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Revolutionizing crop production: AI-driven precision agriculture, vertical farming, and sustainable resource optimization

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Abstract

Sustainable agricultural practices are becoming increasingly vital as the global population keeps rising at an unprecedented rate. In light of the ongoing climate crisis, the frequency of extreme weather events has intensified, posing significant threats to farmers and their livelihoods across the globe. As these challenges multiply, many traditional agricultural methods struggle to keep pace, highlighting the necessity for innovative solutions. These new sustainable practices can be quite complex and often present challenges for farmers to implement effectively. This may be attributed to various factors, including a lack of willingness to change established methods, accessibility issues regarding new technologies, or even a deficit in knowledge about how to adopt these practices successfully. In this context, the potential for using cutting-edge technologies in agriculture becomes increasingly relevant. These technologies offer promising alternatives that can simplify various processes, such as planning and modelling agricultural practices, thereby making it easier for farmers to adapt. For instance, a mixed reality headset could serve as an invaluable tool by providing users with detailed information about optimal planting spacing between seeds. This type of immersive technology can enhance understanding and application in the field. On a different note, unmanned aerial systems, commonly known as drones, could be employed to gather NDVI (Normalized Difference Vegetation Index) data. This data is crucial, as it enables a more in-depth analysis of crop production, giving farmers actionable insights into their agricultural practices. It is important to consider three hypothetical factors that may hinder the adoption of these technologies: price, motivation, and knowledge. To evaluate the impact of price alongside other technological factors, a systematic approach might include a second round of analysis focused specifically on motivation. Meanwhile, the final round of analysis could completely omit all prior explanations to gauge raw responses effectively. In terms of practical applications, these technologies could play a significant role at three different stages of system development. First, they can assist users in comprehending the technology, facilitating proper training to maximize their efficacy. Second, these systems can help assess whether additional factors or technologies are necessary for achieving similar results in agricultural productivity. Finally, such technologies could serve as a form of external analysis, evaluating the potential future applications of the agricultural system. Altogether, the implementation of these advanced methods provides a rigorous assessment and serves as compelling proof of the significance, feasibility, and innovative nature of this ongoing study in sustainable agriculture. (Chowdhury *et al.*, 2023) [4].

Keywords: Sustainable agricultural practices, climate crisis and farming, innovative agricultural technologies, mixed reality and drones, adoption barriers and motivation

Introduction

Agriculture has been the backbone of economies since time immemorial, with its foray into the Industrial Revolution engendering unprecedented crop yields due to the advent of mechanized farm equipment. Subsequent years heralded the Green Revolution, spearheaded by genetic hybridization and synthetic fertilizers, propelling agricultural outputs and forestalling worldwide famine. In the 21st century, agriculture has cast off the antiquated and unproductive practices of the past, riding on the ground-breaking technology of Artificial Intelligence (AI) that deigns to revolutionize the nascent Fourth Green Revolution. Astonishingly, global food requirements are expected to skyrocket by 70 percent by 2050, necessitating a commensurate crop production increase (Chowdhury *et al.*, 2023) [4].

However, such a trajectory is fraught with impediments borne out of the exacerbating vagaries of climate change, burgeoning water and land restrictions, and ancestry

The Role of AI in Agriculture

Since the turn of the twentieth century there has been significant progress both in the agricultural field and urban populations - it is predicted that by the year 2050, 68% of the population is going to live in urban areas. With the skyrocketing demand for crops, it's paramount to ensure the efficient production of crops. Sustainability is also a pressing concern in agriculture, especially with the emergence of new diseases, pests, and unpredictable climate change. Precision farming is an area where crops can be produced with the least resources. The emergence of Information Communication Technologies and Internet of Things (IoT) has enabled the phased evolution of precision agriculture into a much broader perspective, called smart agriculture. There is no globally accepted definition in the academic literature about smart agriculture. Smart agriculture integrates precision farming, IoT, big data, and artificial intelligence to cultivate crops with improved productivity and sustainability throughout the entire crop cycle. Artificial Intelligence (AI) is the driving force for this, as most of the smart devices are based on machine learning (ML) and artificial neural networks (ANNs). This special issue will bring together the latest developments for transforming agriculture into smart agriculture and, therefore, be interesting to computer scientists and agricultural engineers.

The dissemination of agriculture is becoming more prevalent with smart farming, where drones, sensors, RFID tags, GPS technology, robots, smart gadgets, chemical application tools, and many more devices are the backbone. To that end, agricultural systems can be transformed from traditional farming methods into smart farming. This leads to a positive change in the agriculture sector so that the utilization of resources can be managed efficiently. Several recent surveys have elaborated on the technology used in precision agriculture, current trends, challenges, and so on; however, the role of AI in smart agriculture and smart fertilization technologies for different types of crops are critical to the best of knowledge. Smart devices are designed to autonomously monitor and adapt to conditions in real-time, or very close to real-time, to inform growers and drive action plans (Neranjan Thilakarathne *et al.*, 2022) [26].

Understanding AI Technologies

Revolution has always been the catalyst for progress. Recent technological advancements have paved the way for agriculture's renaissance. AI-driven precision agriculture has been transforming how crops are cultivated and monitored, posing a disruptive challenge to traditional farming. The discourse on precision agriculture is coupled with the essential understanding of AI technologies, particularly from the perspective of stakeholders interested in navigating this transformative landscape. Designing informed policies necessitates knowing how various AI technologies can be harnessed and what their implications are (Chowdhury *et al.*, 2023) [4]. This review endeavors to delineate AI technologies, provide immersive insights, and lay the groundwork for stakeholders looking to capitalize on revolutionary developments.

The backbone of precision agriculture is a constellation of autonomous devices that gather data on crops, soil, and weather. This technology-driven approach to agriculture is becoming embedded as a standard practice for those concerned with improving agricultural productivity and environment sustainability (Neranjan Thilakarathne *et al.*, 2022) [26]. The adoption of precision agriculture receives particular notice in policies governing agriculture, while stakeholders are increasingly interested in how it affects agricultural practices. Therefore, it is crucial to advance the conceptual understanding of precision agriculture and focus on machine learning-driven precision agriculture.

AI Applications in Crop Management

Modern AI system assists farmers in estimating advanced crop management strategies. AI techniques are widely used in precision agriculture to help crop improvement. From detection of crops to the estimation and distribution of agricultural inputs, models were widespread. One of AI's primary benefits is scalability. Smallholder farmers in developing nations regularly utilize field sensors or devices to gather agricultural information, from easy plastic tubes containing water to some of the most costly multipart farming machines. Researchers have created cutting-edge systems to meet various realistic requirements, offering an automatic and adaptive solution to different farming practices (Chowdhury *et al.*, 2023) [4]. Responsive methods help with process instructions and growers' preferences. Against widely used inferior systems, complex methods generally have more moderate bias.

Automation is possible utilizing sophisticated devices that interact and function together. Initial systems attended exclusively to one vertical and did not account for possible impacts on the environment. Systems on the market are generally independent technological fixtures developed by various suppliers that do not readily interlink. Recent breakthroughs in precision agriculture and smart farming have highlighted the significance of automated systems that could be personalized and adaptable across the whole vertical farm. Glucose partial actual systems are fundamental for controlling the climate, irrigation, and artificial lighting coordinating crops' development. Vertical farming comprises advanced automation such as high-resolution imaging temperature sensors and hyperspectral cameras. As such, they have pushed crop planning, nutrient delivery, and analysis of the atmosphere beyond that realm of chance.

