

Precision Agriculture: The Transformative Way Forward for Indian Agriculture

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Abstract: *The Green revolution transformed India from being a food-deficit nation to a global agricultural powerhouse. Although, Agriculture continues to be the crucial backbone of the Indian economy employing 42 per cent of India's workforce while contributing 17-18 per cent to the country's GDP, the rates of agricultural productivity gains have begun showing signs of slowing in recent years. Stagnating farmer incomes are also causing considerable distress in the rural areas. There is an urgent need for a transformative change in Indian agriculture to raise productivity, ensure higher incomes, reduce risk, and make Indian agriculture more resilient to climate change and sustainable. This paper discusses the benefits and challenges of large-scale adoption of Precision agriculture as the transformative step forward.*

Keywords: Agriculture, IOT, precision agriculture, hydroponics, aeroponics, aquaponics, land degradation, climate change, sustainability, ground water, landholdings, rural productivity, GDP

1. Introduction

The Green Revolution stands as one of the most transformative periods in modern Indian agricultural history, making it the most crucial sector for the stability of the Indian economy. With the world's second-largest agricultural land area, India is a global leader in farm output. By 1990–91, agriculture accounted for approximately 35 per cent of India's GDP. However, by 2024–26, this share has declined to nearly 15 per cent. Although its contribution to national income has steadily declined over the past few decades, the sector continues to provide direct and indirect employment to nearly half of the country's population. Importantly, this decline does not signify stagnation or contraction in agricultural output but rather reflects the comparatively faster growth of the industrial and services sectors [1,2,3].

Since the early 2000s, although the services sector has emerged as the principal engine of overall economic growth, a shift generally considered desirable, India's experience reveals a critical mismatch between output transformation and employment reallocation. The capacity of non-agricultural sectors particularly manufacturing to absorb surplus labour from agriculture has remained limited. Consequently, agriculture continues to employ a disproportionately large share of the workforce, resulting in disguised unemployment, low labour productivity, and persistently depressed farm incomes [4,5].

According to the International Monetary Fund (IMF), India's agricultural labour productivity is only about 12.2% of the median productivity in advanced economies and 42.6% of the median for emerging markets. Meanwhile, the sector employs about 44–46% of the workforce but contributes only around 16–18% of GDP. Indian agriculture continues to face the twin challenges of low productivity and stagnating farmer incomes despite decades of reform [6,7]. Although the sector employs nearly half of India's workforce, its contribution to GDP remains disproportionately small, indicating very low labour and land productivity. Small & fragmented land holdings which makes mechanization and large-scale farming difficult, dependence on monsoons with approximately 60% of the net sown area being rain-fed, erratic consequences of climate change, ground water depletion, soil degradation, lack of

supportive infra structure, inefficient transportation and market access are some of the principal causes for this progressive decline. This progressive stagnation and gradual decline in productivity coupled with the continued concentration of a large workforce in agriculture and modest income growth in the sector, has far-reaching implications for poverty alleviation, income inequality, and the overall pace of economic development [8,9,10].

While the green revolution made India secure and self-sufficient in terms of food production, it also involved the widespread adoption of high-yielding seed varieties (HYVs) along with chemical fertilisers that resulted in higher yields and shorter crop cycles to boost food production. In practice, it led to large scale adoption of high-yielding seed varieties, chemical fertilisers and pesticides, controlled irrigation through electric pump sets or tubewells, and tractors, threshers and other machinery. Initially limited to wheat and Punjab-Haryana-western Uttar Pradesh, the techniques spread over time to rice-growing regions in the south, and then other parts of the country, though unevenly. The tremendous growth also influenced policy and shaped remunerative support prices and marketing opportunities at the State level, to favour a select group of crops. Which further led to an increased cropping intensity [10,11,12,13,14,15].

India is among the biggest producers of pesticides in all of Asia as a result of the sharp rise in pesticide usage leading to increased pesticide's residual activity. Pesticides are present in large quantities in soil and waterbodies, which contaminate the ecosystem. Use of chemical pesticides and fertilizers led to a decline in the soil quality depleting important nutrients and destroying beneficial pathogens due to the buildup of heavy metals and hazardous chemicals in the soil. Soil water is another effect of intensive agriculture. Large adoption of water intensive grains also led to reduction in the ground water further worsening the problem of water pollution. It also led to the extinction of indigenous varieties as India lost about one lakh native rice types as a result of the green revolution [16,17].

According to data from the Food and Agriculture Organization (FAO), millets have been produced less

frequently between 1961 and 2017 while rice and wheat have increased. As a result, the nation's basic diet consists of rice and wheat. The green revolution thus, raised calorie intake even though it guaranteed food security but not in nutrient security which is equally important for the human health. This has also led to a wide scale nutrient deficiency across India [18,19,20].

The existing system is not sustainable anymore as these conventional and input-heavy models face severe constraints from climate change, depleting water tables, and degrading soil. A fundamental paradigm shift is necessary to ensure long-term sustainability, food security, and farmer viability. This is where precision agriculture can bring transformative change. Precision agriculture (PA) is the science of improving crop yields and assisting management decisions using high technology sensor and analysis tools [21,22].

