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Applications of Internet of Things (IoT) in agriculture: A review

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Abstract

The rapid growth of the global population and increasing pressure on natural resources have created an urgent need for innovative technologies to enhance agricultural productivity and sustainability. The Internet of Things (IoT) has emerged as a transformative technology that integrates sensors, connectivity and data analytics to support smart and precision farming. This paper reviews the applications of IoT in agriculture and examines its potential to improve farm management and decision-making. IoT-based systems enable real-time monitoring of soil moisture, temperature, humidity and crop health through interconnected devices and sensors. These technologies facilitate automated irrigation, precision fertilization, disease detection and livestock monitoring, thereby reducing resource wastage and improving production efficiency. The study also highlights the role of IoT in smart farming components such as drones, greenhouse monitoring systems and data-driven farm management platforms. In the Indian context, several government initiatives and private sector innovations are promoting the adoption of IoT-based smart agriculture solutions. However, challenges such as high initial investment, poor rural connectivity, data management issues and limited technical knowledge among farmers continue to hinder large-scale implementation. Strengthening digital infrastructure, providing training and promoting public-private partnerships are essential for expanding IoT adoption in agriculture. Overall, IoT-based smart farming offers a promising pathway toward sustainable, efficient and climate-resilient agricultural systems capable of meeting future food security demands.

Keywords: Internet of things, smart farming, precision agriculture, digital agriculture, sustainable agriculture.

Introduction

Modern day agriculture and civilization together demand increased production of food to feed the global population. New technologies and solutions are being applied in agricultural domain to provide an optimal alternative to gather and process information while enhancing net productivity. At the same time, the alarming climate change and increasing water crisis demand new and improved methodologies for modern age agricultural and farming fields. Automation and intelligent decision making are also becoming more important to accomplish this mission (Hart and Martinez, 2006; Tong *et al.*, 2022) [28, 64]. In this regard, Internet of Things (IoT) (Atzori *et al.*, 2010; Gubbi *et al.*, 2013; Rai *et al.*, 2013) [5, 27, 55], ubiquitous computing, wireless ad-hoc and sensor networks, remote sensing (Morais *et al.*, 2008) etc. technologies are becoming increasingly popular.

Information and communication technologies (ICTs) are playing an increasing role in addressing problems faced by agriculture. The challenges faced by agriculture from climate change alone are enormous and the need for the farming communities to adapt and become resilient is key to feeding the world's growing population. Harnessing the growth and transformative potential of ICTs provides a tremendous platform not only for addressing some of these challenges but also for accelerating efforts to achieve the Sustainable Development Goals (SDGs) by 2030. As technology continues to saturate modern society, agriculture has started to adopt digital computing and data-driven innovations. This emergence of "smart" farming has led to various advancements in the field, including autonomous equipment and the collection of climate, livestock and plant data. As

connectivity and data revolutionize the farming industry, empirical research is a necessity for understanding these management continue to technological developments. (Ahmed, M., 2023) ^[3]. Artificial Intelligence and IoT-Based Technologies for Sustainable Farming and Smart Agriculture provides emerging research exploring the theoretical and practical aspects of critical technological solutions within the farming industry. Sensor networks based on the Internet of Things (IoT) are increasingly being used in the agriculture sector to meet the challenge of harvesting meaningful and actionable information from the big data generated by these systems.

Internet of Things – Concept

Internet of Things (IoT) (Atzori *et al.*, 2010) ^[5] (Nayyar, 2016) ^[48] consists of two words – Internet and Things. The term “Things” in IoT refers to various IoT devices having unique identities and has capabilities to perform remote sensing, actuating and live to monitor of certain sorts of data. IoT devices are also enabled to have live exchange of data with other connected devices and applications either directly or indirectly or collect data from other devices and process the data and send the data to various servers. The other term “Internet” is defined as Global Communication network connecting trillions of computers across the planet enabling sharing of information.

Internet of Things (IoT) refers to the implementable Machine-to-Machine (M2M) communications which is a crucial component of recent growth in the digital market. IoT has been described by various notions such as:

- A dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual ‘Things’ have identities, physical attributes and virtual personalities and use intelligent interfaces and are seamlessly integrated into the information network (Kranenburg, 2008) ^[38].
- IoT combines people, processes, device and technology with sensors and actuators. This overall integration of IoT with human being in respect to communications, collaboration and technical analytics enables to pursue real-time decision (Giusto *et al.*, 2010) ^[23].