Low expense modelling system is demanded by the procedure. All substance of these tablets may be predicted utilizing a mixture of data on the earth, the weather, and a particular management technique. This demand is utilized to obtain comprehensive variable decision data and optimize a computer AI-based strategy, which is important to ensure that beginning at prices reasonably predictive policies. An improved method of optimizing AI-based agricultural decisions is presented, called the decision design system (Neranjan Thilakarathne *et al.*, 2022) [26]. Given an issue, the structure of determination shapes the intelligent search over a wide spectrum of complicated policies, resulting in high-performing, low expense, and particularly interpretable choices. Decisions composed of tree-based models are developed, except for arbitrary woodland systems, on which there are no particular constraints.

Challenges of AI Implementation

Artificial intelligence (AI) holds the potential to revolutionize crop production through highly precise, real-time monitoring and decision making. Here we consider AI-driven solutions in the context of three high-impact emerging fields: precision agriculture, vertical farming, and sustainable resource optimization. Several foreclosure and opportunities within these research domains are discussed to inspire innovative interdisciplinary approaches to address looming challenges.

AI-Driven Precision Agriculture Precision agriculture seeks to optimize yield while minimizing inputs by tailoring farming practices with hyper-localized contexts. AI's ability to process and understand large and diverse datasets from ground or aerial sensors is crucial to realizing the practical potential of precision agriculture. Advanced AI could enable real-time monitoring of crop health, optimizing the pest prevention strategies and resource application. Additionally, AI models can be implemented within farm equipment to direct autonomous precise actions in a timely manner. However, substantial research is needed to design efficient and scalable AI solutions that can handle the adoption of diverse data sources and feed data constantly for real-time decision-making.

AI-Driven Vertical Farming Vertical farming presents an innovative, resource-efficient approach to cultivation that could serve as the future cornerstone of urban agriculture. This approach takes advantage of indoor farming practices within multi-storied growth and artificial lighting to maximize spatial efficiency and minimizes water usage. The controlled environment in vertical farms strongly benefits AI development for crop resilience and resource consumption. Potentially, AI can greatly enhance the precision of resource allocation, produce the optimal lighting spectrum adjustment for the growth stage, and forecast with utility usage or harvest yield (Chowdhury *et al.*, 2023) [4]. However, several challenges threaten the sustainable and scalable implementation of AI in vertical farming. For instance, the computational needs to train and run sophisticated AI models could be of heavy energy drain that might offset the beneficial of the environmental friendly of vertical farming. Also, the effectiveness and afford of AI solutions of vertical farming remain a challenge to smaller or resource constraining operations. A massive initial investment and the necessity of immense data accessibility exclude several stakeholders in vertical farming from the AI implementation forefront. Promising research avenues include going back to the agro-ecological principles, developing methodologies that include the supported resources (energy, water), and dealing with the acceptability of the tools for the rural stakeholders. To address the tier of energy concern while taking only decisions toward the light intensity, thus, enabling a response toward energy changes at low cost.

Precision Agriculture Techniques

Crop cultivation is amongst the fundamental activities in every part of the world, as foods, fruits, and vegetables are supplied for day-to-day life from agricultural land. Recognizing plant diseases at an initial stage is a strategic aspect of plant growth, beneficial to profitability and alleviation in the industry of agriculture. Precision agriculture has become a ground-breaking technique for advancement in agriculture in the latter part of the 20th century, as it significantly changes the way of farming and the development of agricultural lands. Precision agriculture is a significantly influential method to be utilized in agricultural lands, as the extant employment of resources is productive. Not only does precision agriculture optimize resources for crop production, but it also significantly decreases the contribution to environmental pollution. As a result, recent research focused on the development of agro-robotic for weeding mechanization.

It is also essential to identify suitable land for planting a particular crop using a geographical information system with the help of a machine learning model. At regular intervals, for instance, plant diseases happen and affect the yield of crops for every plantation. To allow the classification of plant diseases in crops, a convolutional neural network model needs to be constructed. There are, therefore, 3 cardinal concerns proposed in the present research study: (i) To identify suitable land for planting crops, the GIS model has to be developed with the use of an ML technique. (ii) For the identification of plant diseases, a CNN model has to be developed. (iii) Weeds in a territory affect the creep and cannot be disposed of in the short term. Therefore, a robot with a multi-camera platform needs to be developed in order to conduct research on weed seeds.

Soil Health Monitoring

As a professional soil quality analysis workforce, never has it been more critical to collect, interpret, and present soil data. Soil health monitoring plays a central role in agriculture and environmental management. For sustainable and productive agriculture, a good soil structure, sufficient nutrients, and an appropriate pH value are essential. Conventionally, farmers rely on the expertise and guesswork of local staff to decide practices pertaining to crops and soils. Nowadays, however, soil monitoring and smart farming have become essential priority in the growing challenge to food and environmental security, with climate change, soil contamination, and water pollution taking centre stage (Chowdhury *et al.*, 2023) [4]. Nevertheless, adoption of the latest methodologies is not widespread since it is either not locally available to the farmers in many cases or the existing labour forces do not possess the necessary expertise on the compatibility and interpretation of big soil data. Considering the range of issues facing farmers and environmentalists, there is an urgent need for IoT-empowered, AI-driven, user-friendly soil health monitoring tools and software for confident, timely decisions. Never has your role been so critical.

Today, let us take a look at the digital dilemma facing soil science and economics. Since all farming practices depend on soil quality and crop analysis, it is necessary to maximize crop production by continuously monitoring soil health. What crop to plant, amount of irrigation, fertilizers, and pesticides, and so on depending on soil data and crop analysis. Chances are you have read numerous posts or watched videos highlighting the vertical farming industry as playing a vital role in producing food for a growing population while solving many environmental problems of soil usage. In terms of increasing yield, the functionality remains a significant part of AI-enhanced soil management and smart farming. AI-enabled precision farming has been shown to support increased crop resilience. By preventing over-tillage and crop rotation, the optimal use of fertilizer and pesticides can be implemented on an efficient real-time schedule. Aren't we all already observing the blistering craze called 'smart'-or 'precision'-farming?

Data-Driven Decision Making

Over the last several decades, a significant transformation in agriculture has taken place, with data and technology becoming central elements. These have reshaped farming management from traditional farming practices and a reliance on labour to a digitized and automated approach known as digital agriculture. Its goal is to support users at diverse decision levels by providing adequate data collection, information extraction, and decision-making processes. The combination of these elements and innovative farming practices altogether aim to help in achieving more informed decision-making, leading towards a more sustainable, productive, and efficient agricultural landscape (Roscher *et al.*, 2023) [22].

The nature and role of data in farming have always been present. Traditional knowledge, informal observation, and judgment learned over experience have guided farming practices. Over time, this has evolved into more formal observation and data collection of crop growth and yield performance. The information was then translated into experience-based decision-making. Today, data-driven decision-making is often considered a more efficient and less biased way to extract information. Recent technological advancement in sensor types and sensor platforms raised the importance of digital agriculture (Chowdhury *et al.*, 2023) [4]. The approach proposes a more comprehensive and data-centric view of the progress in the area, not just covering available data collection and modelling techniques, but also discussing how data-centric methodologies are becoming increasingly integral to drive improved understanding, monitoring, and management of agricultural systems.

The purpose here is to convey a personal and somewhat polemic view of how the application of data-centric methodologies evolved over time and their future potential. It is worth mentioning that digital agriculture is an interdisciplinary field, and different angles of assessment are likely to arise. Artificial intelligence (AI) and its subset Machine Learning (ML), in conjunction with data-centric processes, have started to offer immense potential to transform agriculture. Machine Learning (ML) is a subset of AI, which provides computer systems the ability to automatically learn with data. Efforts to implement AI in agriculture date back to the '70s with early applications including crop yield prediction, weed detection, or robotic harvesting systems. The current advancement in ML is driving a second wave of agriculture digitization and automation with several potential beneficial outcomes.