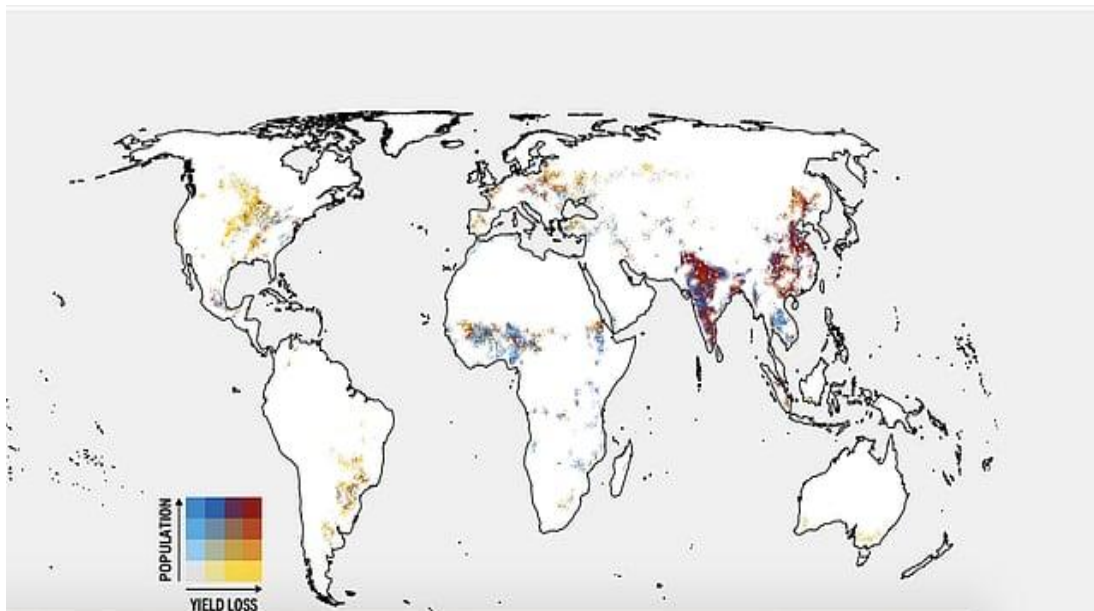
According to the International Society of Precision Agriculture, precision agriculture is characterized as a method aimed at improving efficiency in resource utilization, productivity, quality, profitability, and sustainability within agricultural production. Precision farming utilizes a combination of technologies to manage resources efficiently. The essence of precision farming lies in executing appropriate actions in the correct location, manner, timing, and in adherence to the proper procedures. This entails the meticulous management of crop production inputs, including water, seeds, and fertilizers, with the aim of boosting yield, quality, profitability, and reducing waste in an environmentally sustainable manner [23]. It strives to align agricultural inputs and practices with crop and agroclimatic conditions, ultimately improving the accuracy of their

applications [24]. It relies on a suite of data-driven and automated tools to optimize crop yields and minimize resource waste. Key technologies include GPS and GIS for mapping, IoT sensors for soil and climate monitoring, drones for aerial imagery, and Variable Rate Technology (VRT) for precision chemical and seed application. These technologies enable site-specific nutrient management, real-time nitrogen management, yield monitoring and vegetation indices analysis. The integration of big data, machine vision, IoT, artificial intelligence and blockchain further enhance precision agriculture. Big data analytics enables real-time forecasting and decision-making. On the other hand, machine vision provides non-destructive monitoring capabilities. IoT and AI, including machine and deep learning, contribute to guidance systems, high-throughput phenotyping and intelligent robots in agriculture. Blockchain technology addresses the challenges faced by the current data sharing infrastructure and improves trust in the supply chain. Its fundamental concept revolves around minimizing the input costs and enhancing the system efficiency through yield optimization [25,26,27,28].

This paper analyses the benefits and challenges of its large-scale adoption in India and why it could be the urgent transformation that Indian agriculture needs.

2. Benefits of Precision Agriculture in an Indian Context

2.1 Optimisation and More Efficient Use of Resources like Land, Water, Fertilizers and Pesticides:



Source: The State of Food and Agriculture 2025, FAO

The alarming human toll of land degradation on croplands was highlighted in the State of Food and Agriculture (SOFA) 2025 report released at the United Nations. The largest affected populations were concentrated in eastern and southern Asia regions burdened by extensive degradation and high population density. The report highlighted that India had some of the highest yield gaps due to human-induced land

degradation as is evident from the above figure [29]. Land degradation refers to the temporary or permanent decline in land productivity due to the deterioration of its physical, chemical, or biological characteristics. This degradation arises from a combination of processes, such as soil erosion by wind and water, deterioration of soil properties, and long-term loss of natural vegetation due to human activities and

habitation patterns [30]. The Intergovernmental Panel on Climate Change (IPCC) characterizes land degradation as a reduction or loss in land productivity resulting from human-induced factors like soil erosion, deterioration of soil properties, and loss of vegetative cover [31,32].

Several factors contribute to land degradation in the Indian context, including unsustainable land use practices, deforestation, soil erosion, water scarcity, and climate change impacts. The expansion of agriculture to meet growing food demands has resulted in the conversion of forests, grasslands, and other natural ecosystems into agricultural lands, leading to soil erosion, loss of biodiversity, and degradation of soil quality. Intensive agricultural practices such as monoculture farming and excessive use of chemical fertilizers and pesticides, contribute to soil erosion and loss of soil fertility [33,34]. Land degradation has far-reaching consequences for ecosystems, livelihoods, and sustainable development in India.