How IoT works

As we all know that Internet has changed the way we work and communicate with each other, by connecting us through the World Wide Web (internet), IoT also aims to take this connectivity to another level by connecting multiple devices at a time to the internet thereby facilitating man to machine and machine to machine interactions.

Here, 4 fundamental components of IoT system, which tells us how IoT works:

Sensors/Devices

First, sensors or devices help in collecting very minute data from the surrounding environment. All of this collected data can have various degrees of complexities ranging from a simple temperature monitoring sensor or a complex full video feed. A device can have multiple sensors that can bundle together to do more than just sense things. For example, our phone is a device that has multiple sensors such as GPS, accelerometer, camera but our phone does not simply sense things. (Atzori *et al.*, 2010) ^[5].

Connectivity

Next, that collected data is sent to a cloud infrastructure but it needs a medium for transport. The sensors can be connected to the cloud through various mediums of communication and transports such as cellular networks, satellite networks, Wi-Fi, Bluetooth, wide-area networks (WAN), low power wide area network and many more.

Data Processing

Once the data is collected and it gets to the cloud, the software performs processing on the acquired data. This can range from something very simple, such as checking that the temperature reading on devices such as AC or heaters is within an acceptable range. It can sometimes also be very complex, such as identifying objects (such as intruders in your house) using computer vision on video.

User Interface

Next, the information made available to the end-user in some way. This can achieve by triggering alarms on their phones or notifying through texts or emails. Also, a user sometimes might also have an interface through which they can actively check in on their IOT system. For example, a user has a camera installed in his/her house he might want to check the video recordings and all the feeds through a web server. (Bonomi *et al.*, 2012) ^[8].

IoT real world applications

1. IoT in Industry

The application of IoT technologies in industrial environments significantly enhances production efficiency and ensures improved communication and networking between operators and machines. This leads to increased competitiveness through optimized quality control and minimized operational losses. A critical aspect of Industrial IoT is the development, design and integration of advanced sensors, which form the backbone of effective industrial management systems (Li *et al.*, 2020) ^[41]. Further research is required to optimize the implementation of IoT in specific industrial sectors and to understand how these technologies can be most efficiently applied. Progress in sensor connectivity, data processing and system integration is essential for the advancement of smart IoT-based Computer-Integrated Manufacturing (CIM), enabling more intelligent and automated production processes (Chen *et al.*, 2020) ^[12-13].

2. IoT in the Smart City Concept

IoT plays a crucial role in the development of smart cities by addressing major infrastructural challenges associated with rapid urban population growth (Janik *et al.*, 2020) ^[31]. Through the use of interconnected devices, IoT enhances the quality of life by improving the efficiency of urban services such as transportation, surveillance, smart metering, energy management and water distribution. IoT-based systems enable real-time monitoring and early detection of infrastructural faults such as traffic congestion, power outages, water leakage and security threats. These technologies support the development of smart grids, smart transportation, waste management systems and intelligent communities. Within this framework, smart homes offer advanced control options for energy usage, contributing to both

time and cost savings while improving residential comfort (Moniruzzaman *et al.*, 2020) ^[45]. Additionally, IoT facilitates the efficient integration and balancing of renewable energy sources at the household level (Stavrakas and Flamos, 2020) ^[62].

3. IoT in Agriculture

Efficient agricultural production is vital to meet the growing food demands of the global population, especially in the face of climate change and resource scarcity (Hussain *et al.*, 2020; Yang *et al.*, 2020) ^[29, 68]. Food waste also remains a significant concern, with over 28% of agricultural land contributing to wasted food while more than 800 million people suffer from hunger (FAO, 2020) ^[19]. IoT technologies enable precision farming through real-time monitoring of crop health, soil conditions, nutrient levels and irrigation needs. Smart irrigation systems help optimize water usage, while early disease detection enhances yield efficiency (Zou *et al.*, 2023) ^[70]. These technologies also support accurate seeding and improved fertility management. However, successful implementation requires farmer education and user-friendly software systems to manage the vast amount of collected data. Standardized training programs and simplified interfaces are essential to prevent data overload and ensure effective utilization (Eceuropa, 2017).