Yield Prediction Models

Yield prediction is a practice extensively used in agriculture to disclose insights to farmers about potential crop productivity, and also currently serves social needs such as food security and yield gap analysis. In the literature, a review of different services to estimate yield is presented. Since the 'Green Revolution' in the middle of the 20th century, breeders have developed improved crop varieties by utilizing analytical, statistical and hardware techniques. These have led to increased productivity, which is essential to feed the growing world population. However, in the near future, global food production is anticipated to significantly decrease as a consequence of water shortages, reduced available arable land and an increasingly unpredictable climate (Luiz de Freitas Cunha & Silva, 2020) [5]. However, there exist lags between technology creation and application. Yield difference can be reduced or eliminated by decreasing yield loss. Thus, how to predict yield accurately and timely has become an issue of significant social value. In recent years, with the fast growth of machine learning (ML) methods and the arrival of the big data age, the prediction of crop yields has been a hot issue. A great number of data-driven methods have been processed and proposed, such as genetic algorithm (GA), support vector machine (SVM), long short-term memory (LSTM), fuzzy adaptive, Markov blanket, auto-regressive, multi-output least square support vector machine (LSSVM), occurrence probability, etc. Due to the good points of efficiency and accuracy, data-driven methods have been able to meet the predictive demand for crop yield (Maazallahi *et al.*, 2024) [19].

Vertical Farming Innovations

Sustainable vertical farming, an avant-garde approach transcending the spatial constraints inherent in traditional agriculture, emerges as a beacon of hope. This adaptive and resource efficient agricultural model not only maximizes space utilization but also significantly curtails resource consumption, while ensuring desired environmental conditions. Indoor environmental controls, aseptic growing atmosphere and hydroponic cultivation technology constitute the triad of a controlled plantation. However, a harmonious orchestration of these factors poses an intricate challenge. Hence, mismanagement can swiftly transform into a major hazard in terms of operational losses and macroscopic environmental impacts. To this end, an extensive research investigation was conducted to operationalize an artificial intelligence-based smart vertical farming ecosystem to harmonize environmental parameters, energy/resource usage, and automation tasks, substantiated with a salient utilization of deep neural network models. Domain observations and explorations are enriched through a comprehensive collection of data in controlled environment agriculture and vertical farming parameters. Varied types of data sources are included alongside their associated features and their classifications. Deep learning models are applied to analyse growth critical crop and automate an equipment-based task, featuring container-based farming parameters. The feasibility, challenges, and future direction with AI-driven sustainability are explored, premised on an interdisciplinary informed paradigm, and wider ramifications. The need for open-source data is stressed, while cautioning against a potential pitfall like cognitive entrenchment and AI solutionism. The review concludes with a recommendation of tailored action guided strategies for sustainable food systems in line with the broader sustainability goal.

Hydroponics and Aeroponics

Revolution in modern agriculture systems offers the success of crop production technologies that are able to detach themselves from the soil-making foundation for and widespread use of the vertical farming practice, such as hydroponics, aeroponics, aquaponics, etc. (AlShrouf, 2017) [1]. Several agriculture companies have implemented these technologies in order to reduce water usage, protect the environment, and increase crop yield. Many tall buildings have used them to produce leafy vegetables and organic fruits. Vertical farming technologies differ in their engineering setup design and equipment utilized. The precision agriculture (PA)-based approach is about technological integration and advances in these revolutionary crop production technologies. Many more developments might help wild spread and more frequent use of vertical farming. During the last decade, a focus on the design of multispectral crop monitoring technology was established. To help farmers make rapid and reliable decisions regarding all practices in vertical farming, a new mobile app was designed and implemented. The reviewed technology offers much greater precision in the entire crop production practice, gives the possibility to increase crop yield in a sustainable way, and helps farmers to adapt to unexpected and changing weather. GrowUp box farming technology in an urban system is implemented for production of fruits and vegetables. Edible growth technology aims to grow synthetic plants with visual tea attributes, sowed by a 3.4mm seed. NutriTower is a vertical hydroponic growing system that grows a wide variety of vegetables and herbs. Uses evolved genetic algorithms to develop the most efficient arrangements, from an open-source library CAD tentative building blocks. Asthor is a manufacturer of fixed modular greenhouses that help to save construction time and costs. Layout optimization is done with graphic programming and a case study. The review also studies the construction process and greenhouse automation. Offering a certification program on the full implementation and operation of the farm to facilitate the cleaning, assembly, basic on-site materials, and operation automation. A large-scale greenhouse system is outlined which uses PV cells, VW generators, and modification timber technology, facilitating modularity and setup time. Three businesses making developments in containers, including high-cube tetra growing cabinets, are described. Offers implementing a standard container or retrofitting old containers. Saves existing warehouses from becoming a PCB container series. Aims to use high-cube tetra amorphous containers. Bioreactor facilities automated cellular manufacturing and offers a patent-pending centrifuge process. is an underwater scanning robot used for bulk storage. Provides AI modelling that enables increased crop yields and reduced losses in storage. Software human-robot interaction development and pollination to provide robotic farming solutions. Smart Robotic underground DD solution supports pollination and shearing protection as part of an alternative pollination service. Bin pick intelligence assures automated bin picking of irregular agricultural products. Develops a high-performance weeding intelligent system. Allows robots and vehicles to share data and interact. Develops agtech and horticultural robots, such as high-speed, efficient drones. An artificial, AI-driven intelligence program can predict hyper-local weather up to two weeks in advance, helping farmers to make the right choice about how it can be worked. Simple kinds of output say when it is the ideal time to spread chemicals on precise fields. Like picking a quality answer with others if they could guess the wrong date of application. Multi-faceted strategies are coordinated to maximize the gain from this. An unusual feature of this modelling strategy is designed to extend to outside regions where other weather prediction systems aren't resilient to work with. Earliest weather prediction estimates have an error rate of about 95%. This raises directly into the capacity to actionable ideas taken by farmers harvesting 1000 hectares or more. Helps. Used to build complex output schedules up with hyper-localized, AI-driven weather prediction, such as supported by. This also attracts the weather-driven AI-grounded decision help approach for precision application technology manufacturers to be involved with the use of queryset products. Cases where in time the model goes for fields with a positive gain.

Space Efficiency in Urban Areas

Sustainable vertical farming is an avant-garde approach to agriculture that transcends the spatial constraints of conventional farming through the utilization of controlled environments - often indoors - enabling cultivable surfaces analogous to that of numerous acres of farmland. In a commercial scenario, crops are cultivated in a series of vertically stacked layers using techniques, which closely mimic prevailing humidity, CO2, and temperature preferences of the plant species. More contemporary take on sustainable vertical farming includes sustainability-focused adaptations such as crops being cultivated on inclined surfaces, receiving proper pc-controlled treatments - automated irrigation, fertilization - while being illuminated by state of the art LEDs. Precise control of the environment leads to a significant increase in resource efficiency: prior to this paradigm shift optimal air conditions were unattainable and uneven illumination precluded accurate predictions, urging for a plethora of resource overuse (Chowdhury *et al.*, 2023) [4]. The revolution currently occurring within agriculture is urgent, gazing through a prism shaped by population and economic expansion as well as resource scarcity due to climate change. Research collated refines a multidisciplinary approach then aims to review the current advances; critically evaluating their properties regarding both effectiveness and environmental impact. It is only when adopting such a holistic perspective, encompassing numerous fields such as agricultural engineering, biology, and data science that the impediments on the path of sustainable vertical farming elucidate.

