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AI-driven monitoring and analysis tools can read which nutrients are present in the soil, and how bioavailable they are for plants. Image: Topraq.

The Future of Farming
How will technology change agriculture?

From the cutting-edge of crop genetics, to soil probiotics, growing protein out of thin air, and AI-powered farm management, the latest breakthroughs in AgriTech are transforming our global food system.

By Lena Hunter | Head of Special Feature Reports: George Clarke

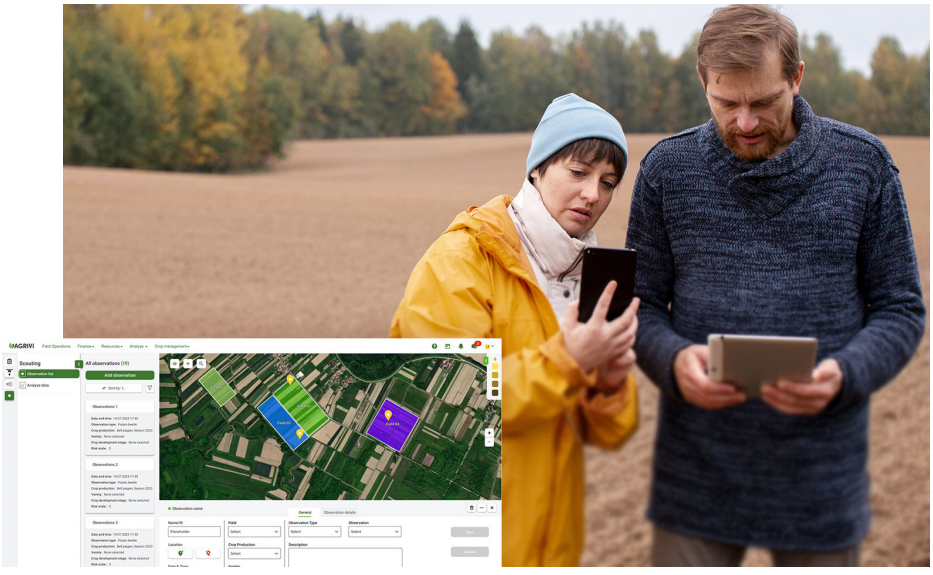
Food security, climate change, global health: Agriculture is where the world's most serious challenges collide. As the global population grows, farms must produce 60 percent more food by 2050, but extreme weather events are wreaking havoc on crop yields worldwide. Meanwhile, existing commercial chemicals that boost yield have proved disastrous for surrounding ecosystems. Farmers are under pressure to replace them with environmentally friendly alternatives and regenerate soil health, or risk depleting the land for good. And, with agrifood systems accounting for one-third of total global greenhouse gas emissions, carbon footprints are under the microscope. Farm owners today must meticulously document and control their emissions to align with trading schemes, regulations, taxes and subsidies. It's no small feat, and tackling these interwoven issues requires new collaborations with labs, developer teams and boardrooms. Across advancements in genetics, biological products, digital tools, and powerful AI systems, we explore the innovations in agricultural technology (AgriTech) that are changing—and even radically reimagining—how we cultivate food.

Big Data and digital farm management

A small number of economically high-output farms dominate the world's total agricultural production. While 85 percent of all farms are smallholdings or family-owned, they account for only around one-third of commercial food. In terms of area, the top 1 percent of farms operate 70 percent of cultivated land. With consolidated ownership of large land areas, and smaller farms competing in the same markets, the agriculture industry is more than ever a numbers game.

As a result, Big Data analytics is transforming farming, and digital agriculture products are in demand. Farmers and growers need comprehensive tools to monitor everything from cattle and corn, to labor cost and chemical use. Australia-based ranch management company AgriWebb, for example, makes a foresight platform for managing pasture livestock based on datasets from 22 million cattle and sheep over 150 million acres in 27 countries. "We combine that data with university research, satellite imagery, weather data, soil testing and on-farm records. Using AI, we can forecast pasture growth, animal performance, and ranch outcomes weeks in advance," explains CEO Justin Webb. Indeed, the number of private companies launching small satellites has exploded by roughly 500 percent in the past decade, and remote sensing constitutes one of the most common applications. Drones and satellites are a boon for farmers managing large areas of land: in Brazil and Argentina, for example, digital farming company Xarvio makes drones that map weed infestations, and process the captured images into create precise, site-specific herbicide application maps.