4. IoT in Healthcare

Healthcare represents one of the most challenging yet promising application areas for IoT, particularly through the e-health framework (Farahani *et al.*, 2020) ^[20]. IoT enhances patient safety and care through continuous monitoring using smart medical devices that track vital signs such as heart rate, body temperature and mobility (Papa *et al.*, 2020) ^[51]. Remote health monitoring allows for early detection of symptoms and prevention of life-threatening conditions (Muthu *et al.*, 2020) ^[47]. IoT solutions also support elderly care by monitoring nutrition and general health status (Nivetha *et al.*, 2020) ^[49] and facilitate rehabilitation in home environments (Bisio *et al.*, 2019) ^[7]. Despite these advantages, cybersecurity remains a critical concern due to potential system vulnerabilities (John *et al.*, 2019) ^[32]. In hospital environments, IoT integration enables the creation of smart hospital systems by connecting medical devices such as MRI and CT scanners with laboratory and patient data, improving diagnosis and treatment efficiency. IoT also supports preventive maintenance, reducing equipment costs and enhancing reliability (Shamayleh *et al.*, 2020) ^[60]. These technologies are especially valuable during global health crises like the COVID-19 pandemic (WHO, 2020) ^[66].

5. IoT in Transportation

IoT is transforming transportation systems, particularly with the growing adoption of electric and alternative fuel vehicles and the gradual phasing out of diesel engines due to environmental concerns (Jonkeren *et al.*, 2019; Capuder *et al.*, 2020) ^[33, 11]. The Internet of Vehicles (IoV) concept highlights IoT's role in enhancing vehicle intelligence and safety (Shen *et al.*, 2020) ^[61]. Smart vehicles utilize IoT to monitor parameters such as tyre pressure, fuel levels, maintenance schedules and potential system failures, enhancing safety and driving comfort (Chugh *et al.*,

2020) ^[14]. Autonomous vehicles rely heavily on IoT for navigation, route planning and collision avoidance systems (Padmaja *et al.*, 2019; Abdou *et al.*, 2019) ^[50, 1]. Additionally, smart parking systems provide real-time information on available spaces, improving urban traffic flow and reducing congestion (Luque-Vega *et al.*, 2019) ^[44]. IoT also supports predictive maintenance, increasing vehicle lifespan and operational reliability (Saki *et al.*, 2020) ^[59].

6. IoT in Waste Management

IoT plays a vital role in advancing smart waste management systems aligned with the circular economy model (Fan *et al.*, 2019) ^[18]. These systems enable intelligent monitoring of waste bins, including fill levels, temperature, vibration, humidity, GPS location and fire detection (DhanaShree *et al.*, 2019) ^[16]. IoT also facilitates efficient coordination of waste collection vehicles, optimizing routes and reducing fuel consumption and greenhouse gas emissions (Idwan *et al.*, 2020; Kozina *et al.*, 2020) ^[30, 37]. Furthermore, IoT supports the proper management of electronic waste and recycling processes, helping conserve raw materials for electronic production (Kang *et al.*, 2020) ^[35]. Smart appliances integrated with IoT technology can also contribute to reducing food waste through intelligent inventory and consumption management systems (Liegeard and Manning, 2020) ^[42].