According to the Indian Ministry of Environment and Forests, approximately 147 million hectares (about 45% of the country's total area) are prone to water erosion. This includes regions susceptible to soil degradation due to rainfall and runoff. This phenomenon leads to the loss of valuable topsoil, diminished soil fertility, and reduced agricultural productivity, which in turn threatens the country's food security and environmental sustainability. Wind erosion is another significant issue in India, particularly in arid and semi-arid regions leading to the loss of topsoil, decreases soil fertility, and can cause significant damage to crop and infrastructure. Climate change impacts like erratic rainfall, prolonged droughts, and heatwaves increase the vulnerability of ecosystems and agricultural lands to degradation, leading to loss of vegetation cover, soil erosion, and desertification [35,36,37,38]. Topsoil is a valuable resource- it takes nature 50 years or more to build a mere centimetre of it and thus it cannot be allowed to go unchecked.

Land degradation is not the only challenge. India agricultural land share is shrinking India has experienced rapid urban growth since the 1991 economic liberalisation, and this process has led to widespread conversion of agricultural land into built-up areas. This poses a significant challenge for the future. Fragmentation of agricultural land in India involves the division of large farms into increasingly smaller, scattered plots. According to the Department of Agriculture, Cooperation and Farmers Welfare's last census, the average size of operational holdings has decreased from 2.28 hectares in 1970-71 to 1.84 hectares in 1980-81, to 1.41 hectares in 1995-96 and to 1.08 hectares in 2015-16. This steady subdivision makes smallholdings economically unviable, severely curbing farm mechanization and overall agricultural productivity [39,40,41].

India has 18 percent of the world's people but only 4 percent of its water resources. Rainfall is highly seasonal; nearly 70 percent occurs in just three months. With rising population, per capita water availability has fallen by half since 1970. Some 600 million people face water stress, while the frequency of both floods and droughts is increasing with climate change. Agriculture consumes 80–90 percent of India's water - two to three times more than China or Brazil.

Farmers have increasingly turned to groundwater, making it the dominant source of irrigation. However, unsustainable use of groundwater has led to the widespread depletion of this precious resource in many areas [42].

India is the world's largest extractor of groundwater, and in many areas, it is being depleted. According to the World Bank, in the last 50 years, the number of wells has increased from 1 to 20 million. About 60% of irrigation water comes from groundwater, a proportion that continues to grow compared to surface water from rivers and lakes. India extracts more groundwater each year than the US and China combined. There are increasingly more studies that classify this situation as very serious in the areas that suffer overexploitation. Different reports from NASA and from universities such as the one in Utrecht assure that the water reserves in the upper Ganges basin could collapse between 2040 and 2060, something that would constitute a socioeconomic catastrophe with incalculable consequences [43,44].

A vast majority of Indian farmers cultivate small, fragmented land plots and cannot afford resources needed for better productivity. They struggle to secure credit and are unable to afford the cost of farming inputs such as seeds, fertilizers, pesticides, and machinery which is increasing every year. However, the prices farmers get for their crops often remain stagnant or even fall. This gap between rising costs and low-income squeezes farmers financially, making it difficult for them to reinvest in their farms or save money. forcing them to rely on toxic, unregulated chemicals over safer, organic alternatives [45,46].

More than 85% of small and marginal farmers cannot easily access institutional loans. Consequently, they rely heavily on local middlemen and unorganized lenders, who often dictate which agrochemicals they must buy often pushing them to purchase substandard fertilizers and pesticides. Considering that they operate at a very basic subsistence level, the slightest weather unpredictability on account of climate change can destroy their livelihoods. Droughts, floods, unseasonal rains, and heatwaves destroy crops or reduce their quality and quantity. These risks make farming income unstable. Unfortunately, many farmers do not have crop insurance or government compensation for such losses, forcing them deeper into poverty when disaster strikes [47,48].

Precision farming could help in each of these trouble points. Precision agriculture improves water management by using sensors, drones, satellites, and other devices to monitor soil moisture, crop water requirements, irrigation scheduling, water quality, and water use efficiency. Data from these sensors is transmitted to a centralized hub via wireless networks, where machine-learning algorithms and agricultural knowledge bases are employed to assess crop growth and forecast future conditions. This information is subsequently used to develop optimized field management plans for irrigation and fertilization. Compared to traditional farming methods, digital precision agriculture systems significantly improve resource utilization by enabling precise control over agricultural inputs, resulting in substantial savings in water and fertilizer, while ensuring high yields and maintaining crop quality [49,50].