Some AI applications allow farmers to diagnose disease simply by photographing their crops. Others, like Croatian Agrivi's "AI Advisor", deliver tailored farm management tips via WhatsApp and Viber. Tech scale-up Aerobotics has created software that can visually analyse yield. "If you take a photo of a bunch of grapes, our technology measures the size, color, quality, and any defects, estimates the berry count, and projects the results through to harvest," explains company CEO James Paterson. "If you think of companies like ChatGPT or Gemini building large language models from text, we're building what we call a large fruit model."



New digital farm management platforms connect to remote sensors to give farmers real-time information from the field. Some also use AI to analyze data and deliver advice. Image: Agrivi.

But the "data-ification" of agriculture is not just about productivity—it's also about sustainability. The EU, for example, now legally requires that companies of a certain size declare their Scope 3 emissions. The U.K., Australia, Turkey and Japan are following suit. In less regulated countries like the U.S., more firms are setting voluntary decarbonization targets with the Science Based Targets initiative (SBTi).

The upshot is that farms need to produce detailed emissions calculations, and, increasingly, are rewarded for low-carbon production. If farmers can produce "auditable measurements," they can monetize them in carbon offset markets or state subsidy applications says Jay McEntire, the CEO of AgriTech company Arva, which helps farmers measure and manage their data. He has watched the data-centric segment boom in recent years: "Consumers motivated by health want to know where their food comes from; packaged goods companies who have made climate commitments need Scope 3 data from the farms they partner with, and there is a growing biofuel market, supported by the 45z tax incentives," he explains.

PepsiCo is one such packaged goods company, relying on a secure supply of crops and ingredients to make its products. With climate pressures intensifying, it has made agricultural resilience a "core business priority." Chief Sustainability Officer Jim Andrew says the food and beverage giant is investing in "sustainable productivity growth" on farms—producing more with

Around one-quarter of the world's labor force work in agriculture.

Source: Our World in Data

the same or fewer inputs.

"We view this not as a trade-off, but as a shared objective," he says. "Data, digital tools, and AI play a critical enabling role by making sustainability measurable, and scalable at the farm level."

Arva is also using farm data to build "geographically aware AI models" that predict which AgriTech interventions will work best in different conditions. But according to McEntire, despite all this the single biggest constraint holding farmers back from adopting new technologies is lack of obvious economic incentives. "Farmers, competing in a global commodity market, are forced to prioritize being the lowest-cost producer by using the most abundant, cheapest generalized inputs. It's a "race to the bottom" that ignores the unique characteristics of each field and is ultimately suboptimal for both profitability and the environment," he explains.

Ilias Sousis, co-founder of WikiFarmer, agrees that "the agricultural industry remains significantly under digitized and heavily reliant on intermediaries." The company has built a B2B marketplace that connects small and mid-sized farmers directly to international buyers, and Sousis believes that educating farmers on how to navigate markets and earn fairer profits is the gateway to greater AgriTech adoption. "Many farmers are still managing their businesses much as they did twenty years ago, despite producing the most valuable part of the supply chain. Digital platforms that remove unnecessary intermediaries offer market access and freedom, and when farmers earn higher and more stable profits, they can reinvest in their businesses and gradually modernize how they operate."

"Developed markets typically have large corporate farm set-ups, which allows for mechanisations and scalable interventions. In contrast, developing markets are predominantly characterized by smallholder farmers. Hence the impact of technology and scientific innovations takes more time to materialize on the ground."

Avinash Kasinathan, Innoterra

Targeted crop genetics

Adoption may lag, but AgriTech R&D investment has grown as the threat of crop loss looms. Some of the world's most important crops are on the front line: Soybeans, for example, are very sensitive to weather variability and water reserves. When global soy yields plummeted in 2012 due to mass failure in key growing regions, one-third of the catastrophe was attributable to climate change. And with the pace of environmental shifts accelerating, the gap between today's soy genetics and future conditions is widening rapidly. AgriTech, therefore, is betting on precision gene-editing. Can we engineer hardier crops to withstand tomorrow's climate?

