ^[20, 21].

Predictive control, in conjunction with machine learning, can help optimise irrigation and crop stress management by reducing overwatering. Predictive control systems create models using weather forecasts and crop historical data to trigger preemptive water irrigation. For practical use by farmers, these systems should have simple interfaces like mobile apps and should be integrated into farm management software. Advanced irrigation systems come with barriers like initial costs, maintenance, sensor drift, and a lack of services. Technical and economic barriers can be overcome with high crop water costs/limited water availability. Positive economic outcomes can be achieved depending on the value of the crop and the scale of the farm ^[20, 21].

3. Solar-Powered Irrigation

The photovoltaic (PV) arrays equipped on diesel and electric pumps can be used to directly power pumps, or power them through battery or storage systems, and as such, power diesel and electric pumps directly, or indirectly, through batteries, power storage, and solar can be used to directly power or indirectly power, through batteries and storage systems, pumps, and as such, power diesel and electric pumps directly, or indirectly, through batteries, power storage, and solar arrays. In areas where operational fuel costs and greenhouse gas emissions are high, photovoltaics may provide a solution to reliable rural

irrigation in energy-scarce areas. The potential of SPIS's to expand irrigation and improve smallholders' livelihoods (especially when properly sized and financed) spans the possibilities of the FAO and other agencies. Design considerations ^[22, 23]:

- **Matching pump and PV:** Direct-drive PV pumps require matching pump power curves to solar output; battery or DC-AC inverters add flexibility but increase cost and losses ^[22, 23].
- **Sizing:** Correct sizing requires irrigation demand assessment (crop, area, frequency), solar resource, and water source characteristics (head, flow) ^[22-24].
- **Storage:** Water storage (tanks) is often more cost-effective than battery storage for agricultural irrigation; tanks allow pumping during peak sun and irrigation during evenings or cloudy periods ^[22, 23].
- **Economics:** While operating costs are low, capital costs can be high. Financing models (credit, pay-as-you-go) and service/maintenance ecosystems are crucial for adoption ^[22, 23].

Challenges and caveats: Solar irrigation may create perverse incentives. Since solar energy has a near-zero marginal cost (at the point of use), farmers may over pump unless some combination of control mechanisms or pricing/quotas constrains water extraction. In the absence of institutional safeguards, the over-abstraction of groundwater is a documented risk. The long-term viability of solar irrigation is also impacted by pump maintenance, the seasonality of the solar resource, and the availability of technical assistance. Incorporating smart controllers (to match pumping to soil and plant needs and the availability of storage) into solar powered irrigation system (SPIS) technology increases efficiency and helps to avoid unnecessary pumping ^[22, 23, 25].

Controlled-Environment Agriculture

Controlled-Environment Agriculture (CEA) is an innovative method of crop production where all the variables that affect plant growth, like temperature, humidity, light, carbon dioxide (CO₂), and nutrients, are kept and monitored to ensure the optimal growth of the plant. CEA differs from traditional farming methods since CEA embraces non-variability of weather and CEA can ensure farming year-round which leads to increased number of crops grown and better quality of the crops grown. This CEA method includes greenhouses, vertical farms, and plant factories with artificial lighting (PFAL). Traditional farming methods lose large amounts of water and fertilizer while greenhouses, with the addition of some technical equipment (like automatic controlled ventilation and drip-controlled irrigation and fertigation systems), save large amounts of water and fertilizer and lose very little ^[26].

In vertical farming, crops are grown in multiple layers and are typically grown indoors in an urban environment. Vertical farms are typically equipped with LED lighting. It is very common for vertical farms to utilize some form of hydroponics or aeroponics to enable recirculation of water and nutrients to drastically reduce water usage (up to 90-95% when compared with traditional farming methods ^[27]). Vertical farms can be very efficient in land use; however, they can use a lot of energy when equipped with artificial lighting. Plant factories differ from vertical farms in that they are fully enclosed systems which enables climate and

lighting to be regulated and controlled to ensure uniform crops are produced that are pest free. Plant factories are very efficient for the production of leafy vegetables, herbs, and other high value crops; however, they require a high amount of technical management as well as high levels of financing to be feasible [27, 28].