IoT in current Agriculture

The Internet of Things (IoT) in agriculture represents a network of interconnected physical objects, including sensors, machines, robots and devices, that communicate via the internet to collect, process and act upon data autonomously (Gralla, 2019) ^[26]. The adoption of IoT in agriculture has grown rapidly in recent years, with approximately 26.5 million installed wireless IoT connections in 2023, projected to reach 38.2 million by 2028, reflecting a compound annual growth rate (CAGR) of 7.6% (Berg Insight, 2025) ^[6]. Similarly, the global IoT in agriculture market, valued at USD 15.42 billion in 2024, is expected to reach USD 48.34 billion by 2034, growing at a CAGR of 12.1% (globalagricultureonline.com). IoT provides numerous benefits for modern agriculture, including labor reduction, error minimization, optimized resource usage, real-time monitoring of crops and environmental conditions and predictive insights for better decision-making (Kim *et al.*, 2020; Zhang *et al.*, 2017) ^[40, 69]. Current applications include automated crop monitoring, precision farming and climate-resilient agriculture, where sensors collect data on soil moisture, weather and crop health to guide irrigation, fertilization and pest management (Saha *et al.*, 2018; Talavera *et al.*, 2017; Patil and Kale, 2017) ^[58, 63]. Despite these advancements, challenges such as limited connectivity in rural areas, high initial costs data management issues and interoperability between devices remain. Nevertheless, ongoing innovations in low-cost sensors, edge computing and integrated platforms are addressing these obstacles, paving the way for widespread adoption. Overall, IoT is enabling a shift toward data-driven, automated and sustainable agriculture, promising to enhance productivity, efficiency and resilience in the global food system.

Smart Farming

Smart Farming is a farming management concept using modern technology to increase the quantity and quality of agricultural products. Farmers in the 21st century have access to GPS, soil scanning, data management and Internet of Things technologies. The goal of smart agriculture research is to ground a decision-making support system for farm management. Smart farming deems it necessary to address the issues of population growth, climate change and labour that has gained a lot of technological attention, from planting and watering of crops to health and harvesting. (Patil, K. A. and Kale, 2017). In IOT-based smart agriculture, a system is built for monitoring the crop field with the help of sensors (light, humidity, temperature, soil moisture etc.) and automating the irrigation system. IOT (Internet of things) in an agricultural context refers to the use of sensors, cameras and other devices to turn every element and action involved in farming into data. We need smart agriculture to expand and develop from what it currently is because this practice will substantially decrease the negative environmental externalities of modern agriculture. (Kumar, A. and Singh, A., 2020) ^[39].

Components of a Smart Farming

- **Sensors:** Soil, water, light, humidity, temperature management.
- **Software:** Specialized software solutions that target specific farm types or Applications agnostic IoT platforms.
- **Connectivity:** Cellular, LoRaWAN (Long Range Wide Area Network) etc.
- **Location:** GPS, Satellite etc.
- **Robotics:** Specific, Autonomous processing facilities.
- **Data Analytics:** Standalone analytics solutions, Software and applications for analytic processes.

Applications of IoT in Agriculture

Drone-based uses

Drones play a big role in smart farming. They can check the quality of soil, air and moisture, as well as help with tasks like preventing outbreaks and spraying fertilizers automatically. While there are some downsides to using drones, they help cut down on manual labour (Verdouw *et al.*, 2016) ^[65], (Kour, V. P. and Arora, S., 2020) ^[36]. In agriculture, drones are used for various jobs like monitoring crops, spraying fields and analyzing soil. They come in different types, like ground-based ones that roll across fields and aerial ones that fly above. Drones can be controlled remotely or set to fly on their own using software and GPS. They collect data on things like crop health, irrigation needs and yield predictions. After collecting data, drones need to be taken to labs nearby for analysis, which helps make better use of Internet of Things (IOT) technology in farming (Kour, V. P. and Arora, S., 2020) ^[36].

Real time crop monitoring

Sensors like motion detectors and light sensors are handy tools for farmers to get instant updates about their farms. They help farmers keep an eye on the quality of their produce. Agriculture experts are working on making farming more digital, so farmers can keep track of how their plants are growing and take actions to get the best harvest. This new idea is great because it allows farmers to monitor their farms from afar and it's very dependable. It could make farming more reliable and profitable. But whether it becomes widespread depends on how much farmers know

about it and how well it works in improving agriculture. (Farooq *et al.*, 2020) ^[21], (Ferrag *et al.*, 2020) ^[22].