Biotechnology company Betterseeds is using an approach based on CRISPR gene-editing, also used in human medical science. In trials so far, it has successfully delivered CRISPR systems into plant cells, resulting in crops with better heat tolerance and more consistent plant architecture —a benefit during harvesting. The new method cuts exiting trait development time from years to months. CEO Ido Margalit calls the need for more resilient crops "urgent," saying, "Food systems are under pressure from every angle and innovation in seeds is one of the highest leverage points for improving resilience."

Other companies are inserting wild genetics into domestic crops. University of Oxford spinout Wild Bioscience combines AI with gene-editing to identify promising traits in different species of wild plant, decipher the genome and bring the trait technology to seed companies who serve regional growers. "Evolution has already produced plants far more efficient than our crops in every meaningful trait: water use, nitrogen use, photosynthesis, resilience," says CEO Ross Hendron. "We don't need to invent new biology. We simply transfer those solutions into our crops."

Beside weather resilience, improved yield is another key target of experimental botany. Light capture, plant shape and energy conversion are the decisive factors for yield and, over the past 50 years, classical breeding

has successfully maximized plant architecture and light capture. Now, labs are zeroing in on photosynthesis. Several studies have found yields can be increased by up to 40 percent by genetically manipulating plants' photosynthetic efficiency, with knock-on effects like higher nitrogen and water efficiency. It's early days, but companies like Wild Bioscience are working towards commercializing the science. "In our field trials across multiple countries, we already see that plants that grow faster early in the season close their canopy sooner, retain moisture better, outcompete weeds, and build a stronger buffer against weather shocks," says Hendron. And there are more biohacks on the horizon: early results suggest precision genetics may be able to increase the carbon storage capacity of root systems. "That is a fundamental breakthrough if we get it right," says Hendron. "If we enhance the ability of crops to store carbon below ground, we improve soil health, strengthen the plant, and contribute to atmospheric carbon reduction at scale."

Regenerative soil science

While industrial monocultures and factory farming deplete the environmental health upon which continued food cultivation depends, regenerative agriculture posits an alternative vision for the future of farming. The term has been circulating since the 1980s but has gained traction in the past decade. Regenerative agriculture aims to allow soil, water, nutrients and CO_2 storage to regenerate themselves, by encouraging natural processes and biodiversity.

On this wave, biologically dynamic soil has become a goal for many forward-thinking farmers —and reading soil health a big focus for AgriTech companies. Turkey-based Topraq, for example, has developed an AI system of soil sensors and biological analysis that can read which nutrients are present, and how bioavailable they are for plants. CEO Cem Ertal describes it as a tool for "capturing the heartbeat of the farm 24 hours a day." "Modern agriculture is in what I describe as a downward spiral. We are degrading soil at an alarming rate, and the food we consume is becoming less nutritious as chemical dependency increases," he says. "By delivering balanced nutrition at the right time and in the right amounts, farmers use significantly less fertilizer. Stronger plant immunity also reduces the need for pesticides and insecticides."

An influx of biological soil products is coming to the market, promising yield improvements. U.S.-based Holganix are making "plant probiotics" for commercial-scale farms. These encourage bacteria in the soil microbiome just like probiotic capsules and cultured yoghurt in the human gut. However, microbes require continuous feeding in the form of carbon from cover cropping, legumes and composting. Depending on starting conditions, it can take up to five years of consistent biological management to restore full soil functionality.