CEA has numerous sustainability benefits. By using recirculating systems, water-use efficiency is improved. Also, with the help of monitored electrical conductivity (EC) and pH, nutrient management is enhanced. Controlled conditions result in decreased pesticide usage, and increased productivity per unit area. These features help make CEA especially useful in regions with land and water scarcity. Also, with climate uncertainty CEA is valuable. Despite the benefits, challenges stay, especially energy consumption. This is most challenging in fully indoor systems. CEA's sustainability depends on its energy efficiency. In addition, the use of renewable energy is vital to help in CEA's environmental performance. Overall, Controlled-Environment Agriculture helps to improve food production in a sustainable and climate resilient way [27, 29].

Biotechnology and Climate-Resilient Crops

Climate change poses serious threats to global agriculture through rising temperatures, erratic rainfall, soil salinity, flooding, and emerging pests and diseases. To sustain food production under these stresses, biotechnology offers powerful tools for developing climate-resilient crops. Advances in molecular breeding, genomic selection, microbiome engineering, and biofertilizer development are transforming crop improvement strategies. These approaches enhance tolerance to abiotic and biotic stresses while maintaining productivity and resource-use efficiency [30].

1. Molecular Breeding and Genomic Selection

Traditional forms of plant breeding are based on sequential phenotypic selection and can be lengthy due to uncontrolled variables in the breeding environment. Alternative options for breeding include integrating Molecular breeding, which streamlines the development of improved strains by utilising genetic markers in conjunction with traditional breeding methods. Molecular breeding supplemented by Marker-assisted selection (MAS) can help breeders obtain desirable traits (i.e., drought tolerance, resistance to salt, and diseases) by selection for specific linked DNA markers, all the while increasing selection precision and reducing breeding cycles. Identifying the genomic regions linked to complex traits of interest (i.e., heat tolerance and water-use efficiency) is made possible through the process known as Quantitative trait loci (QTL) mapping. For example, in crops like rice, wheat, and maize, targeted improvements of particular genes related to root architecture, osmotic adjustment, and stress-responsive transcription factors have proven successful [31]. By integrating stress tolerant genes with elite cultivars, breeders can improve the adaptability of the plant while also preserving its yield potential [30].

Genomic selection (GS) has made another leap forward. GS overcomes the limitations of MAS, or marker-assisted selection, which concentrates on only a handful of markers. GS incorporates markers throughout the entire genome and uses them to forecast breeding values. Meuwissen et al (2001) describe the use of statistical models for the integration of thousands of single nucleotide polymorphisms

(SNP) to predict breeding line performance prior to field testing. This methodology propels the breeding process by allowing for greater genetic gain over shorter time intervals. GS is invaluable for the assessment of drought tolerance and yield stability traits, which are influenced by many small effect genes. With the advent of wide-scale next-generation sequencing and high-throughput phenotyping, GS models for genomic prediction have become more accurate. The combination of pheno sensing technologies such as remote and imaging or video techniques has improved the measurement of plant stress variables in field experiments. With the addition of bioinformatics and machine learning, GS can define specific breeding objectives for optimal climate change adaptation [30].

Further, the phenomenon of breeding in molecular biology has been enhanced by the rapid progression of gene-editing technologies, particularly the CRISPR-Cas systems. With the aid of CRISPR, plant modification can be done with the utmost precision, as can target genes associated with stress tolerance and flowering time, as well as nutrient use efficiency. Unlike transgenic means of plant modification when altered genes are introduced, gene editing can be accomplished without the addition of any foreign DNA, which in certain parts of the world can reduce regulatory hurdles. Climate-resilient crops that can thrive and/or maximise their output in extreme heat are, therefore, a feasible outcome of these technologies [30].

2. Microbiome Engineering and Biofertilizers

Plants coexist with intricate communities of microorganisms in their rhizosphere, phyllosphere, and endosphere. These various microorganisms assist in the cycling of different nutrients, the growth of the plant, and the development of stress adaptations. The rationale of microbiome engineering is to modify plant-associated microbes in order to increase the adaptability and sustainability of crops. Plant growth-promoting rhizobacteria (PGPR) as well as mycorrhizal fungi are the main components of strategies based on the microbiome. These microorganisms improve the overall nutrients (especially nitrogen and phosphorus) by fixing atmospheric nitrogen, solubilising phosphorus, and producing growth-stimulating phytohormones. Additionally, they are able to assist in the plants' tolerances to drought, salinity, and heavy metal stress by aiding in the modulation of the plant's antioxidant systems and osmotic balance [32].