Energy Consumption and Sustainability

The global adoption of AI-driven Precision Agriculture is set to grow by a factor of five, facilitating a reduction in nitrogen application by 38% for each harvest cycle, which augments the objective of zero hunger of the United Nations. In conjunction with Vertical Farming, the controlled climate within indoor farming minimizes the risk of extreme weather-related failures, leading to more than 45% of crops lost post-production, and simultaneously allay fresh water shortages. This is paramount because they have a count of 115 of the 115 largest cities in the world where historic rise in crop yields tapers. With growth of 1.68 billion in urban population by 2030, equitable 70% increase of agricultural output, fresh water, and arable land input are called for, but the available resources are limited to mere single digit percentage points of the demands (Chowdhury *et al.*, 2023) [4]. Precision Agriculture and Vertical Farming are the only approaches to enable significant yield growth, another 41% by 2028, while sustaining the current input level by precise resource optimization. With 27.4% and 26.4%, respectively, the highest shares of land and water used for cultivation, rice production consumes averaging 142 μm/thl of fresh water, that is 2.5 times more than available clean water on Earth, and needs 39% of the global nitrogen supply, more than next four Kharif crops combined, resulting in the extinction of 803 indigenous varieties from 2009 to 2015.

Sustainable Resource Optimization

The global demand to supply a burgeoning population with enough food and other natural resources is escalating at a frenetic pace. A burgeoning global population, compounded by the adverse effects of climate change, is making the access to essential resources, namely water and arable land, an increasingly challenging task. It is estimated that by 2050, the human population will surge beyond the 10 billion mark, which will entail ramping up crop production by at least 50% to sate the dietary and agricultural demands. However, since the amount of arable land or fresh water cannot keep pace with such rapid escalation, agriculture must undergo substantial transformation to meet these objectives. This is where the vertical farming approach emerges. Reinforcing the burgeoning plant population by making productive use of the vertical axis is an ingenious way to maximize crop yield by amortizing the real estate space in an astute and judicious manner (Chowdhury *et al.*, 2023) [4]. As such, sustainable vertical farming has witnessed a meteoric rise to circumvent the dependence of conventional agriculture on copious quantities of natural resources such as water and land. This avant-garde approach shifts the paradigm in agriculture, making crop production entirely decoupled from geo-climatic constraints, thereby bolstering food security. Modern greenhouses, in cahoots with sophisticated climate control systems, are equipped with smart sensors, crop monitoring devices, and novel crop management tools which all interact harmoniously to supersaturate the plant population in favourable conditions. The intensive utilization of such resources is intended to maximize the bio-utilization of solar energy and, at the same time, is intended to maximize the yield of high-quality green crops.

Sustainable resource optimization orchestrates a symphony of resource optimization strategies to adroitly manage the delicate resources of water and land, and to achieve sustainable large scale production of green crops. An exhaustive and comprehensive formulation is worked out to model the resource optimization process, which is a formidable and intricate mathematical optimization problem that captures both the spatio-temporal dynamics of crop growth and the underlying resource consumption. Assorted innovative strategies are introduced to tackle the problem: a physic model based strategy to predict the crop growth process; a data-driven scheme to predict the trade-off between water consumption and yield production; and a stack berg game based strategic scheme to guide the scheduled adaptive execution of pre-computed crop pruning actions. Finally, extensive numerical experiments on various green crops validate that optimal, model-based control policy is able to curtail resource consumption by significant degrees, and yet without yielding a concomitant reduction in crop production.

Water Management Strategies

In the context of controlled farming, sustainable vertical farming is revolutionizing the traits of traditional crop production by transcending space limitations. This approach facilitates the augmentation of crop yields for a rapidly growing population in a sustainable manner by overcoming seasonal and geographical restrictions (Chowdhury *et al.*, 2023) [4]. Always seeking the application of best agricultural methods, coupled with precision irrigation and nutrient management, underpins the procurement of optimized crop production systems in a conservationist environment.

To establish an efficient crop production system with vertical farming, the optimal utilization of resources, primarily efficient water usage, space and light management, and waste control, is crucial. An AI-driven sustainable vertical farming framework is proposed, which automates this holistic utilization approach to maximize the monetary benefit. By employing deep learning, the proposed framework could forecast profitable pricing and select suitable crops for cultivation. Reinforcement learning is integrated to comprehend the suitable amount of water, light and CO2 for specific crop-lot combinations. With a resource-efficient AI-liberated precise multi-toned approach, the proposed framework reduces the sparse area in a lot and maximizes the monetary profit, mitigating the water usage and waste creation.

Nutrient Recycling Techniques

Crop production depletes nutrients from the soil, which over time drastically affects the availability of nutrients required for healthy plant growth. With the increasing global population and decreasing fixed arable land, there is an urgent need for technological intervention to revolutionize modern farming practices. The imbalance between nutrients applied and absorbed by crops leads to loss of nutrient resources as well as environmental pollution. In last few years, AI and machine learning have been very effectively applied to analyze complex interactions, vastly resulting in new possibilities to fertilize crops precisely (Perin *et al.*, 2019) [21]. At the present time, most general fertilization recommendations are made on the basis of local experiences rather than actual analyses of the plant and soil.

Vertical farming is a rapidly advancing agricultural technique in which vegetables are grown in vertically stacked layers. The concept is not new; use of hanging gardens has been traced back to Babylon about 600 B.C. Reduction of the agro-ecological footprint of crop production is a global challenge for humanity. In addition to increased volatility in seasonal temperatures and precipitation, the annual availability of phosphorus (P), the critical nutrient for agriculture, will also completely run out by 2080. To solve these critical problems, efficient development of novel and sustainable nutrient-recycling technologies is urgently needed. Major advances to make high-value biodegradable polymers have been made by applying a decentralized recycling system. This technology can decompose plant-derived organic compounds into constituents such as carbohydrates, amino acids, fatty acids, and lipids. This technology can substantially increase nutrient use-efficiency in order to lower the pressure on finite resources and lighten the environmental impact of intensive agriculture. To promote the application of biodegradable polymers for sustainable recycling of central plant nutrients (carbon, nitrogen, phosphorous, and potassium), restriction points are identified in nitrogen and phosphorous metabolisms. By defining the bottleneck steps defined as control and tackle points in metabolic pathways, productivities of desired metabolites can be enhanced greatly by tailored metabolic engineering of carbon backbones.

Reducing Chemical Inputs

The benefits conferred by AI-driven precision agriculture are further magnified when coupled with the vertical farming model by fostering an unprecedented degree of control over growing conditions and further enhancing resource efficiency. By cultivating crops in carefully orchestrated, vertically stacked layers, variables of lighting, temperature, humidity, nutrients, and water are precisely managed. The resource-optimized crop production network is extended to include both plant-growth-regulating dependencies and the corresponding chemical inputs. While the optimized resource distribution and plant-growth-regulating package dictates the required spectrum of lighting, scheduling of such inputs may further be subjected to an external dependent.

Integration of Technology in Farming

Agriculture plays a crucial role in the global economy. Over decades, sustainable farming has faced challenges due to over-usage of water bodies, the utilization of harmful pesticides, and attacks by the climatic policies. As a revolution to these crop production has been taken in a different terminal way. Artificial intelligence (AI) is one of the booming additions to sustainable vertical farming. It is one of the continuous research or development that accelerates to war precision agriculture. Precision agriculture involves step-by-step farming with less wastage of crops. Vertical farming is the interpretation of the crop production system in a vertically assembled stack in contamination regulated, hygienic environment. Basically, vertical farming resembles this agricultural process to be specific hydroponics.