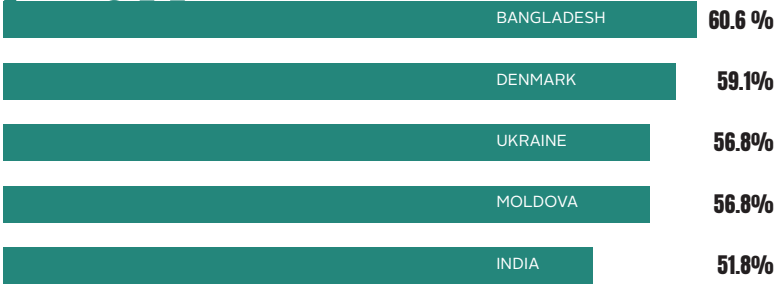
Minimizing the use of synthetic chemicals on the land is another important route to soil health. But fertilizers like MAP and DAP are often overapplied due to crops' poor uptake rates, and the resulting runoff of phosphate chemicals depletes oxygen in streams, ponds and soil water, creating "dead zones" in the landscape. With more studies consistently linking soil health to environmental resilience, many AgriTech companies are now developing fertilizers that can deliver phosphorous with less harmful side-effects. For example, Phospholoutions has developed RhizoSorb, a dry fertilizer replacement for MAP or DAP that releases phosphate based only on plant demands. "Mineral innovations like these modify how applied phosphate is released from the granule into the soil, meaning greater uptake using roughly half as much phosphorus fertilizer," explains Hunter Swisher, CEO of Phospholutions. "They

"Agriculture is very different from human pharmaceuticals. Once you have a drug that works for a particular disease, that same treatment can often be used worldwide. In agriculture every field, every valley, every region can be different. We need very local solutions."

Steve Hawkins, Syngenta

The world's 5 most cultivated countries

(farmland as % of total land)



Source: World Bank Group

will be indispensable for feeding a growing population without increasing environmental impact in the next decade."

Advancements in AI have supercharged the evolution of products like these. Models can now quickly discover potential active molecules for new fertilizers or pesticides and simulate how each candidate is likely to perform against different pests and diseases, and impact soil. Steve Hawkins, global president of the Swiss-headquartered agriculture company, Syngenta Crop Protection, says he has seen the scale of innovation "change completely." "If I think back to earlier in my career, you would walk into a research center and see a small assembly line of scientists preparing and shooting tiny amounts of different compounds into test tubes. It was an impressive effort but still very manual and constrained. Today we can almost skip that first part. We are no longer talking about testing hundreds of thousands of candidates per year, but millions." He points out that fast, detailed molecular analysis also helps companies "prescribe" products to farmers more accurately: "When we talk to growers, we can be much more precise about which seed variety, which crop protection product, and which combination of practices is likely to work best in their situation."

Bees and biodiversity

In the conversation about the urgency of rewilding, little has peaked public sympathy like the plight of honeybees. Around 70 percent of crops depend on insect pollination, and a healthy hive can pollinate more than ten million flowers per day. But in Europe and North America, bee populations are in freefall.

In the United States last year, beekeepers lost around 62 percent of their colonies compared with the usual 40 percent. "We're not sure whether this spike is a one-off or the new normal, but it makes the system very fragile," says Omer Davidi, CEO of BeeHero, the world's leading provider of crop pollination services.

The company has created a hive monitoring system that detects "symptoms" of poor hive health, so farmers can treat them. "The hive is a complex and sensitive superorganism. From the first real sign of trouble to complete collapse can be a few days," says Davidi. "You can replace the queen, feed the colony, treat mites and viruses. But by the point you see visible symptoms in the hive, it is already too late. That is why early detection is so central."

Intensive farming methods, urbanization and pollution are some of the primary reasons for honeybees' decline. However, there are lessons to

"Investments should prioritize KPI driven solutions that deliver proven results for farmers, not technology for technology's sake. From a policy standpoint, subsidies and incentives should be aligned with performance metrics such as soil health improvement, input efficiency, and yield stability."

Cem Ertal, Topraq

Left: Using CRISPR gene-editing systems like those in human medical therapies, crop scientists can engineer desirable plant traits in just a few months. Right: As climate change accelerates, extreme weather events are threatening yields of the world's most important crops, like soybeans (pictured), rice, and wheat. Images: Betterseeds; Wild Bioscience.

learn from other regions: While bee numbers are plummeting the West, they are growing in parts of Asia, according to the UN Food and Agriculture Organization. China (the world's largest honey producer) and India have both seen steady increases since the 1960s, and Turkey has doubled its population in the past 20 years. On farms, techniques like polyculture (growing multiple crops together), seeding wildflowers and reducing synthetic chemicals can support hive health, says Davidi—and the payoff is environmental and economic. "We are not at a point where bee extinction is on the table. But the agenda is to protect them, to work with them, and to use data and precision to make that relationship more resilient," he adds.