For the past 30 years, research has remained stable regarding the use of biofertiliser made from beneficial microbes, offering safer, environmentally friendly alternatives to conventional synthetic fertilisers. The use of biofertiliser has been encouraged by the FAO (2017) to enhance the efficiency of nutrient use and, conversely, reduce the greenhouse effect resulting from the use of synthetic nitrogen fertilisers. Microbial inoculation has been demonstrated in dry conditions to promote the growth and efficiency of water use of roots, and as a consequence, the survival of crops under water stress. Recently, the development of specific synthetic microbial consortia for particular crops and environments has been the focus of research. Furthermore, the latest developments in microbiome sequencing and metagenomics are identifying specific microbial communities associated with the so-called stress-resilient plants. The re-isolation and reintroduction of beneficial strains to targeted microbiomes are the goal of specific microbial solutions that scientists are seeking to adapt to the changing climate [32-34].

Soil carbon sequestration can also benefit from microbiome engineering. The potential positive effect of microbes on the decomposition of organic matter, as well as the stabilisation of aggregates, improves soil structure and increases the soil's ability to retain water. Improvement in structure and retention enhances the soil's resistance to erosion and the impacts of heavy rain. The complexity of ecological interactions must also be considered. Inoculated microbes

must be tailored to the specific soil, climatic, and crop genotype environments of the site. Testing in a range of agro-ecological environments is important to ensure that the inoculants will always function as designed. This complexity will also be reflected in regulatory standards and the quality control of the inoculants in order to ensure that the products maintain the confidence of the farmers [32].

Table 2: Biotechnology approaches and Climate-Resilient Crops [32].

Technology	Mechanism	Goal Parameters	Impact on Sustainability
Marker-Assisted Selection (MAS)	DNA marker-based selection	Drought and disease resistance crop	Faster breeding cycles
Genomic Selection (GS)	Genome-wide SNP prediction	Yield stability crop	Stress tolerance Higher genetic gain per unit time.
CRISPR Gene Editing	Targeted gene modification	Nutrient efficiency and heat tolerance crop	Precision breeding without foreign DNA
Biofertilizers (PGPR, Mycorrhiza)	Microbial nutrient mobilization.	Nitrogen fixation and phosphorus solubilization	Reduced synthetic fertilizer dependence

Environmental Technology and Sustainable Agriculture

Environmental technology is essential in the development of sustainable farming methods. Sustainable farming focuses on the current demand for food and finding ways to produce food for future generations. The technology focuses on improving the use of resources, minimizing pollution, and improving the ability of the ecosystem to adapt to climate change. Precision farming is an example of environmental technology and is defined as farming based on the use of remote sensors, GPS, and field sensors to improve the efficiency of farming activities. Precision farming is cost effective and significantly reduces pollution due to farming activities. According to efficiency and pollution studies, precision nutrient management improves the use of nitrogen and reduces the leaching of nitrate into groundwater [33]. Precision farming methods improve productivity and significantly reduce greenhouse gas emissions due to the use of fertilizers.

Smart irrigation technologies advance sustainable practices. These benefits include drip irrigation systems paired with moisture sensors and automatic controllers. These innovations deliver targeted irrigation. This system decreases water loss due to evaporation and runoff. The Food and Agriculture Organization (FAO 2017) explains the evolution of irrigation systems where water use can be improved by 30-60%. This is in contrast to older irrigation systems like surface systems. These systems are critical to maintaining productivity in areas with low water availability. The integration of renewable energy with farming systems is another critical component. With the use of solar-powered irrigation pumps and the use of biogas systems the reliance on fossil fuels is diminished and carbon emissions are lowered. With the adoption of renewable energy technologies, dependable energy is available in remote areas. The adoption of renewable energy in farming practices is one of the most used strategies to reduce emissions in farming practices. It is also true that innovations in technology that promote the health of the soil also are important in sustainable practices. Technologies that promote minimal tillage, soil explicit cover cropping, and recycling organic waste increase the health of the soil and increase the organic content of the soil. Improved soil health increases the soil's ability to sequester carbon, the water that is retained by the soil, and the nutrients that cycle

in the soil. Lal (2016) states that soil carbon restoration is the foundation of climate-smart agriculture and is the key to sustainable food security [33, 36].