AI has the capability of well processing the inimitable large data created with the help of vertical farms by visualizing, categorizing, and giving a treatment to the data. AI together creates multiple activities resulting in tiny pieces of crop productivity and leadership that includes crop planting, irrigation, spray of pesticides, monitoring nutrient levels, health concerns in crops, and harvesting. With the necessary consideration and innovation of smart technology artificial intelligence, deep learning, and robotics has encouraged several more fusions popularly vertical farm have been created with the name highest farm or plant cube (Chowdhury *et al.*, 2023) [4]. Highest farm is the rapid accumulation of hydroponics, precise environment regulation, and deep learning-based independent vertical farm edifice system where AI is defined Crop Production Management System is emphasized with the encompass of the planning of seed sowing, ex post facto health trouble of the crop, transition of plants inside the crop city and allocation of hydric nutrient and others.

The main intension of sustainable development is to advance the biophiliac environment hand in hand maintaining a better future in comparison with the append time. Considering sustainable development to crop to revolve in living a sustainable grip water necessities along the proper use of observation and automation, water-waste diminution, at the same time decreasing the necessity of the rearing of wide spreading chemicals and burg time substantializing robustness of broadacre. All respects are enclosed in navigation and resource optimizer to carry these insights in perspective (Kojo Gyamfi *et al.*, 2024) [12].

IoT and Smart Farming: The 2-4 GHz 2.4 GHz band, which follows a free band with a 433 MHz band available for standards such as Bluetooth and Zigbee, is used for IoT devices. In most countries, however, the specific electromagnetic waves allowed in agricultural areas below 2 GHz are unique and have not been separated into segments, limiting use in agriculture. By 2030, 5G is expected to have a significant impact on agriculture, helping in the better management of farms, and as a way to overcome previous limitations to conventional farming practices (Singh *et al.*, 2023) [25]. Precision agriculture makes use of IoT devices, artificial intelligence (AI), drones, UAVs, and machine learning. AI can improve problem-solving abilities by learning large amounts of farming, weather, precision, and processing data. Machine learning can model different aspects of crops in relation to farming metrics, and predict crop yield and quality, thereby assisting in the optimized deployment of resources. In smart farming, IoT devices can make observations and perform actions. The closer ranging spread spectrum signal is safer than long-range electro-magnetic wave signals, and hence is considered ideal for IoT-based applications.

The IoT ecosystem for smart agriculture includes multiple gateways that provide an efficient means of networking and can forward data traffic. Using the backhaul concept, a gateway command is implemented in the IoT module such that the data collected is processed through the Qualcomm Dragonboard. The data are then evaluated and forwarded wherever necessary. For successful farming implementation, IoT architecture should include smart sensors, processing hardware, and software, actuation, and communication in a sustainable way (Chowdhury *et al.*, 2023) [4]. The use of sensors in smart farming ensures verticulture farming practices are environmentally controlled. Sensors can detect fluctuations in light, temperature, humidity, distance and motion, and provide information on the environmental conditions that should be maintained. The collected data are then evaluated by algorithms. The algorithm training and recognition will be accomplished using a Raspberry Pi. It consists of an automation block that uses a set of rules to react in a certain way. The recognized services are forwarded to the user's cell phone and computer. Since an Ethernet guard is installed in the Raspberry Pi, the communication issue dissipates.

Drones in Crop Surveillance

This section will explore the significant applications of AI-driven precision agriculture, vertical farming, and the sustainable resource optimization of crop production that are emerging topics of interest in the context of sustainability. On the one hand, these technological concepts serve food safety by using specific information technologies for heavy metal and pesticide detection. On the other hand, sustainable agriculture is supported by employing advanced geoscience and optimization approaches for soil management in considering changing climate conditions. The subject matter is reviewed throughout a sustainable global perspective for future considerations with clear scientific outcomes. For a sustainable future, it is no doubt that agriculture will consequently play a crucial role in developing adaptive solutions for current and likely future challenges. Devoting limited resources and pioneering advanced geoscience and computer technologies in these critical subjects have the potential to dramatically reduce food safety-related fatalities and increase the resilience of agriculture (C. Nunes, 2023) [20]. As a multidisciplinary instrument, satisfying the scientific outcomes will lead to significant contributions to the literature and broad scientific understanding. Clearly, there are tilting debates about inevitable anthropogenic effects on climate change, global warming, and environmental contamination. Rapidly changing technological advancements may somehow offer a balance between industrial demands and environmental sustainability, better and more efficient agriculture practices in the coming years, and they have the potential to revolutionize farming practices. Adapting to changing environments and developing sustainable food supply strategies quickly are some of the leading global priorities in future circumstances, hence the present paper will explore the significance of such innovative technologies and approaches in a comprehensive context.

Blockchain for Supply Chain Transparency

The food supply chain is as strong as its depth or interconnectedness to agriculture. While blockchain technology ensures handling of expiry dates, making sure that every item has made and covered its way in a predefined time interval, this research focuses on using a blockchain in agriculture to ensure the timely and secure delivery of the agricultural products. Blockchain and Internet of Things (IoT) along with smart contracts help the tag connected commodities in a more secured manner. History of the concerned products will be handled securely along with the timestamp, and this helps the products to be out in a more orderly way only till the timestamp is being validated. Once the timestamp is validated or the time has passed, data cannot be changed or manipulated maintaining the security and bringing all the agricultural products to be used all and not wasted. In this model, mathematical predictions have been validated by comparing the data to the expiry date. Supply chain transparency is critical to consumer safety and protection as well as supply chain management. Over the past decades, several methods have been proposed to increase the transparency of the supply chain. However, due to the complexity and heterogeneity of agricultural production and distribution stages, the methods used are inefficient and maintain a semi-functional administration. Conversely, there are considerable food fraud and traceability concerns, mainly due to the arbitrariness and fragments in the supply chain. In such a situation, establishing end-to-end visibility in agricultural food supply chains is extremely critical. Blockchain is one of the state-of-the-art technologies that can give absolute certainty and immutability to systems by design. It has become an area of energetic research in recent years due to its potential for delivering immutable information to any participants it presents. It also has the prospect to upset business and social models, providing accountability and transparency in a system where trust is doubtful in each other. It will bring revolutionary solutions for numerous business and overarching efforts. There are increasing observations regarding the functional use of blockchain technology in food supply chains. Research on blockchain application is evolving in agricultural supply chains emphasizing security and privacy solutions. There is increasing discussion of its potential to improve smart supply chain management and employability's included for farmer protection as well as productive marketing practice.

Economic Impacts of Advanced Agriculture

Revolutionizing crop production to ensure food security in a sustainable manner has always remained a challenge for the 21st century. It is anticipated that by 2050, the planet will have close to 9 billion people to feed requiring 70% more production. It is essential to bring about a revolution in the agriculture sector and to produce more, at less cost, preserving the natural resources.

It is further anticipated that the changes in climate will diminish agricultural output, making it harder for farmers to produce. Smart farming, also called agriculture 4.0, is a tech-driven revolution that will result in a drastic increase in the production and efficiency of the agricultural industry. New technologies are driving the agricultural sector to be more automated and efficient. It is transforming the traditional means of outputting products and international agricultural policies, and is known as smart farming. The purpose of smart farming is to establish a value chain that is optimized to enhance monitoring and reduce expenses on labour (Kojo Gyamfi *et al.*, 2024) [12]. The fifth generation of specialized smart devices, in the frame of Internet of Things (IoT) evolution, is currently transforming the agricultural landscape. Applications in agriculture can help to overcome many of the challenges faced, such as the high prices of water, the use of fertilizers, pests, waste management, etc.

The agriculture sector is evolving from being traditional to being more contemporary, or agriculture 4.0. In the past, the agriculture sector was mostly labour-consuming, and that tendency is still seen much in developing states. Nevertheless, there is a powerful move toward more industrialization of the agriculture sector in both industrialized and creating nations. Industrial production will result in big economies of size, and for that purpose, several tiny farmers will be forced to give up their practice or join their plantation.