Precision irrigation methods integrate different tools to monitor and control the irrigation water supply to the plants and deliver precise water supply (where and when irrigation is needed) based on real-time field collected data according to the requirement of the plant. Water is used precisely and is delivered directly to the plant roots in only the required proportions. This avoids critical issues such as run-offs and deep percolation. Besides, precision irrigation systems are customized to the soils and the plant's water absorption abilities, thus ensuring that the water sticks to the active root zone and is utilized by the crop. This subsequently results in achieving a higher yield, with the use of lesser resources through efficient irrigation systems for Indian farms. Large sprinklers could cause water evaporation to a large extent (somewhere around 15-30%). Precision irrigation eliminates this possibility as it supplies water directly to the roots. Excessive application of water through irrigations systems such as pivot or flood could result in saturation conditions in the soil, further resulting in bad aeration, and distressing plants roots that don't receive equal proportions of air and water. Nevertheless, with precision irrigation, as water is used in appropriate, and only the required quantities, and in accordance with the prevailing type, the air-water ratio is perfectly maintained, thus allowing crop growth as desired. New technology has also enhanced the performance of the existing Sprinkler and drip irrigation systems are low-water consumption-based irrigation techniques compared to surface irrigation methods. Unlike traditional irrigation methods, sprinkler and drip irrigation systems are highly efficient and water-saving but require operators to run, control, and monitor them. The efficiency of these systems can increase by adding modern features or existing systems (precision technologies) to develop them as intelligent systems. Smart methods can help these systems perform their work without human intervention. The smart tools continuously monitor the water level in a field by predicting and comparing the available water content in soil and plants with ordinary water needs. If the plant needs water, the system will automatically send commands to sprinklers or drips to start working until the crop water needs are fulfilled [50,51,52]. Therefore, optimizing the irrigation manner the usage of particular data-pushed predictions is critical for each water conservation and maximizing agricultural output. These parameters play an important function in supporting the farmers in not only making irrigation choices of when and how much but also in terms of fertilization, pest control and lots of different essential crucial actions leading to efficient use of scarce resources and preventing wastage and chemical leaching [53,54,55].

The land limitations faced by majority of small holding in India can be overcome by using precision agriculture techniques like hydroponics, aquaponics and Aeroponics. Hydroponics is a type of vertical farming that involves the cultivation of plants in nutrient-rich solutions in the absence of soil or an inert medium. This method accelerates plant growth and reduces the risk of soil-borne diseases. Rather than depending on the soil to support and nourish their roots, plants are frequently irrigated, supported, and fed with nutrient-rich water, an essential component of plant growth, using an inert developing medium such as cocopeat. 60–70 % less water is used by hydroponic systems than by traditional

conventional agriculture. According to UNESCO, traditional farming uses approximately 70% of global freshwater resources. Much of this water is lost to evaporation, runoff, and deep soil percolation before plants can use it. On the other hand, studies have found that hydroponics system reduce water consumption by up to 90% compared to conventional farming methods. This is because in hydroponics, water circulates through a closed-loop system with minimal evaporation loss. It requires lesser land and can give all around productivity as the growing environment is controlled. Vertical hydroponic systems stack growing areas, utilizing three-dimensional space allowing farmers to grow up to 10 times more food per square foot than traditional dirt farming. A single acre of vertical hydroponic greenhouse can produce yields equivalent to 200-350 acres of traditional farmland, depending on the crop. This stands out in contrast to traditional farming practices, which frequently involve extensive land use and may use ineffective irrigation techniques. Furthermore, several studies have shown that hydroponic farms have noticeably higher output rates with lesser use of water, fertilizers and pesticides [56,57,58,59,60,61].

Aeroponics is a technique for cultivating plants in nutrient-rich mist surroundings devoid of soil. Aeroponics differs from the hydroponic system as the plant roots are not engrossed in fluid media, instead straight way absorb nutrients from the aerosol. When compared to soil-cultivated plants, these cultivation systems provide improved growth, yield, quality, and metabolite production. In aeroponics system, the plants have 100% access to CO₂ (450 ppm to 780 ppm) for photosynthesis and also consume 70% less water than hydroponics. This requires very little land and other resources as nutrients are targeted and crops grown in a controlled environment [62,63,64].

Aquaponics is a convenient method of growing plants and fish in an aquatic environment that is very similar to hydroponics in terms of technology. This system's primary benefit is its crop and fish farming integration, which produces the nutrient exchange that occurs via the shared water between the two systems. Its benefits are comparable to those of hydroponic and aeroponic systems with the advantage of added revenue per parcel of land as farmers can have crop and fish farming happening simultaneously [65,66].

Importantly, these precision agriculture systems do not involve excessive use of any harmful pesticides and herbicides because the risk of pest infection is greatly decreased in an under-control environment of indoor farming, thus maximizing the overall nutritional value of the cultivated crops [67].

2.2 Enhanced yield per acre improving farmer income:

Research has shown that, Precision Agriculture Technologies (PATs) increase crop yields by 20%-30% and reduce input waste (water, fertilizers, pesticides) by 40%-60%. It leverages advanced technologies to optimise agricultural production management. This farming approach has several applications to improve productivity; for example, drones have been used to monitor crop health and detect water stress, enabling timely

interventions to reduce losses. By using GPS-guided tractors, drones, and satellite imagery to monitor crop health, soil conditions, and moisture levels in real time, these tools enable variable-rate application (VRA) of inputs, reducing fertilizer and pesticide overuse by 40-60%. Variable-Rate Application (VRA) is a smart farming technology that adjusts the amount of seeds, fertilizers, or pesticides applied to a field based on exact, localized needs. Drones, satellites, and soil sensors scan the field to identify variations in soil type, moisture, and crop health. This gives plants optimal condition improving their yield manifold [68,69,70].

Use of latest biotechnology inventions, including genetically modified organisms (GMOs) and CRISPR gene editing, farmers are able to grow crops resistant to pests, diseases, and climate stressors. For instance, Bt cotton reduces pesticide use by 50% while increasing yields [71,72]. Internet of Things (IoT) devices, such as soil sensors and automated irrigation systems, optimize water use by adjusting delivery based on real-time data preventing both over-watering and water distress both of which can impact yield [73]. Automation and robotics, like autonomous harvesters and robotic weeders, address labor shortages and cut production costs by 25% [74].