Smart irrigation system

It is one of the parts of smart agriculture using IOT. IOT checks the water lanes created by the farmer or the moisture level in the environment. The efficient and intelligent utilization of water for farming is smart Irrigation (Boursianis *et al.*, 2022) ^[9], (Kour, V. P. and Arora, S., 2020) ^[36]. A smart irrigation system consists of an IOT-based system. This system can further be enhanced to amplify its software capability and functionality. Third-party APIs can be integrated to access important information that can help you substantially in irrigation planning for the crops. In this article, we will discuss smart irrigation and its role in agriculture. (Gondchawar *et al.*, 2016) ^[25]. An efficient irrigation system can enhance crop yield and quality and minimize the usage of pesticides and fertilizers. A successful crop harvest depends on various inputs that should be focused on. The optimized usage of inputs like water, fertilizers, pesticides, etc. Along with technological solutions help in providing a good yield with better quality. We will discuss smart irrigation and its role in agriculture. An efficient irrigation system can enhance crop yield and quality and minimize the usage of pesticides and fertilizers. (Verdouw *et al.*, 2016) ^[65] (Boursianis *et al.*, 2022) ^[9].

Data analytics

It is an end-to-end IOT platform and cloud-based data storage play a vital role in smart agriculture system. Data analytics helps in the analysis of crop conditions, weather conditions and livestock conditions. In IOT sensors are the primary source of collecting the data on a large scale (Patil *et al.*, 2012) ^[53]. In agriculture, IOT helped the farmers in maintaining the quality of crops. Using the analytics tools the data is analyzed and transformed into meaningful information. There are some of the benefits of IOT in agriculture that are listed as follows –

1. Excellent efficiency
2. Cleaner process
3. Reduced resources
4. Agility
5. Expansion
6. Improved product quality (Rudrakar, S., and Rughani, P. 2023)

Greenhouses

Greenhouses are like special homes for plants, providing just the right environment for them to thrive. Normally, people have to keep checking and fixing things in the greenhouse to make sure everything's okay. But with a smart greenhouse that uses Internet of Things (IOT) technology, it can do all that by itself. This saves time and means people don't have to be there all the time. Using IOT in greenhouses is also a good deal because it's cheaper and makes everything more accurate by removing mistakes made by people. For example, you can use solar-powered IOT sensors to make affordable and modern greenhouses. Greenhouse farming is popular because it helps plants grow better. There are two main types: fully controlled, where everything is watched closely and partially controlled, where some things are left to nature. Greenhouses are great for growing veggies, fruits and crops because they manage things like temperature and humidity. With a smart design, the greenhouse can handle all this without needing constant

attention from people, making farming simpler and better. (Ferrag *et al.*, 2020) ^[22].

Livestock monitoring

Big farm owners can use wireless IOT technology in farming to keep track of where their animals are and how they're doing. They gather data on things like where the animals are, their health and if any of them are sick. This helps them find sick animals and keep them away from the rest of the group, stopping illnesses from spreading. It also saves money on labour because farmers can find their animals easily with IOT sensors. There are organizations that provide solutions for monitoring livestock. One solution helps farmers keep an eye on pregnant cows. When a cow's water breaks before giving birth, a sensor pops out and sends a message to the farmer. This lets farmers focus on helping cows that are having babies, saving time and effort (Gondchawar *et al.*, 2016) ^[25], (Kour, V. P. and Arora, S., 2020) ^[36].

IoT in Indian Agriculture

Agriculture is one of the most vital sectors in any country, especially in developing nations such as India, where it plays a crucial role in economic growth and food security. The agricultural sector contributes significantly to the national economy and serves as the primary source of livelihood for a large portion of the population. Historically, agricultural productivity during and before India's independence was considerably higher when compared to the present scenario, highlighting the need for technological intervention and modernization. Agriculture continues to be the backbone of the country's economy, with more than 50% of the population directly or indirectly dependent on it. As India's population continues to grow, enhancing agricultural productivity has become essential to meet increasing food demands. Crop yield is strongly influenced by various environmental factors such as temperature, rainfall, soil characteristics and geographical topology. In order to protect crops from natural disasters and unpredictable climatic conditions, farmers are increasingly interested in analyzing seasonal variations. The prediction of crop yield based on historical and nearby field data can be effectively achieved through the application of computer-based techniques and data mining methods, which provide valuable insights for informed decision-making and sustainable agricultural practices. (Rao, N. H., 2008) ^[56].

Government Policies and Private Sector Initiatives

To accelerate the adoption of IoT-based smart farming, both the Indian government and private sector have launched various initiatives to support farmers in integrating technology into agriculture. These efforts focus on providing financial aid, technological infrastructure and training to improve productivity and sustainability.