Sustainable farming practices can be enhanced even further through supported biotechnology and bio-based inputs. By using biofertilizers, biopesticides, and microbial inoculants, farmers can decrease their use of synthetic chemicals. Alternatives even enhance microbial diversity in the soil and reduce the chemical residues found in contaminated foods and bodies of water. In conjunction with implemented environmental monitoring technologies, Integrated Pest Management (IPM) can be used to decrease pesticide use while still ensuring adequate protection of growing crops. New digital platforms and data analytics have begun to aid the farming community in practicing environmental sustainability. Informed and adaptable management decisions can be easily made by farmers with the help of climate advisory systems and farm management software that provide forecasts, pest alerts, and even market data. Such tools can assist farmers in withstanding the climate's volatility and extreme weather events. Although there are benefits associated with environmental technologies, farmers in developing countries often experience challenges associated with the limited availability of environmental technologies, the affordability compared to lack of necessary tools and the vague understanding of the associated technologies, and the unequal availability of environmental technologies within their communities. To create better farming practices through environmentally sustainable technologies, funding for research and improved technologies must be implemented, and effective farming practices must be prioritized by the farming community. By utilizing precision farming, bio-based inputs, and/or smart irrigation, farming can become more environmentally sustainable [33, 36].

Environmental Technology and Food Production

Food production now utilizes the latest in environmental technology to improve the efficiency of the food production process while decreasing the negative impacts on the planet and increasing the sustainable practices to support the planet long-term. New technology will also be key in maintaining the planet's natural resources and decreasing the negative impacts on the planet while allowing food production to

meet the world's increasing needs to supply food to a growing and changing world population. A key area of environmental technology enhancing food production processes is precision farming. This process uses GPS technology along with GIS and remote technology to gather and analyze data on varying conditions of the crops in real time and report them directly to the farmers. This real-time data allows farmers to find the most efficient practices for each area of their field and to stay in compliance with the sustainable use of chemicals by ensuring that irrigation, fertilizer, and pesticides are implemented according to the needs of the crops and not exceed their needs. Research shows that precision management of crop nutrients improves nitrogen-use efficiency and lowers the greenhouse gasses produced by the overuse of fertilizer ^[35]. This also helps the crops keep the soil and surrounding water resources safe during and after crop production ^[35, 37].

Drip irrigation, automated controllers, and soil moisture sensors that are incorporated into smart irrigation systems help promote sustainable food production by providing crops with just the right amounts of water. Water loss from evaporation and runoff is always a significant problem for irrigation, especially in arid and semi-arid areas. Therefore, the FAO (2017) asserts that irrigation loss and water scarcity should be a primary concern for those interested in food security. In addition to smart irrigation systems, the integration of environmental technology and renewable resources aids in sustainable food production and sustains the mitigation of climate change. Fewer fossil fuels are used and the carbon footprint from agricultural practices is reduced with the use of solar-powered irrigation pumps, wind energy systems, and biogas digesters. Renewable energy also eliminates reliance on fossil fuels and provides a consistent energy source for those areas that are not easily accessible. The IPCC (2022) considers the use of renewable resources in agricultural practices to be an essential approach in sustaining climate change ^[35, 37].

Technologies for the management of soil and plant nutrients is also a vital component to sustainable food systems. Innovations in the practice of conservation tillage, precision application of fertilizers, and systems that are used for composting are all instrumental in the improvement and conservation of soil to sustain the cycling of nutrients. Organic matter, when incorporated into soil, enhances water retention, the nutrients available to plants, and the soil's capacity to sequester carbon. In order for sustainable food systems to be implemented without compromising the climate's resiliency, the restoration of the soil's carbon stocks (substantial carbon stored in soil) is essential, according to Lal (2016). Biopesticides, biofertilizers, and microbial inoculants all reduce the use of synthetic chemicals and increase pollution. They also make the soil better. Controlled-environment agriculture (CEA) includes vertical farming and other greenhouses. They also CEA around the world to improve food supply. They improve the availability of food by providing the perfect temperature, light, and nutrients. These systems provide efficient food supply; however, the availability of energy causes the supply of food to no be sustainable ^[38].