Controlled Environment Agriculture (CEA), including hydroponics and vertical farms, enables year-round production with 95% less water than conventional methods multiplying yield multiple times. Artificial intelligence (AI) further enhances decision-making through predictive analytics, forecasting pest outbreaks and yield trends [75,76].

Both increased and more nutritious yield has the potential of improving the farmer's income which is becoming a huge stress point in India's agricultural sector

2.3 Improved Economic Viability

Declining incomes are a severe challenge for Indian farmers. The cost of farming inputs (such as diesel, fertilizers, and labor) has risen faster than the wholesale prices they receive for their crops, pushing many smaller farmers into debt.

Precision farming uses Recording and Mapping Technologies (RMT) which uses systems to monitor and map what exists in the crop environment (soil, crop, micro-climate), using yield and soil mapping, facilitating the development of detailed field blueprints, thereby guiding agricultural operations in efficient, targeted, and environmentally friendly directions [77]. By using technology to target exact needs, farmers drastically lower their expenses on inputs and labor while maximizing crop yields and profitability. Comprising sensors that oversee and regulate processes such as watering, pest control, fertilization, and harvesting, it offers flexibility to align with the resources available to individual farmers, facilitating seamless integration into their operations. An IoT based automated system is designed to streamline every aspect of farming, from seed sowing to post-harvest cleanup. Sensors are deployed to measure soil moisture, temperature, humidity, and other environmental factors. Automation of farming tasks reduces the need for daily manual intervention. Consequently, efficiency in farming is enhanced, leading to reduced labor costs and increased farm productivity. Through the use of IoT, farmland operations have the potential for

greater efficiency and becoming less labour-intensive, resulting in overall cost savings while resulting in higher yields in the agricultural industry [78,79,80].

Since precision agriculture targets specific zones in a field rather than treating the needs of the entire surface area as uniform, it cuts down on unnecessary waste of fertilizers and pesticides reducing input cost. Smart irrigation systems and soil sensors reduce water waste by ensuring plants only get what they need [81].

UAVs can perform tasks, such as aerial mapping, targeted pesticide spraying, and remote sensing of crop health, that were previously labour-intensive or impractical. Moreover, AI can further assist drone technology by detecting crop disease and pest damage, allowing for timely and targeted interventions. Drones equipped with high-resolution cameras and multidimensional or hyperspectral sensors allow users to monitor crop health and analyse agricultural growth phases with high accuracy and efficiency [82,83,84].

Fuel also escalated agricultural costs making it unviable. Agriculture accounts for roughly 13% to 15% of India's total annual diesel consumption. A standard 45–50 HP tractor burns through 4 to 6 Liters of diesel per hour while tilling or disc harrowing. Deep ploughing can spike that even higher. Since most farmers depend on ground water, they have to factor in extra fuel for irrigation. Running a traditional 5 HP diesel pump set to irrigate just one acre of land consumes around 1.2 to 1.5 litres of diesel per hour. Consequently, the slightest fluctuation in fuel cost has a rippling impact on the agricultural sector. When diesel goes up by just ₹3–5 per Liter, an average 5-acre farmer sees their operational expenses jump by thousands of rupees in a single cropping season. Modern field prep heavily relies on mechanization. When diesel powers tractors, rotavators, and harvesters, every single pass across a field costs real money. When diesel prices soar, custom-hiring rates for tractors increase by 15% to 20%. For small and marginal farmers who don't own tractors and must rent them by the hour, this instantly eats away their thin profit margins before seeds even hit the ground [85].

GPS-guided tractors and autonomous machinery drive straighter paths and prevent overlapping, which saves fuel and time. Precision technologies such as auto guidance reduce overlapping of passes while planting seeds or applying chemicals and fertilizers, which results in less fuel usage and labor time. The decreased application of chemicals and fertilizer also results in reduction of energy consumption by the agricultural machinery and reduced expenditure on inputs.

Natural Resource Conservation Service (NRCS) of the United States Department of Agriculture (USDA) estimates that even if only 10% of the US farmers use a guidance system for planting seeds in the USA, 16 million gallons of fuel, four million pounds of insecticide, and two million quarts of herbicide can be saved annually [86,87]. This will not only result in energy savings, but also financial savings for producers. A study by Clemson University showed that spatially varied tillage depth reduced energy requirements by 56% and fuel consumption by 34%. They also found that there is a potential energy savings of up to 52% by using variable rate irrigation systems [86,87].

Little research has been done relative to energy saving through precision agriculture, but USDA-NRCS has estimated the savings. A recent study by USDA notes that overlaps can be reduced from 24 to 2 in. by using a guidance system, which saves about US\$13,000 in variable costs annually for a farm of 1,000 acres. Based on these estimates, a GPS guidance system provides a substantial return on investment and pays for itself within one year. The return-on-investment increases with the size of the farm as the annual savings increase and the equipment cost is spread over more acreage. Provision of free GPS signals by the federal government has encouraged producers to use new precision tools, techniques, and services to enhance their efforts to save energy and reduce costs [88,89].

2.4 Environmental Sustainability

The latest 2026 Environmental Performance Index (EPI) highlights the environmental challenge for India. India ranked 176th out of 177 countries, ahead of only Laos, with an overall score of 22.46 out of 100, while Estonia topped the rankings with 74.79. India also ranked last among South Asia's eight countries [90,91].