1. Government Policies Supporting IoT-Based Smart Farming

- a) Digital Agriculture and Policy Frameworks
National e-Governance Plan in Agriculture (NeGPA):
 - Promotes the use of ICT and IoT for precision farming and smart agriculture.
 - Encourages state governments to implement digital solutions for farm management.

National Mission for Sustainable Agriculture (NMSA):

- Focuses on climate-resilient farming, integrating smart irrigation and real-time weather data analysis.

Smart Agriculture Program under the Digital India Initiative:

- Aims to develop IoT-based platforms for small and marginal farmers.
- Supports data-driven decision-making for water and soil management. (Joshi, J., 2024) ^[34].

b) Financial Incentives and Subsidies

Pradhan Mantri Krishi Sinchayee Yojana (PMKSY):

- Provides funding for smart irrigation systems like IoT-enabled drip irrigation.
- Encourages efficient water management using digital monitoring.

Startup India Initiative:

- Supports agritech startups working on IoT-based solutions.
- Offers tax benefits, funding support and incubation programs for innovative smart farming businesses.

2. Private Sector Initiatives Driving IoT Adoption

a) Agritech Startups and Innovations

Several Indian agritech startups are pioneering IoT-based smart farming solutions:

- **Fasal:** Provides AI-driven weather forecasting and real-time farm monitoring to optimize water use and pest control.
- **CropIn:** Uses big data and cloud computing to offer farmers predictive analytics for better crop management.
- **DeHaat:** Integrates IoT to connect farmers with market linkages, advisory services and credit access. (Joshi, J., 2024) ^[34].

b) Corporate Investments and Collaborations

- **Tata Group and Mahindra Agribusiness:** Partner with startups to develop automated farming equipment and precision agriculture tools.
- **Reliance Jio's Agri IoT Platform:** Provides rural connectivity solutions to enhance IoT adoption in farming.
- **Microsoft AI for Agriculture:** Uses AI and IoT to develop predictive models for farmers, helping them increase yield and reduce risks.

3. Public-Private Partnerships (PPP) for Smart Farming

- **ICAR (Indian Council of Agricultural Research) and Private Sector:** Collaborative projects focusing on IoT-based soil testing, disease prediction and smart irrigation.
- **World Bank-funded Agriculture Digitization Projects:** Works with state governments and agritech startups to develop IoT-based farm advisory services. The combined efforts of the government and private sector are crucial in making IoT-based farming accessible, affordable and scalable for Indian farmers. (Joshi, J., 2024) ^[34].

Benefits of IoT in Agriculture

Just like in other fields, using Internet of Things in farming can make things work better, save resources and cut costs. It also helps make farming more automatic and based on data.

But in farming, these benefits aren't just improvements they're solutions to some serious problems the industry faces.

1) Improved Productivity

Modern farming is challenging. Farmers must produce more crops despite worsening soil, shrinking land and unpredictable weather. With IOT technology, farmers can monitor their crops and conditions in real time. They quickly learn about problems, predict issues in advance and make smart decisions to prevent them. Also, IOT brings automation to farming, like watering and harvesting based on demand, as well as using robots to help with harvesting. (Liu, S., and Wu, Y. 2021) ^[43], (Verdouw *et al.*, 2016) ^[65].

2) Growth

As the world's population reaches 9 billion, most people will live in cities. Using IOT technology, we can grow fresh fruits and vegetables close to where people live, making the food supply chain shorter. With smart farming systems, we can grow food in many places, like on the walls and roofs of buildings, inside shipping containers and even at home. (Liu, S., and Wu, Y. 2021) ^[43].

3) Reduced resource

IOT solutions help farmers use less water, energy and land more effectively. In agriculture, IOT relies on data from various sensors in the fields. This data helps farmers distribute the right number of resources to each plant, reducing waste. (Verdouw *et al.*, 2016) ^[65].

4) Cleaner process

Smart farming with IOT is a great way to use fewer pesticides and fertilizers. Precision farming helps farmers save water and energy, making farming more environmentally friendly. It also reduces the amount of chemicals used, leading to a cleaner and more natural final product than traditional farming methods. (Adesta *et al.*, 2017) ^[2].