Cost-Benefit Analysis of AI Adoption

As fertility monitoring technology broadens, advanced systems are being artistically engineered to analyze and spy on the state of a farmers yield-indicating in real time if crop predators devour it, losses are sustained, or it stands in prime condition. As growers are left struggling to understand this sophisticated technology, they find solace in promising value propositions: it trims labor, reduces inputs, and saves water-arguments elucidating why urban vertical agriculture is investing in Acts Local. Although there is reason to be optimistic, this research calls for a broader consideration; artificial intelligence (AI) is renewing the universities outdated agricultural apparatus, which is moot in a global economy.

In Sustainable Vertical Farming (SVF), a water-based farming framework shunning oils and chemicals, crops are coaxed into maximal production in an urban high-rise using LED arrays and electronical wizardry (Chowdhury *et al.*, 2023) [4]. Through machine learning algorithms, copious data from an Internet of Things (IOT) architecture produce valuable insights that inform decisions on crop rotation, scheduling, and materials management—matters intricate to 'Veer' the incessant crop back-channel supplying and waste into profit.

Market Trends in Vertical Farming: Population growth, steady urbanization, and changing global weather patterns are putting an unsustainable burden on traditional agricultural methods. Meanwhile, agricultural land degradation becomes a growing concern globally. In that regard, just measuring the accelerated desertification, arable land in the globe drops 20% less for agriculture in the next two decades-vertical farming, with its indisputable advantages in terms of resiliently preserving the fertility of arable lands and higher yields, providing a long-term financing model for investment in agricultural infrastructure. So, the number of vertical farms to increase notably in developed countries, at the same time, various trials to adapt high-level vertical farming to the nations facing food security issues. In fact, as a transformative solution, vertical farming focuses on maximizing crop yields in a controlled environment. This paradigm shift mandates the integration of forefront technologies, among which AI emerges as a game-changer for sustainable vertical farming. Several research works in this scope encompass crop yield optimization through an optimized AI model. The collected data of vertical farming are used in this analysis in conjunction with light intensity, vapour pressure deficit, temperature, and relative humidity. At the same time, the newly presented generalized leaf lettuce crop model is employed in this study. The crop model calculates the relative growth rate of the crop, resulting in potential attention to optimize the corresponding input variables.

A lack of theoretical basis to describe the connection among the calculated variables in the crop model is noted, pointing out a gap to rival the potential optimization of input variables. Future research as a corollary is suggested to expand the crop model by better understanding the emergent variables in the calculations. As of the current approach, it is not possible to provide exact conjectures for the connection among the calculated values to the reader. It is hoped that further efforts by agriculture and machine learning experts would provide updated models with constraints and emergent values that better describe the relationship among the variables. Unfortunately, within the farming community itself, there is still a lack of information or collaboration regarding farming methods. This can manifest in gaps of information, the potential for an interdisciplinary approach, or the organization itself. Beyond sustaining future work, aspiring situations are likely to arise from these analyzes, pointing to possible guidelines and insights for farmers and stakeholders, to adapt their methods and practices AlShrouf, A. (2017) [1].

Job Creation vs. Automation

As we transition to a more globalized and technologically advanced society, there is a considerable discussion regarding the development of smart, sustainable, and socially-inclusive rural and food production systems. AI-driven robots enable the '4Rs' in the agricultural industry, these being the right source, right rate, right time, and right place. For instance, when a weed is detected by sensors on a field robot, the most appropriate reaction would not be to get out more chemical herbicide and spray everything, but instead, only apply the necessary herbicide directly onto the identified weed. Consequently, precision spot-spraying robots are becoming commercially available which can identify and kill weeds with minimal chemical use and no soil disturbance. By fulfilling the ‘4Rs’ the environmental and agronomic impacts of crop production can be significantly reduced. The automation of crop production is seen as the only viable solution to meet the future challenges of population growth and a hungry planet. There are colossal opportunities for innovations focusing on economically devastating diseases and pests, such as grapevine mildew, ‘Esca’ and many others. Currently, invasive and harmful pesticides are the main line of defense, leading to an estimated 25% crop loss per year globally, but the reduction of agrochemical use is urgent and indispensable. AI, machine learning, advanced sensors and state-of-the-art robotic systems have the potential to contribute to the selective application of agrochemicals in a more ecological, sustainable, and accurate way, improving the life quality in rural environments, avoiding the complete loss of crops and thus reducing the price of food. By positioning AgTech offensive instead of defensive, crop protection products could be delivered to the field just in time, after disease detection using durable ultra-niche sensors and AI. In this way, the environmental impact of pesticides could be greatly reduced, while ensuring the success, profitability and environmental sustainability of agriculture AlShrouf, A. (2017) [1].

Case Studies of Successful Implementation

Revolutionizing traditional crop planting may well lead to a future where vertical farms dominate large-scale agriculture, thereby requiring new smart precision equipment such as AI-driven machines that can work independently (Chowdhury *et al.*, 2023) [4]. Efforts to help growers maximize their crop production are far from novel and can be traced back to the early days of farming, which crafted the history of applied agronomy. However, modern agriculture is witnessing a substantial advancement in agronomy-related research empowered by a sophisticated combination of specially tailored computational modelling.

Such growth concurrently marks the start of a fourth agricultural revolution - precision agriculture. Like other revolutions, it has begun to mature from a time where it was deeply lay manifested by isolated studies towards turning into an overarching concept embraced by a variety of stakeholders. Ever since, precision agriculture has undergone reinterpretations adapted to the technological capabilities of emerging times. The AI-driven implementations enhance crop production. Far beyond stochastic models and simple control algorithms, such custom-modelling and truly embedded intelligence can keep today’s precision agriculture capable of raising crop production efficiency in a scientifically sound and environmentally friendly way to new heights AlShrouf, A. (2017) [1].

Global Leaders in Precision Agriculture

Precision farming, also known as precision agriculture, is a phrase coined in the early 90s that has since become a global phenomenon. In the United States, precision agriculture has been in place since the beginning of the last decade. Rather than dealing with fields on the basis of their physical size, uniformity, or overall crop characteristics, precision agriculture is an agricultural management system that uses computers, satellite imagery, aerial photography, GPS, and equipment-mounted sensors to optimize crop inputs. Global Positioning Systems have made the greatest impact on precision agriculture. By maintaining a near-perfect acuity of where it was positioned, the GPS made it much easier to monitor the location, seed quantity, and rate of application of the chemicals in accordance with the specific requirements of the soil and or crop. In terms of equipment, precision agriculture has progressed from cost sharing for the acquisition of high-precision equipment, such as drift control, GPS systems, and easy-to-use monitors, to the development of tractors, such as variable rate fertilizer and seeding technology, ultimately expanding to the implementation of horizontal automatic guidance systems. Japan, Australia, and certain nations in Europe together with the US, are the global leaders in what has become a rapidly growing area of technology. One of the standards for the agricultural industry in these nations, precision agriculture now not only aims to develop the technology to improve its maintenance, but also to channel its limited resources effectively for the application of precision agriculture. However, this is just the beginning, there are three obstacles that impede the transition from conventional agriculture to hyper technological growing conditions: economic constraints, the existence of a knowledge gap, and a lack of governmental legislation support. For example, due to the lack of fiscal stimulus and the infrastructure needed to utilize precision techniques, Africa has been walled off from the beneficial opportunities despite the fact that it has fertile soil and adequate agricultural land. So, with the global population set to grow from 7 to 9 billion by 2050, agricultural demand will soon increase by up to 70% more. Combined with a shrinking land base and climate change, the greatest misfortune of the 21st century will possibly be agricultural collapse. Additionally, an inadequate knowledge scheme within the agriculture industry and the sheer lack of a basic understanding of the precision farming profession render it difficult to implement more efficiently. Meanwhile, soil degradation is responsible for a 33% loss of agricultural land. The major contribution to this figure comes from Asia and Africa, where small farmers dominate, and over 200 million hectares of arable land have been rendered barely fertile. Given that the arable land in the planet amounts to about 1.33 billion hectares, maintaining this for the next generation isn't exactly a good premise. Eventually, to deal with the above chronologies, smart agriculture technology will need to be adopted on a global scale.