While the Green Revolution helped India achieve food security as discussed earlier, the economic prosperity observed in the agricultural sector in the initial years has plateaued because of unsustainable agricultural practices. The country is witnessing a catastrophic increase in farmer suicides because of high debt burdens, and crop failure. A lot could be blamed on faulty government policies. For example, the adoption of the Green revolution was targeted at prosperous farmers of Punjab and Haryana. They were encouraged to adopt the wheat-rice (paddy) cycle and shift away from their traditional crops like maize, millet and pulses by providing incentives like subsidised electricity and fertilisers, and a guarantee of procurement of their crops at a price two times higher than the cost of production. Producing a kilogram of rice requires an average of 2,800 litres of water, while a kilogram of wheat takes 1,654 litres according to a WaterAid India report. These water-intensive crops aren't sustainable for regions with sandy loam soils such as that of North India's. This has led to the recession of the water table to alarming levels and the indiscriminate use of electric pumps to irrigate paddy have led to potable groundwater becoming alkaline due to contamination from saltwater intrusion. The unthinking application of pesticides and fertilisers has also polluted the groundwater, increased its chances of getting into the food chain through bioaccumulation and risk rendering the soil fallow (ironically) eventually. This also makes the crops prone to locusts and other resilient insect species, as was seen in June 2020 across the West Asian landscape. Eventually, the productivity of the land decreases and thus the vicious cycle for farmers of taking loans for improving soil fertility by the use of fertilisers and pesticides begins. The credit burden weighs heavy on the shoulders of poor farmers, and they are left with little choice [92,93,94,95,96].

Additionally, Climate change has been an alarming danger to agricultural productivity and food security in recent years. Achieving climate resilience through reducing greenhouse

gas (GHG) emissions and increasing the efficiency of available resources is one of the prime approaches that help to attain higher productivity under changing climatic conditions. Precision and digital strategies involving different tools and management practices have the potential to pave the way for attaining higher yields with lesser inputs. Methane (CH₄) and nitrous oxide (N₂O) are the major anthropogenic greenhouse gases (GHGs) from agriculture, with global warming potential of 28–36 and 265–298 times that of CO₂ in a 100-year time horizon, respectively. Improper irrigation and nutrient management practices are major contributors to CH₄ and N₂O. Judicious use of water and nutrients will help curtail these gases' emissions to a certain extent. At this juncture, precision water and nutrient management play a pivotal role in reducing emissions and improving resource use efficiency [97,98,99].

One of the primary benefits of precision nutrient management is optimizing fertilizer application, minimizing waste, and increasing efficiency. Another advantage of precision nutrient management is its ability to reduce agricultural and environmental impacts. Precision agriculture can help to avoid nutrient runoff and pollution by lowering fertilizer use and optimizing the application, which can have severe consequences for water quality and ecosystem health. It also helps in more judicious use of scarce land and water resources as discussed earlier [100,101,102].

Precision and digital agriculture strategies have great potential to help build climate resilience by enabling land managers to make more informed decisions about land use suitability. Land use suitability refers to the ability of a particular land use to meet the needs of a particular region, taking into account factors such as soil type, water availability, and climate conditions. By using precision and digital agriculture strategies, land managers can better assess land use suitability and make more informed decisions about which land uses are most appropriate for a particular area. Digital tools such as satellite imagery and machine learning algorithms can help farmers analyse soil health and crop growth patterns and identify areas that are prone to soil erosion, nutrient depletion, and other issues that can impact crop productivity and contribute to climate change. They can then use this information to develop more targeted land management strategies that address these issues and help build climate resilience. Precision farming's techniques reduce tillage operations, soil compaction and erosion, and preserve soil health and structure. Due to this, the top fertile layer of the soil is preserved and indirectly helps in improving crop production [103,104,105,106].

2.5 Improved market understanding and accessibility:

Small and marginal farmers, who constitute over 85 percent of the total agricultural workforce in India, often face serious challenges in accessing fair and profitable markets. These farmers typically rely on local traders or middlemen, selling their produce at village-level aggregators or traditional Agricultural Produce Market Committees (APMCs). Due to lack of scale, bargaining power, real-time market information, and storage facilities, these producers frequently accept low prices for their goods. According to the National Sample Survey Office (NSSO), over 65 percent of farmers sell their

produce within 5 kilometers of their fields, leading to distress sales, especially during harvest peaks (Shelake et.al., 2016). Without access to multiple buyers or price discovery mechanisms, these farmers remain trapped in low-margin cycles. Post-harvest losses, estimated at 15 to 20 percent for perishables, add to economic strain, largely due to inadequate supply chain infrastructure and market connectivity [107,108].

Digital technology is reshaping traditional agricultural marketing by removing geographical, informational, and transactional barriers. Mobile phones, internet connectivity, and cloud-based platforms have enabled farmers to access real-time price information, connect directly with buyers, and even sell produce from the farm gate. Technological innovations reduce dependency on physical mandis, increase transparency in price discovery, and help manage logistics more efficiently. Mobile applications, AI-driven marketplaces, and digital payment systems are bridging the gap between producers and consumers. These platforms also improve access to institutional buyers, supermarkets, and exporters, thus opening new revenue channels. By integrating supply chains digitally, technology facilitates demand aggregation, better quality control, and more predictable income for producers [109,110].