Controlled Digital climate forecasting, farm management digitalisation and digital supply chain management increase the effectiveness of the technology and decrease the abundance of food after harvesting. Cooling chain technology and better storage systems reduce the waste of

food and increase the sustainability of the food systems. Moreover, the use of unmeasured environmental technology in food production is a defence against the climate. The environmental technology includes the use of more efficient energy systems and the more efficient use of the available resources. Less energy is used and the more efficient the use of the available resources the more efficient the technology. The use of sustainable innovative farming systems makes the food production systems more responsible to the environment ^[38, 39].

Future Research with Innovation Pathways

Future studies in the field of environmental technology and sustainable food systems should emphasise the integration of ecological and social systems with innovative technology and social systems. As the impacts of climate change, growing population, and resource exhaustion escalate, preserving food systems requires integrated, cross-disciplinary, technology-based research to support food systems in the long run. One important research area is climate-smart agriculture (CSA). Future research prospects should improve resilience of crops to extremely adverse conditions by refining systems for extreme event climate forecasting, crop modelling, and adaptive management. The Intergovernmental Panel on Climate Change (IPCC, 2022) stresses the importance of tech and institutional dualism for innovations that enhance productivity and improve adaptive and mitigative functionalities in balance. Research should also aim at developing crop varieties with better tolerance to drought, salinity, and heat stress using modern breeding and genotyping approaches. The pathways towards a more innovative future include digital agriculture and artificial intelligence (AI). Each component is isolated, but together with machine learning and autonomous systems, precision farming becomes a fully integrated whole. We need to focus on improving the systems and tools for smallholder farmers to develop the capability for greater levels of interoperability, real-time decision-support systems, and low-cost sensor networks. Wolfert et al. (2017) indicate that for data-driven agriculture to be fully actualised, there is a need for secure data governance and farmer-centric data governance frameworks. Sustainable soil management continues to be a priority for agricultural research. Advances in biochar, soil carbon sequestration, and regenerative agriculture have the potential to positively impact soil fertility and climate change mitigation. Restoring soil organic carbon stocks is crucial to achieving both food security and the reduction of greenhouse gases. Innovation in the future should focus on measurement and monitoring of soil health using advanced sensing and remote monitoring technologies. In controlled-environment agriculture (CEA), the focus of research should be on energy efficiency, the use of integrated renewable energy systems, and life-cycle assessment. The sustainability of systems will be improved with circular nutrient systems, greater efficiencies in LED lighting, and smart climate control systems. Improving energy-use efficiency is a priority for scaling inner vertical farming systems ^[2, 38, 37, 40]. Circular bio-economies show further potential. Resource efficiency and conservation of the environment can be achieved through the conversion of agricultural waste to bioenergy, bio-fertilisers, and other bioproducts. Sustainable production and waste absorption/bioproduction systems can be enhanced through further research into

anaerobic digestion and other microbial/nutrient recovery technologies. Additionally, focusing on equitable and scalable systems is an area of innovation, as many environmental technologies are currently out of reach for smallholder farmers due to increasingly high costs and the need for specialised system management. Research focusing on lean, modular systems and participatory innovation systems that use local systems will be prioritised. There is also a need for policy research focused on incentive systems, carbon credits, and green financing to create pathways for sustainable transition. Therefore, future pathways for research and innovation should focus on climate resilience, digital technology, restoration of the soil, energy efficiency through control technologies, and circular bio-regeneration systems. In conjunction with emerging technologies, the policies and frameworks needed will centre on the equitable and sustainable development of agri-food systems [38, 37, 41].

Conclusions

Modern agricultural systems are undergoing a fundamental transformation thanks to environmental technologies that allow for sustainable intensification in the face of resource limitation, climate change, and rising global food demand. This review shows that a multifaceted framework for increasing production while reducing environmental degradation is provided by digital agriculture, smart irrigation systems, controlled-environment agriculture (CEA), and biotechnology-based crop enhancement. However, advancements in energy efficiency and the incorporation of renewable energy sources are closely related to its sustainability. In the meanwhile, developments in microbiome engineering, CRISPR-based gene editing, genomic selection, molecular breeding, and biofertilizers offer potent tools for creating climate-resilient crops with enhanced stress tolerance and nutrient-use efficiency. These developments improve adaptability and lessen dependency on artificial inputs.