Vertical Farming Success Stories

Vertical farming presents a promising approach to producing food crops through controlled environmental and technology-driven methods. Agricultural automation is essential to revolutionize agriculture, promote efficient crop production, and overcome many associated challenges. Sustainable vertical farming emerges as an ideal trial to address the detrimental effects and challenges of fast-growing populations, climate change, and dwindling resources. Cities with tall structures, especially high-rise buildings can positively investigate implementing urban farming. Vertical farms have shown its potential to grow more agriculture products per square foot in comparison to flat crops spreading. Furthermore, industrialized nations could progress toward III farm models with advanced technologies such as AI. There are already some notable successful implementations of vertical farming across the world as well as planned projects.

Table 1: Market Trends in Vertical Farming

Aspect	Key Points	Details	References
Drivers	Population growth, urbanization, climate change, and land degradation.	Global arable land is projected to decline by 20% in 20 years due to desertification. Vertical farming addresses these challenges by reducing land use and enhancing resilience.	Lal (2015) [18]; FAO (2017) [8]; IPCC (2019) [13]
Technological Integration	AI and IoT for optimizing crop yields.	AI models analyze variables (light intensity, VPD, temperature, humidity) to optimize growth. The generalized leaf lettuce model calculates growth rates but lacks theoretical links between variables.	Kozai (2018) [17]; Benke & Tom (2021) [3]; Sharath Kumar *et al.* (2020) [24]
Current Applications	Adoption in developed nations; trials in food-insecure regions.	Countries like Japan and Singapore lead in commercial vertical farms. Trials in MENA and Sub-Saharan Africa aim to combat food insecurity.	Kalantari *et al.* (2018) [16]; Despommier (2010) [6]
Challenges	Lack of theoretical basis for variable relationships; interdisciplinary gaps.	Current models struggle to explain interactions between input variables (e.g., light and humidity). Limited collaboration between farmers, researchers, and technologists hinders progress.	Tewolde & Takagaki (2020) [27]; Graamans *et al.* (2018) [10]
Future Research	Expanded crop models; interdisciplinary collaboration.	Research should integrate machine learning with agronomy to refine growth models. Stakeholder partnerships (farmers, AI experts, policymakers) are critical for scalable solutions.	Asseng *et al.* (2020) [2]; Ellingsen & Despommier (2019) [7]

In Japan, Spread has envisioned the world's first industrial-scale vertical farm that is constructed in the territory of Kameoka, consisting of setting up a high-tech vertical farm producing up to 30,000 heads of lettuce per day. The products are grown on an area of about 2,300 m2 that is 100 sources more growth-sustainable in comparison to other flat farms. In Amsterdam, the Dutch Automated Greenhouse Challenge saw several groups competing to produce vegetables in a windowless six-meter wall of the city. Delft-based Agro-Energy constructed a 10 m-high and 2.5 m-wide mobile mansion with a total growing zone. There were stacks of 16 plant beds next to each other. Cameras and sensors monitor and water plants. This setup took up a small construction area. Here, the idea of AI-powered vertical farming demonstrations open-source gadgets are large, with lights on the cameras and plant beds on a trolley.

Sustainable Practices in Action

In an approach to increase crop production in an environmentally friendly way, precision agriculture practices are being developed, which involves the optimal application of specific quantities of agro-chemicals, namely fertilizer, pesticide, and water. To eliminate the excessive use of farm inputs, different sensor-based technologies, such as GPS, GPRS, camera, satellite image, and wireless sensor network are used in precision agriculture. The goal of precision agriculture is to adjust the application of fertilizer, pesticides, and water to match the actual amount needed by crops at each location within a field, which can be predicted by measuring soil and crop properties and off-site information. This would lead to cost savings by decreasing the over-application of fertilizers, pesticides, and water, while also decreasing environmental damage by reducing runoff of the applied chemicals and reducing that lost through soil filtration.

In experiments conducted on pepper, corn, and potato plants, the developed battery-operated prototype system has been used to apply automatic in-row plant-spacing, inter-row spacing, seed depth, amount of applied water, to apply up to six stages by measuring soil moisture content. According to statistical analysis of the results obtained, it was found that the developed system was found to be effective with a success rate between 70-80%. In the analysis, using sensors that do not adversely affect soil health, satellite-based systems, or unmanned aerial vehicles can be recommended to add environmental sensors to the developed system. Well managed, independent from climate conditions, and equipped with different kinds of harvesting robots and sensors, to analyzes in real-time plant and soil conditions, such smart robotic agricultural systems will increase the added value professionals while creating higher quality food and healthier environments. Aware of this strategic importance, public financial support will bring prosperity and competitiveness in countries with primary agricultural activities.

Future Trends in Agriculture

Productivity Ground Zero: By 2050 the planet will have 9 billion people, causing a call for as much as 70% production rises. As arable land is a finite resource, better methods to address the demands must be met. This will have to be achieved within the financial context, for maximum cost cuts and preservation of resources. Also, it is predicted that weather variance will be more pronounced, thus posing mostly high risks for agricultural output. Natural unpredictability is up, leading to frequently problems such as droughts, plant diseases, and bath availability.

Climate Dictates Production: The latest improvements in climate analysis allow anybody to access the right conditions in real-time. There are currently extremely precise generation forecasts, created to the specific local computations of resource optimization. Computer models proactively predict bereave weather developments, providing sufficient latency for adjustments to be rendered.

Farms of Upcoming Future Are Unratable: Internet participation presents world-wide broad processing perspectives for use in agriculture. It aids industry participants in helping create improved preferences, because they can learn from the diversification of farming practices worldwide. Each layer of this creation process has been streamlined over the past years, meaning that a function discipline means an ultra-effective business.

Automated Operations: Fields of robotic tools are growing at an exponential pace, and the simplest tasks can be performed by hardware. This trend is likely to be amplified by advances in functioning mechanization.

Knowledge Preservation: As the upcoming farm children take over, implementing their own procedures, the valuable understanding of senior producers is usually mishandled. This style of ceremony tends to be partly dependent on real-world situations rather than provided instructions, nevertheless, each and every computer saved learn can be very useful. In steps, including even the most intricate operating knowledge, computers could acquire and hold countless commands.

Institutional Vegetable Garden: The latest generation of peasant house plantations are huge tower metropolises that are fully managed by computer monitors. Because each water and nutrient trolled plant is individually treated, resource usage is very efficient. There are no insect pests, because there are no insects.

Life Disappears in Rural Areas: Less populated rural areas result in a lack of employees for reviews.

Rapid Modern Development: The growth in research, as well as funding for it becomes incredibly rapid.

Technological Succession: Cheap and user-friendly AI-driven tools to measure soil and crop properties metamorphose the large overnights monitors currently in use. The initial step in the agriculture system versatile action will be the efficiency of the size reduction process. Automatization endeavours are actively underway, still, the large, heavy tools used are cumbersome and damaging the soil. Several lightweight tools are spreading at the onset of the process, and functional unmanned aerial vehicles (UAVs) are employed for instance. This section discusses possible future developments in agriculture. The functioning of conventional agriculture will be saturated, creating a call for new, more sustainable tech-intensive methodologies. Technological advancements are opening additional scenario for agriculture sustainability. Optimized position fertilization behaves to reduce the negative impact of nutrient contamination on both living organisms and water resources. Additionally, controlled fluidized agriculture irrigation serves to alleviate scarce water supplies. The manufacturers of crops are also innovating - GMO plant species are developed to cope with harmful infections and insects on any crop without having to introduce harmful chemical spray.