Digital marketplaces and e-commerce platforms have emerged as transformative solutions for addressing the long-standing challenges faced by agricultural producers in accessing fair and efficient markets. By leveraging mobile connectivity, cloud infrastructure, and real-time data systems, these platforms empower farmers to bypass traditional intermediaries, gain access to wider buyer networks, and receive better prices for their produce. The integration of services ranging from digital payments and logistics to input procurement and quality assurance has streamlined the entire agricultural value chain, reduced costs and improved transparency. These systems also support post-harvest planning, inventory management, and traceability, aligning smallholder operations with modern supply chain requirements [111,112].

Precision farming connects the farmer to the end user directly. It shifts agriculture from a guessing game to a planned supply chain, reducing crop waste and giving farmers better control over when and where to sell their harvests. Sensors and drones ensure crops grow evenly ensuring better sale as buyers prefer even sizes and shapes, which helps farmers fetch better prices. Digital platforms can help farmers sell directly to supermarkets, exporters, or consumers, skipping local auction markets. Farmers use mobile apps to list their fresh produce, set their own prices, and sell straight to local households. Farmers are able to keep a larger share of the final sale price by cutting out traditional auction fees and middlemen. Digital tools allow consumers and large buyers can track exactly where their food comes from, which builds brand trust. Post-harvest sensors can be used to monitor temperature and humidity in storage units, preventing crops from rotting before they reach the market. Thus, larger portion of the harvest makes it to market, increasing overall profits.

The existing logistic information systems in Agri-Food supply chains like Costco, Walmart, Cargill, Albert Heijn,

etc., just store, track orders, and supplies, without giving characteristics such as transparency, auditability, and traceability. These characteristics in an agri-food supply chain will certainly improve the food quality and safety, thus are in demand from consumers. Therefore, numerous R&D communities both in industries and academia have engaged their efforts in developing efficient food chain traceability systems based on emerging technologies like the IoT and blockchain technologies, to facilitate remote monitoring at every stage all along the supply chain, from farm to fork. Most of the above-mentioned companies have started using blockchain for their supply chains. Unlike conventional business processes, which are based on trusted centralized third-party service providers with their standards and architectures controlled by large players, blockchain technology allows these processes to be conducted in a distributed manner, lowering entry barriers, and encouraging process innovation. This supports entrepreneurial activity by deploying extra confidence inside firm networks and supply chains. Furthermore, blockchains are often open and transparent, allowing all supply chain players to view, update, and check data, while modifying or deleting blockchain secured data is practically hard, resulting in increased transparency of all supply chain activities. As a result, supply chain providers may publicly advertise their availability to the whole market, as well as the capacity they have, enhancing their market position and increasing their independence from transportation brokers [113,114,115].

2.6 Improved National Food Security

Agricultural productivity growth has been declining globally in recent years. Climate change is probably the most complex and intractable environmental challenge faced by the world today and is increasingly being recognized as a potent threat to agriculture in general and specific to food security. The situation in India is even more challenging as compared to the global scenario with the high vulnerability of agriculture to changing climate and continuously increasing demand for food for a large population of over 1.3 billion which is growing. An increase of 1–2 °C in temperature is going to have a significant negative impact on the yield of major food crops in India, which in turn will impact the nutritional status of the population [116,117].

India's economy is heavily dependent on agriculture. Climate change significantly threatens the country's food security and nutrition. In recent years, extreme weather events such as floods, droughts, and cyclones have become more frequent and severe, disrupting food production and distribution systems as a result affecting the livelihoods of millions of people, making it essential for farmers to adopt technology for increasing yield without harming the environment further. Moreover, Precision agriculture mitigates climate risk by ensuring a more informed and controlled growing environment [118,119].

Precision agriculture, which involves collecting, analysing, and taking actions based on data, represents one of the most promising avenues for reversing this trend. By enabling farmers to apply exactly the right amount of inputs precisely where and when they're needed, these technologies directly address the efficiency challenge at the heart of agricultural

productivity growth. As global agricultural systems face mounting pressure to produce more with fewer resources, precision agriculture emerges as a critical pathway to achieve the sustainable productivity growth needed to meet the growing demand. By using advanced technology, like AI, GPS, and sensors, to grow more food on existing farmland while protecting natural resources. It makes the food supply stable and reliable by increasing crop yields, preventing food shortages, and lowering farming costs. By decreasing production costs and increasing productivity, precision agriculture also lowers per unit production costs, making farming more profitable for farmers which in turn empowers the rural economy [120,121,122].

4.7 Improved Risk Management

Advanced monitoring systems, powered by the Internet of Things and artificial intelligence, help farmers detect disease outbreaks, pest infestations, and weather-related threats early. Timely interventions can prevent significant crop losses and improve farm resilience. Crop monitoring IoT systems are crucial for modern agriculture, offering real-time insights into crop health, growth conditions, and environmental factors. Sensors continuously collect data on environmental conditions and crop parameters. This data includes temperature, humidity levels, soil moisture content, nutrient levels, and more. Farmers can access the processed data through web or mobile applications. These insights help farmers make informed decisions about irrigation scheduling, fertilization, pest control, and harvesting timelines to minimise risk [123,124].