Precision-fermented foods

Almost half (44 percent) of all habitable land is used for farming. If we combine the land used to graze animals with the cropland used for animal feed, livestock accounts for 80 percent of the world's agricultural land use. It's primarily cows for beef and dairy. But animal-based protein sources, especially beef, are resource-intensive to produce. If the rising global population's demand for protein is met with livestock and poultry, the damage caused by pollution, land exploitation and climate change could be irreversible—to say nothing of the moral dilemma of raising tens of billions of animals under intensive food production conditions. But you can't grow protein out of thin air... can you? In fact, with precision fermentation, you can. Biotechnology companies today are using microorganisms to make specific ingredients—enzymes and proteins—where farming would face natural limits in resources or capacity.

Finnish Solar Foods, for example, has created a novel protein product by "feeding" a natural single-cell organism with captured CO_2 and electricity. It can be grown anywhere, taking just 0.1 percent of the land and 1 percent of the water that a similar amount of beef would. The company's co-founder Pasi Vainikka considers animal-free protein to be one of the most important new developments in AgriTech. "Technologies that are not dependent on long, global supply chains offer a form of resilience. Price volatility across major food commodities has increased dramatically over the past two decades. Coffee, wheat, soy, rice, almost all of them show growing instability. It's an early warning signal that supply is becoming tighter," he explains.

Precision fermentation has become a particularly big focus in the Nordic biotechnology industry. But it should be considered a complement to, not a replacement for agriculture, says Thomas Schmidt, CEO of 21st Bio. The Danish biotech has developed an approach that turns five kilograms of plant-based sugar into one kilogram of protein in a process roughly ten times more efficient than a Western dairy cow.

"Conventionally producing one kilogram of beta lactoglobulin, the most sought-after whey protein, requires hundreds of liters of milk. With precision fermentation, we can produce it with a significantly lower cost and environmental footprint, and the resulting proteins are lactose free, hormone free, vegan, and never exposed to antibiotics," says Schmidt.

Genetically modified seeds account for 80% of corn and soybean crops in the United States. Source: U.S. Department of Agriculture

Vainikka believes new food technologies present a "major opportunity" for farmers: "New technologies can separate cultural and premium food production from baseline calorie supply. Many traditional foods are deeply cultural. They are not just nutrition, they are identity. Those products can be produced in lower volumes, with much higher value, and priced accordingly. At the same time, new technologies can provide the bulk of efficient, low impact nutrition. In practice, a farmer could reduce production significantly while earning the same or even greater income."

"The AgriTech innovations that will have the greatest impact on small and mid-sized farmers include tools that measure water usage, automate irrigation, and analyze crop health. AI driven disease detection is another area with enormous potential."

Ilias Sousis, WikiFarmer

Systems-thinking technologies

Ultimately, the challenge is ensuring efficient food production and environmental stewardship are not at loggerheads. "There was a time when a grower might assume that if they reduced chemical use or made certain changes to protect biodiversity, they would inevitably lose yield. That creates a direct trade-off between doing what's good for the environment and what's good for business," says BeeHero's Davidi. But as technological solutions become more precise, and the long-term benefits of regenerative approaches come into focus, environmentalism and profitability are starting to align. AgriTech breakthroughs, especially in data- and biological modelling, increasingly point back to natural cycles and processes, and the best products in the market work with, not against, nature. "We need to think in systems," says Wild Bioscience's Hendron. "If you give farmers the tools to achieve both yield and sustainability, it becomes a reinforcing cycle. That is when you see real scalable change." ●

Left: Precision fermentation involves growing microbes under lab conditions to produce animal-free proteins and enzymes. Above: Around 70% of crops depend on insect pollination: almost all fruits, many vegetables, and most nut trees. Images: Solar Foods; BeeHero.