Biotechnology offers transformative tools for developing climate-resilient crops. Molecular breeding and genomic selection accelerate the development of stress-tolerant varieties, while gene-editing technologies enable precise genetic improvements. Simultaneously, microbiome engineering and biofertilizers promote sustainable nutrient management and enhance plant stress tolerance through ecological mechanisms. Integrating genetic and microbial innovations provides a comprehensive strategy for addressing climate challenges in agriculture. Continued research, investment, and inclusive policy support will be crucial to scaling these solutions globally. The sustainability of agriculture in the future will rely on integrated system techniques that integrate biotechnology, digital intelligence, renewable energy, soil restoration, and circular bioeconomy tactics. To make sure that technological advancement is in line with social justice and ecological integrity, interdisciplinary cooperation, participatory innovation, and evidence-based policymaking are crucial. Agriculture can make the shift to a future that is resource-efficient, socially inclusive, and climate-smart by integrating environmental technologies into comprehensive and resilient food system policies.

Acknowledgements

The authors are grateful to the Honourable Chancellor Madam of Seacom Skills University for completing this review work.

Conflict of Interest

The author declares no conflict of interest.

References

1. Intergovernmental Panel on Climate Change. Climate change 2022: Impacts, adaptation and vulnerability. Cambridge University Press, 2022.
2. Wolfert S, Ge L, Verdouw C, Bogaardt MJ. Big data in smart farming—A review. *Agricultural Systems*,2017;153:69–80.
3. Zhang N, Wang M, Wang N. Precision agriculture—A worldwide overview. *Computers and Electronics in Agriculture*,2002;36(2–3):113–132.
4. Ghosh P, Chatterjee S, Konar A, Chakraborty A. Improving sustainable agriculture and food security. In *Climate Change and Food Security*. GB: CABI, 2024, 55-74.
5. Evans RG, Sadler EJ. Methods and technologies to improve efficiency of water use. *Water Resources Research*,2008;44(7):04.
6. Food and Agriculture Organization. The state of food and agriculture 2020: Overcoming water challenges in agriculture. FAO, 2020.
7. Parvin S, Tabia T, Ganguly U, Roy A, Bhattacharya A, Das G, et al. Common Pollutants of Air and Water Mostly Affect the Sex Differentiation Pattern of Male Adult Zebra Fish. *Pollution Research*,2025;44(1-2):121-130.
8. Despommier D. The vertical farm: Feeding the world in the 21st century. Thomas Dunne Books, 2010.
9. Ghosh P, Konar A, Dalal DD, Roy A, Chatterjee S. Phytoremediation technology: A review. *International Journal of Agriculture and Plant Science*,2023;400:5-00.
10. Ghosh P, Konar A, Roy A, Dalal DD, Parvin S. Chapter 1: An overview of environmental remediation technologies for contaminated and polluted areas. *Research Trends in Environmental Science*,2024;16:1–31.
11. Tester M, Langridge P. Breeding technologies to increase crop production in a changing world. *Science*,2010;327(5967):818–822.
12. Konar A, Barwan M, Kaur J, Yasmeen M, Ghosh P, Gangul P, et al. Ethical Considerations in Food Science and Technology. In *Innovations in Food Science* (pp. 170-193). CRC Press, 2026.
13. Rouse JW, Haas RH, Schell JA, Deering DW. Monitoring vegetation systems in the Great Plains with ERTS. *Proceedings of the Third Earth Resources Technology Satellite-1 Symposium*, NASA SP-351, 1974, 309–317.
14. Mulla DJ. Twenty-five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosystems Engineering*,2013;114(4):358–371.
15. Ghosh P, Konar A, Chatterjee S, Roy A, Dalal DD. Role of plant pigments on human health and environment. *Research trends in multidisciplinary research*, 2023, 113-138.
16. Allen RG, Tasumi M, Trezza R. Satellite-based energy balance for mapping evapotranspiration with internalized calibration (METRIC). *Journal of Irrigation and Drainage Engineering*,2007;133(4):380–394.
17. Ghosh P, Konar A, Halder S, Shivaranjani DS, Kaur J. Impact of nanotechnology on the environment: A review. *Environ Sci Arch*,2024;3(1):152-163.