Challenges of IOT in Agriculture

1. Poor Infrastructure

Many farmers struggle to benefit from IoT because they lack good communication systems. Their farms are often far from the internet, making it hard to access important crop data when they need it. Without reliable connections, fancy monitoring systems are basically useless.

2. Expensive Equipment

Setting up IoT on farms is costly. While sensors are relatively cheap, outfitting all fields with them can cost over a thousand dollars. Automated machinery is even pricier, as it includes things like farm management software and cloud access for data recording. While these technologies can boost profits, it's tough for farmers to afford the initial investment.

3. Security Concerns

IOT devices interact with older equipment and connect to the internet, raising security issues. There's no guarantee that they can securely access drone maps or sensor data through public connections. Plus, IOT systems collect a ton of data, which can be hard to protect. If someone hacks into the IOT

provider's database, they could steal or tamper with the data posing a big risk.

4. Technical Challenges

Using and handling IOT systems needs special technical knowledge that many farmers might not possess. Everything from installing sensors to understanding data can be difficult for those not used to technology.

5. Compatibility Problems

Mixing different IOT devices and systems made by different companies can be tough. Farmers might encounter issues where sensors, machines and software don't work well together, causing problems and making communication harder. (Ferrag *et al.*, 2020) ^[22].

6. Data Overload

Even though IOT gives lots of data, farmers might find it hard to understand. Sorting through all the data to find useful information can take a lot of time and feel overwhelming. This might make it hard to make decisions or miss chances to improve things. (Ferrag *et al.*, 2020) ^[22].

7. Reliability Worries

IOT relies on sensors and connections, which can break or stop working. Problems with hardware or software, as well as issues with connections or power, can make IoT less dependable on farms.

8. Privacy and Ownership

Farmers might worry about who owns their data and if it's safe. Sharing private farm data with IOT companies or others could lead to questions about who controls it and if it could be misused. This might make farmers hesitant to use IOT solutions. (Liu, S., and Wu, Y. 2021) ^[43].

Recommendations for Scaling IoT based Smart Farming in India

a) Making IoT Solutions Affordable for Small Farmers

- Government subsidies and low-interest loans should be introduced to support smallholder farmers in adopting IoT technologies.
- Promotion of shared IoT infrastructure, such as community-based sensor networks and automated irrigation systems.

b) Strengthening Digital Literacy and Training Programs

- Launch IoT skill development programs for farmers to educate them on using smart farming tools effectively.
- Multilingual mobile apps and helplines should be developed to assist farmers in understanding real time IoT data.

c) Expanding Public-Private Partnerships

- Encourage collaboration between agritech startups, research institutions and government bodies to develop scalable and region-specific IoT solutions.
- Strengthen corporate social responsibility (CSR) programs to fund IoT initiatives in underserved rural areas.

d) Enhancing Rural Connectivity and Infrastructure

- Invest in high-speed internet expansion in rural India to ensure seamless data collection and IoT device connectivity.

- Promote the use of solar-powered IoT devices to counter electricity shortages in farming communities.
- e) **Data Security and Regulatory Frameworks**
 - Implement strict data privacy laws to protect farmers' sensitive agricultural data from misuse by corporations.
 - Establish a centralized agricultural data repository for farmers to access secure, real-time market insights and climate reports. (Joshi, J., 2024) ^[34].

Startup Ecosystem for Northeast India

Software Technology Parks of India (STPI) has launched OctaNE, a bouquet of eight internetworked Centre of Excellences (CoEs) to support technology led innovation in North East India. Locations wise CoEs are IoT in Agriculture (Guwahati), Animation (Shillong), Emerging Technologies (AR/VR) (Imphal), IT in Healthcare (Gangtok), GIS Including Drone Technology (Itanagar), Graphics (Kohima), Data Analytics (Agartala) and Gaming (Aizawl) along with an "Open Challenge Program" to identity, recognize and reward aspiring and early-stage tech entrepreneurs.