3. Challenges Stalling Large Scale Adoption:

3.1 High Installation and Maintenance Costs and Operational Expertise

High implementation costs and the requirement for farmers to possess specialized technical expertise is a very big challenge specially in the case of India where over 85% of farmers are classified as "small and marginal", meaning they own or cultivate less than 2 hectares (roughly 5 acres) of land. More specifically, about 65% to 70% of all Indian farmers are marginal farmers, holding less than 1 hectare (about 2.5 acres) of land. Studies show that around 17% to 25% of the rural farming population is completely illiterate, with many more having never completed primary school. Additionally, literacy rates among small and marginal farmers (the < 1 hectare group) are often estimated between 48% and 55%, which is notably lower than the national average. Advanced equipment like drones, automated sprayers, and soil sensors are very expensive to buy and maintain and thus, affordability becomes a huge factor. Lack of awareness also makes them even more apprehension of making the investment or collectively contributing to it. Moreover, precision tools work best on very large farms, and it is a challenge in hugely fragmented landholdings [125,126,127].

3.2 Connectivity Issues

In remote agricultural areas, poor communication infrastructure often causes significant connectivity issues. Precision agriculture relies heavily on reliable internet

connectivity and high-speed data. Farm automation, artificial intelligence, and smart machinery process massive amounts of data that demand continuous, high-bandwidth connections to function effectively. This is a huge challenge for Indian farmers [128,129].

3.3 Data Security Risk

Data is the cornerstone of precision agriculture. This dependence on digital technologies and vast amounts of data, poses cybersecurity challenges. The integration of IoT devices, cloud computing, and big data analytics in farming systems has expanded the attack surface for cyber threats, making data integrity and privacy a critical concern. Cybersecurity in precision agriculture is not just about protecting sensitive information from unauthorized access; it is also about ensuring the reliability of the data that drives essential farming operations [130,131].

4. Conclusion

The crisis in Indian agriculture, which has been building up for decades and could begin to threaten India's food security if not addressed on an urgent basis. The rate of growth of agricultural output is gradually declining in the recent years. The relative contribution of agriculture to the GDP has also declined steadily over time and it is alarming that India is moving towards a point of no return, from being a self-reliant nation of food surplus to a net importer of food. Agriculture which employs more than 50 percent of India's population has come to be regarded as unprofitable when compared to other enterprises. It means that the income derived from these activities is not sufficient enough to meet the expenditure of the cultivators. And therefore, unless agriculture is made a profitable enterprise, the present crisis cannot be solved. The related factors responsible for the crisis include dependence on rainfall and climate, liberal import of agricultural products, reduction in agricultural subsidies, lack of easy credit to agriculture and dependence on money lenders, decline in government investment in the agricultural sector and conversion of agricultural land for alternative uses. Rising input costs, supply-chain disruptions, inflationary pressures, and fiscal stress are already affecting the sector, with risks likely to deepen as the region faces geopolitical tensions. India is the world's second-largest consumer of fertilisers after China. Although it is the and third largest producer globally, the country relies heavily on imports of phosphatic fertilisers and remains almost entirely dependent on external sources for potash, making it particularly vulnerable to global supply disturbances. For farmers, higher fertiliser prices have translated directly into increased cultivation expenses. Fertilisers remain critical for sustaining yields of staple crops such as rice and wheat. As prices rise, many farmers reduce fertiliser application to control costs, a strategy that can lower productivity and threaten food security over time. Agricultural economists caution that continued shortages could eventually lead to lower crop output and delayed increases in food prices [132, 133,134,135,136].

Earlier water stress would be found only in drought area, but now it is evident even in regions with decent rainfall frequently experience due to pollution of natural water bodies and depleting groundwater levels. Large parts of smallholder

farming still rely directly or indirectly on groundwater extraction. In 2024, India's total annual groundwater extraction was 245.64 billion cubic meters (BCM), which is more than the combined usage of the US and China. For farmers, this has slowly altered the economics of agriculture itself. Tube wells go deeper every few years. Diesel costs rise. Electricity demand increases. Climate change will only add to the water stress [137,138]. Add to this land degradation and fragmentation and one is looking at a crisis threatening to assume dangerous proportions, the consequences of which will hit all the other sectors and the national economy in several ways. In specific, it has adverse effects on food supply, prices of foodgrains, cost of living, health and nutrition, poverty, employment, labour market, land loss from agriculture and foreign exchange earnings.

The only remedy to the crisis is to do all that is possible to make agriculture a profitable enterprise and attract the farmers to continue the crop production activities. This is where precision agriculture could make the desired impact. Its challenges of high cost and expertise and cybersecurity could be resolved through offering subsidies to private Agri-tech businesses enterprises who could serve farmers in specific areas. Farmers from smaller land holdings will be encouraged to consolidate once they see their return on investment go up. Targeted grants by the government could help private companies lower their fees. This makes advanced farming tech affordable for everyday growers. The same enterprises can train local staff to ensure seamless delivery of services and advise. Private enterprises can invest in secure, cloud-based networks that individual farmers cannot afford. This already being done in technology companies in other sectors. the same can be backed by strict laws to ensure farmer data stays private and protected from hackers. Investment in agriculture and its allied sectors, including irrigation, transport, communication, rural market, rural infrastructure and farm research, should be drastically increased and better planned. The solution of the problem does not lie in quick fix isolated packages, but in overhauling the system with technology as a huge driver of change.

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