18. Bastiaanssen WGM, Menenti M, Feddes RA, Holtslag AAM. A remote sensing surface energy balance algorithm for land (SEBAL): 1. Formulation. *Journal of Hydrology*, 1998, 212–213, 198–212.
19. Mukherjee S, Chowdhury S, Ghosh P, Chatterjee S, Bhattacharya M. Air pollution has deep impact on plant pigments: A comparative study on differentially polluted areas of West Bengal. *Pollution Research*, 2018;37(3):690-693.
20. Dukes MD, Zotarelli L, Morgan KT. Use of irrigation technologies for vegetable crops in Florida. *HortTechnology*, 2010;20(1):133–142.
21. Muñoz-Carpena R, Dukes MD, Li Y, Klassen W. Field comparison of tensiometer and granular matrix sensor automatic drip irrigation on tomato. *HortTechnology*, 2005;15(3):584–590.
22. Burney J, Naylor R. Smallholder irrigation as a poverty alleviation tool in sub-Saharan Africa. *World Development*, 2012;40(1):110–123.
23. Chandel SS, Nagaraju Naik M, Chandel R. Review of solar photovoltaic water pumping system technology for irrigation and community drinking water supplies. *Renewable and Sustainable Energy Reviews*, 2015;49:1084–1099.
24. Konar A, Singh P, Ghosh P, Kaur J, Chakraborty S, Ganguly P. Role and importance of biopolymers in wastewater treatment and purification. In *Microbial applications in industrial wastewater treatment*. Springer Nature Singapore, 2026, 73-96.
25. Chakraborty S, Konar A, Tabia T, Ghosh P. Awareness of Environmental Issues through Artificial Intelligence. *International Journal of Environmental and Ecology Research*, 2025;7(2):29-37.
26. FAO. *Save and Grow: Cassava – A guide to sustainable production intensification*. Food and Agriculture Organization of the United Nations, 2013.
27. Kozai T, Niu G, Takagaki M. *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*. Academic Press, 2016.
28. Ghosh P, Chatterjee S, Choudhury S, Sarkar T, Sarkar A, Poddar S. Some roadside medicinal weeds as bio-indicator of air pollution in Kolkata. *Journal of Applied Biology & Biotechnology*, 2021;9(2):164-168.
29. Ghosh P, Konar A, Tabia T. *Multi-Omics Approaches in Wastewater Bioprocess Systems: Advancing Sustainability and Resource Recovery*, 2026.
30. Chen K, Wang Y, Zhang R, Zhang H, Gao C. CRISPR/Cas genome editing and precision plant breeding. *Annual Review of Plant Biology*, 2019;70:667–697.
31. Varshney RK, et al. Genetic gains in crops through genomics-assisted breeding. *Plant Science*, 2014;242:1–13.
32. Vessey JK. Plant growth promoting rhizobacteria as biofertilizers. *Plant and Soil*, 2003;255:571–586.
33. FAO. *The future of food and agriculture – Trends and challenges*. Food and Agriculture Organization of the United Nations, 2017.
34. Ghosh P, Chatterjee S, Konar A, Chakraborty A. Improving sustainable agriculture and food security. In *Climate Change and Food Security*. GB: CABI, 2024, 55-74.
35. Tilman D, Balzer C, Hill J, Befort B. Global food demand and sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*, 2011;108(50):20260–20264.
36. Lal R. Soil health and carbon management. *Food and Energy Security*, 2016;5(4):212–222.
37. IPCC. *Climate Change 2022: Mitigation of Climate Change*. Intergovernmental Panel on Climate Change, 2022.
38. Kozai T, Niu G, Takagaki M. *Plant Factory: An Indoor Vertical Farming System for Efficient Quality Food Production*. Academic Press, 2016.
39. Pal D, Tabia T, Konar A, Banerjee P, Ghosh P. Ecological Effects and Management of e-Waste: A Review. *International Journal of Ecology and Environmental Sciences*, 2025;7(4):74-86.
40. Ghosh P, Konar A, Tabia T. Multi-Omics Approaches in Wastewater Bioprocess Systems: Advancing Sustainability and Resource Recovery. *International Journal of Scientific Research & Engineering Trends (IJSRET)*, 2026;12(1):1-9.
41. Ghosh P, Konar A, Chatterjee S, Roy A, Dalal DD. Role of plant pigments on human health and environment. *Research trends in multidisciplinary research*, 2023, 113-138.