This platform facilitates aspiring entrepreneurs/start-ups/innovators with strategic networking, seed funding, mentoring, providing support for training, marketing, patenting, access to the CoE labs, tools, software and state-of-the-art incubation facility. In the North-Eastern states of India, OctaNE is expected to accommodate 164 start-ups under phase-1 and phase 2 together (74+90) in emerging technologies in the field of Electronics and IT by providing financial/ technical assistance and mentoring support and will create direct employment for over 1,250 local youth (in-house units only). Further, direct employment in graduated units is expected to reach over 4,000 by Year-15 on a conservative basis. In addition, the local start-ups will be able to avail of good quality incubation facility to start operations without investing capital for the same.

The objective of opening this CoEs is to boost start-ups and to contribute to "Make-in-India" and "Digital India" programmes of Govt. of India. It will create a holistic eco-system for encouraging RandD, innovation and entrepreneurship by the creation of robust eco-system and incubate minimum of 164 number of start-ups, facilitating e-Commerce activities from the region, creation of employment opportunities through new innovative start-up units in NER, creation of entrepreneur's platform to enable networking, knowledge sharing and co-learning and developing tinkering and innovation culture amongst students and professionals. (Software Technology Parks of India., 2024).

Success story from Assam

AgSpert, an agri-tech startup, co-founded by the students of IIT Guwahati and alumni of NIT Silchar and Dibrugarh University, Assam, has developed AgSpeak, a multi-lingual Smartphone application for farmers to smartly manage their farms and remotely monitor distress activities. Developed with a goal of optimizing the in-farm productivity through Artificial Intelligence (AI), this application will help the farmers in making decisions and managing farm activities by the click of a single button on their smartphone or computer. AgSpeak was launched by Prof. T. G. Sitharam, Director, IIT Guwahati on 13/12/2020 at Guwahati. AgSpert is leading this initiative in the North-Eastern India which has untapped potential, with diverse ecosystems having

agriculture as the major economic activity. The developed application is multi-lingual and has an option of Assamese as well. This feature is a first among all the agri-tech applications available in the market. Driven by hyper local crop data coming from satellite and smart IoT devices, AgSpeak considers up to 20 local crop parameters which are key indicators of their health like temperature, rainfall, sunlight hours, soil health status, among others, to alert farmers about probable crop threats in advance and suggest best practices to tackle the incoming threat, hence optimizing the resources used and maximizing productivity. The app along with the IOT hardware has been tested for the past 3 months with 500 farmers and 2 tea estates. Some of the major breakthroughs by the algorithm were precise prediction of BLIGHT IN POTATO and TEA MOSQUITO BUG, along with WATER STRESS in winter crops. These are major reasons of woes to farmers and small tea growers of Assam and cause lakhs in crop damages if not controlled in time. Nearly 250 farmers have already been provided hands on training in utilizing the full potential of the app. However, the user friendliness and multilingual features of the app make it extremely easy for farmers to use and seldom require training. (Jaiswal, U., 2020).

Conclusion

IoT has helped implement modern technological solutions to time-tested knowledge in almost every sector. With seamless intelligent operations and improved business process execution, produce gets processed faster and reaches supermarkets in fastest time possible. Further development of data and application infrastructures and their institutional embedment will play a crucial role in the battle among several technology related scenarios. With continuous improvement in technology, IoT will bring revolution in the agriculture field also. Growing number of smart IoT devices are helping farmers in collecting meaningful data. Farmers should understand the power and potential of IoT for agriculture. As the population is increasing rapidly, farmers can successfully meet the demands. While Smart technologies will continue to influence Indian farming, the looming concern is the vulnerability to cyber threats from hostile attackers. Securing the platform with embedded firewall when upgrading or replacing older legacy systems, stringent risk analyses to understand where vulnerabilities may be and how best to address them and applying analytics to derive definitive insights will play a major role. On the other hand, IoT is transforming the agriculture industry so that farmers can master the enormous challenges. As the industry still to overcome growing water scarcity, limited land supply, the difficulty of managing costs and meet the growing demand for world consumers, which is expected to grow by 70 percent by 2050. Moreover, using IoT still open the doors for agriculture industry and farmers through improve the quality, quantity, sustainability and cost effectiveness of agricultural production by implementing them into reality as it's the only promising in 21st century.

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