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Smart Farming 2.0: How AI, IoT and Digital Twins Are Reshaping Precision Agriculture

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Precision agriculture has moved well beyond GPS-guided tractors. A new wave of artificial intelligence, low-cost sensors, satellite imagery, and increasingly autonomous machinery is giving farmers field-level insight that was unavailable even a decade ago. This article surveys how AI-driven pest and disease detection, variable-rate irrigation and fertigation, agricultural robotics, and emerging digital twin models are being combined to raise productivity while reducing water, fertiliser, and pesticide use. It also examines the practical barriers to adoption, particularly for smallholder farmers, including cost, rural connectivity, digital literacy, and fragmented landholdings, and discusses the extension, financing, and cooperative models that could help bridge the gap between technology developed in research labs and technology used on real farms. The article argues that the productivity gains from smart farming will only translate into broad-based food security if adoption is deliberately extended to smaller and resource-constrained farms, not just the largest commercial operations.

Introduction

Farming has always depended on close observation of soil, weather, and crop condition. What has changed in the past decade is the scale and speed at which that observation can now happen. Satellites revisit the same field every few days, soil sensors report moisture levels continuously, and drones can scan a hundred acres in the time it once took to walk a single row. Layered on top of this flow of data, artificial intelligence is increasingly able to turn raw sensor readings into specific, actionable recommendations: how much water to apply, where a pest outbreak is likely to begin, or which part of a field needs additional nitrogen. Industry surveys suggest that a majority of large commercial farms in developed agricultural economies have now adopted at least one form of AI-assisted technology, whether yield mapping, automated irrigation scheduling, or machine-vision-based sorting. The picture looks different in smallholder-dominated farming systems, where fragmented landholdings, limited rural connectivity, and the upfront cost of sensors and software have slowed adoption. Understanding both the technological promise and the practical barriers is essential to judging how quickly, and for whom, smart farming will actually deliver benefits.

The Data Revolution on the Farm

Modern precision agriculture rests on three data streams working together: satellite and drone imagery that shows crop vigour and stress patterns across a whole field, ground-based sensors that measure soil moisture, temperature, and nutrient levels at specific points, and increasingly, weather stations that feed hyper-local forecasts back into farm management

software. Machine-learning models trained on years of these combined datasets can now flag a moisture deficit or a nutrient imbalance days before it becomes visible to the human eye, giving farmers a lead time that was simply unavailable under traditional scouting. The value of this data depends on how it is delivered. Dashboards and mobile applications that translate sensor readings into a simple recommendation, apply fifteen millimetres of water to the north-east block today, are proving far more useful to working farmers than raw charts and numbers, and much of the recent progress in agri-tech has focused on this last step of turning data into a decision a farmer can act on immediately.

Precision Inputs: Variable-Rate Irrigation and Fertigation

Water and fertiliser are among the costliest inputs in modern agriculture, and both are frequently applied uniformly across a field despite significant variation in soil type, slope, and crop need within that same field. Variable-rate irrigation systems, guided by soil moisture sensors and weather data, apply water only where and when it is needed, and field trials in water-stressed regions have repeatedly shown double-digit reductions in water use without any loss of yield. Similarly, variable-rate fertigation, applying fertiliser through irrigation systems calibrated to real-time crop demand, is helping reduce nitrogen runoff, a major contributor to both input cost and water pollution, while maintaining or improving yields. These systems increasingly rely on AI models that combine soil test results, satellite-derived vigour maps, and crop growth-stage data to recommend an application rate down to specific management zones within a single field.

AI-Powered Pest and Disease Detection

Early detection remains one of the most effective defences against crop pests and diseases, and it is also one of the areas where computer vision has made the most tangible progress. Smartphone applications trained on large image datasets can now identify many common crop diseases from a single photograph of a leaf, often before visible symptoms would prompt a farmer to seek expert advice through traditional channels. Drone-mounted cameras extend this capability across entire fields, flagging localised outbreaks that would be easy to miss during manual scouting. These tools work best as a support to, rather than a replacement for, agricultural extension services. Image-based diagnosis is most valuable when it is paired with a clear recommended action and a route to expert confirmation for ambiguous cases, an integration that many public extension systems are still in the process of building.

Robotics and the Rise of Agentic AI

Agricultural robotics has advanced substantially beyond simple automated guidance for tractors. Robots capable of identifying and mechanically removing weeds, reducing herbicide use, and machines that use computer vision to selectively harvest ripe fruit are now being tested and, in some cases, commercially deployed. Labour shortages in several major agricultural economies have accelerated interest in this kind of automation for tasks that are repetitive, time-sensitive, or physically demanding. A more recent development is the emergence of what researchers call agentic AI in agriculture: systems that move beyond simply predicting an outcome to actively making and adjusting decisions across a farm in near real time. In an emerging model, a central digital twin, a continuously updated virtual replica of a farm's fields, crops, and equipment, coordinates multiple specialised AI agents responsible for irrigation, pest control, and fertilisation, allowing the whole system to adapt as conditions change through a growing season rather than following a fixed, pre-season plan.

Barriers to Adoption on Smaller Farms

The technologies described above have been developed and proven largely on medium to large commercial farms with the capital to invest in sensors, connectivity, and software subscriptions. Smallholder farmers, who still produce a significant share of the world's food, face a different set of constraints: fragmented landholdings that make per-hectare sensor costs prohibitive, patchy rural internet and mobile connectivity, limited digital literacy, and, in many cases, no clear financing route to purchase even relatively low-cost tools.

Cooperative and shared-service models are emerging as one practical response. Rather than each farmer purchasing individual sensors or a drone, farmer producer organisations and agricultural cooperatives are beginning to provide shared access to drones, soil-testing services, and AI-based advisory platforms, spreading the cost across many members. Public agricultural extension systems, working alongside private agri-tech companies, have a significant role to play in translating these tools into a form that smallholder farmers can realistically use.

Conclusion

Artificial intelligence, IoT sensors, and increasingly autonomous machinery have given precision agriculture a level of sophistication that was science fiction only fifteen years ago. The productivity, water-saving, and input-efficiency gains are well documented on farms that can afford the technology. The central challenge for the coming decade is not primarily technological but distributional: ensuring that these tools reach smallholder and resource-constrained farmers through affordable, shared-access models, stronger rural digital infrastructure, and extension systems built to bridge the gap between a sensor reading and a farmer's decision in the field. Smart farming will only earn the name if it becomes farming that is smart for everyone, not only for those who can already afford to be.

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