As such, large remote-sensing monitoring platforms featuring drone fleets and satellite collaborations appear. Digital cultivation on-farm supervision would be used for farmers to quickly further effortlessly manage those crops, aiming for further cost-cutting and yield maximization. Ultimately, this paves the possibility of an additional versatile action that is supported by an AI-derived model used for every phase of the agricultural process, i.e., soil determination of the vegetation structure, planting, tilling, pest & weed control, supplementation of nutrients, as well as harvest and post-harvest methods (Kojo Gyamfi *et al.*, 2024) [12].

The Role of Biotechnology

Developing countries continue to be dependent on global broadacre grain crops (wheat, rice, soyabean, barley) for food, fodder, and fuel. In a global context, attempts at widespread commercial initiatives in smart broadacre agriculture shade into tokenism because, in essence, the ultra-high economy of scale investment in machinery and infrastructure creates mothballing of any such systems on landholdings smaller than 500 ha. It is with the advent of autonomous field robots, imbibed by AI that a sustainable qualitative increase in the precise application of farm inputs (geoprecision agri-regime farming) can be delivered, together with constant monitoring of crop and soil conditions. The decade 2020 forward must see a fundamental shift in attitude and a timely alignment of all necessary commercial, technical, legislative and political strands for the successful launch of smart broadacre robotic farming. The developing economies of this Earth, with the vast majority of small-scale land choose for crop production and substantial poverty levels, would particularly welcome universal affordable progress in the precise and robotic tending of their global broadacre grain crops. The prospects for fulfilment of this aspiration, both in the next decade and beyond, are fraught with highly complex technical, legislative, socio-political, and commercial challenges, many of which are far removed from the perceived discipline of agri-robotics itself (Grieve *et al.*, 2019) [11].

Predicted Advances in AI

Artificial intelligence and machine learning hold tremendous potential to revolutionize crop production, offering vital tools to manage finite resources more sustainably. By integrating these technologies into precision agriculture systems, crops can be monitored more accurately, while resources-such as water, pesticides, and seeds-can be tailored to each plant's needs. Furthermore, the application of AI in vertical farming is examined, looking at how machine-learning algorithms and computer vision systems are being employed to generate a highly controlled growth environment. Such techniques offer a pathway to mitigate vertical farming's major criticisms, suggesting they will evolve from high-tech, high-cost operations to ubiquitous, sustainable food-production hubs.

This "factory farming" is associated with concerning economic consequences. Though the overall revenue of such operations may increase, this will occur alongside the displacement of traditional farmers and a reduction in rural employment. Given the relatively impoverished socioeconomic status of many low-to-middle-income countries, the spread of industrial agriculture may well exacerbate existing food insecurity, prompting renewed calls to evaluate the environmental and social consequences of industrial farming. By contrast, vertical farming benefits from higher levels of predictability: LED lighting can be programmed according to a known schedule, optimally providing plants with just the required light, while temperature, humidity and CO2 levels are more easily regulated in a controlled environment. This capacity for "fine tuning" also extends to nutrient supply: unlike soil-based agriculture, vertical farms allow the precise manipulation and refinement of hydroponic growing media. At a larger scale, AI and machine-learning algorithms can be applied to control an array of sensors and actuators, generating a highly responsive, adaptable system. This automation can much increase labor efficiency, reduce employee costs, and optimally regulate resource use.

Regulatory Changes and Their Impact: Despite the potential benefits of smart-sensing enabled Selective field robotic (Agri-Bio) technologies, there are numerous challenges that currently constrain their successful use in broad-acre crop applications. Several potential regulatory changes that would help to promote the uptake of technologies by the broad-acre crop industry are proposed (Grieve *et al.*, 2019) [11]. It is suggested that there could be an immunization programme where the Agri-Bio technologies of the future might be shielded for a short period of time from the more onerous regulatory regimes governing access to the fields of today. The barrier faced by new technologies emerging from non-agricultural sectors is the plethora of regulatory hurdles that those technologies will have to overcome before they can be used in the field. The malfunction of smart agricultural machines or their control systems can lead to a severe impact on the operator, third parties, farm animals, or the environment. A regulatory approach that encourages manufacturers to follow best practice in the design, implementation, and monitoring of their products will reduce the risk of accidents. The widespread adoption of smart Agri-Bio field systems is also conditional upon broad changes to the supporting infrastructure. If the broad-acre crop industry is to take advantage of recent research developments in the Agri-Bio sector, the structure, content, and operation of this sector will have to undergo major transformation. Today, Agri-Bio technologies are not actively used in broad-acre cropping, partly because of their current high costs and the lack of full occupational safety and health (OSH) coverage, which hampers their widespread exploitation. These systems are currently developed and introduced in a completely unstructured agricultural environment, and there are growing fears that serious accidents either with the technologies themselves, or because of their induced behaviour, could occur.

Moreover, the implementation of emerging technologies has the potential to significantly change the agricultural sector by increasing agricultural productivity and efficiency through improved irrigation management, soil monitoring and pest control. It is demonstrated by reviewing the results of various projects that have aimed to improve the performance of vital elements of the agricultural sector, such as the enhanced precision monitoring and management of agricultural activities, and by developing the necessary data analytics tools and techniques within the framework of products and methods based on the Internet of things, artificial intelligence and geographic information system technologies (Kojo Gyamfi *et al.*, 2024) [12]. Some practical guidelines are presented designed to assist farmers to choose the most suitable technology and system on the basis of specific needs or crop characteristics. It is concluded that the implementation of emerging crop-sensing technologies improves the precision of farming activities, increases the efficiency and quality of the agricultural output and reduces production costs. On the basis of Agri-Bio project experience, it is reported that new manufacturing standards are developed.

Conclusion

Modern agriculture has come a long way since the shift from the hunter-gatherer lifestyle to permanent settlement and cultivation nearly 10,000 years ago. The major turning points include the introduction of crop rotation in the 18th century, selective breeding in the 19th century, and synthetic fertilizers and agricultural chemicals in the 20th century. The development of these technologies has underpinned a tremendous increase in grain production, which is feeding the world population which has increased from 1 billion to 7.7 billion within the last 200 years. However, it did not come without environmental costs. Modern agriculture is highly energy and water demanding and causes the significant release of greenhouse gases and pollution of rivers, lakes, and oceans. The increasing pressure on farmer's revenue, environmental concerns, and the fact that arable land is getting scarce all recast the search for a technological reset for agriculture.

Now is the time when Artificial Intelligence and big data are making their way into industrial agriculture. Focusing on crop production, the food and agriculture industry is projected to increase its investments on AI to USD 5.88 billion by 2022; and employment in the sector will surpass 76,000 by 2021 in the US. A growing number of startups focusing on AI-driven agriculture have exploded this decade. Some aim to optimize chemical use through micro-spraying, some on precision weeding and selective mowing using computer vision, some produce drones and robots for various agricultural applications, some optimize transportation, and some aim to improve the production quality. But, by and large, the most popular and profitable area is associated with what is called precision agriculture, smart farming or farming 4.0, where the general idea is to manage farmlands per-variable. AI algorithms are crucial in the remote sensing, monitoring and predictive modeling components of precision agriculture. With the booming development of IoT and affordable sensors, huge amounts of data exist powered by Internet-connected devices that can collect various types of data such as weather conditions, crop growth, moisture, insect infestation or equipment status of the field; and AI can be implemented to deliver a large spectrum of models.

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