

REVIEW

Open access

Opportunities and Challenges in Implementing Artificial Intelligence in Smart Farming Systems

Elena Petrova^{1*}, Ivan Georgiev¹, Nikolay Stoyanov², Petar Kolev¹

Abstract

This paper delivers an interview-based investigation and literature analysis examining the potential benefits and barriers to adopting Artificial Intelligence (AI) in farming enterprises. Three branches of agriculture are examined: crop cultivation, dairy farming, and beef farming. As groundwork for the study, a literature analysis re-evaluates earlier work on intelligent farming. Subsequently, an interview study with 21 participants examines receptivity and readiness for intelligent farming tools and provides technical detail on three selected AI applications in agriculture. Though centered on circumstances in Sweden, the results apply to the wider European agricultural context and beyond. The study uncovers a broad range of elements that both promote and hinder the transition. Chief among the recognized opportunities are the strategic weight intelligent farming carries on the agendas of numerous sector players, the overall shift toward software-as-a-service models through co-owned equipment, the enormous stockpiles of existing data, and the substantial eagerness among farmers for novel technology. Conversely, the study highlights primary obstacles, including technical and legal difficulties related to data ownership, looming cybersecurity threats, the need for a clearly articulated economic rationale, and the occasional lack of technical competence within the sector. The paper finds that the overarching direction signals a shift toward intelligent farming, but the pace of change will depend on how well the identified barriers are resolved.

Keywords Precision agriculture, Artificial intelligence, Precision livestock farming, Smart farming, Sweden

*Correspondence:

Elena Petrova
elena.petrova@gmail.com

¹ Department of AI Implementation and Agricultural Innovation, Faculty of Agriculture, Medical University of Sofia, Sofia, Bulgaria

² Department of Smart Farming Systems and Challenges, Faculty of Agriculture, Technical University of Sofia, Sofia, Bulgaria

Background

Farming enterprises are confronting an extensive array of concurrent pressures. Tightening profit margins, intricate Europe-wide regulatory frameworks, and pressures from both outside and within to shrink their ecological impact are examples of demands to be satisfied. As a countermove, various methods are proposed to meet farmers' needs. Even though agriculture has advanced technologically for hundreds of years, the current century offers a wide range of technological options that could substantially reshape farming going forward. One is Artificial Intelligence (AI).

AI largely supplies the "intelligence" within intelligent farming. The label 'intelligent farming' implies a broad scope and ambitious anticipations. In this paper, intelligent farming is defined as an ecosystem of data-driven tools that aid decision-making across one or more parts of a farm's output, neither confined to nor limited by any specific agricultural branch. Intelligent farming could yield larger harvests, lighten farmers' load, support climate adaptation, and safeguard farming for generations to come. Given this, intelligent farming is expected to impact multiple domains within the agricultural sector.

To note just a few, trained AI systems are deployed to forecast optimal sowing and harvesting times for crops, prevent nutrient deficiencies and disease outbreaks, and ensure food safety [1-6].

Unlike most prior research, this inquiry examines the technical and non-technical dimensions of intelligent farming. Multiple earlier studies have examined technical issues such as optimal remote sensing image sharpness and key cybersecurity features for sensor arrays. Here, those concerns are acknowledged, but other vital, hands-on matters, such as data ownership and data exchange, are also evaluated. Furthermore, non-technical elements of intelligent farming, such as confidence and cost-effectiveness, are deliberated. Through this cross-cutting approach, a fresh understanding of the possible deployment of AI in agriculture is contributed. Moreover, the expansive reach enables a contrast among three agricultural branches: crop cultivation, dairy farming, and beef farming. The study was conducted in Sweden, yet a sizable portion of the conclusions may apply internationally as well.

Materials and Methods

This study combines a literature review and an interview study to identify the benefits and barriers to integrating AI into agriculture.

Literature review

First, a broad-scope literature analysis surveys the agricultural domain, its technology-oriented projects, and earlier scholarship on intelligent farming. This was conducted through a methodical literature analysis, as detailed by Berrang-Ford et al. [2]. The analysis was performed during the first half of 2021, drawing on the Web of Science database with the following search phrase: ((“machine learning” OR “deep learning” OR “artificial intelligence” OR smart OR AI) AND (“precision farming” OR “precision agriculture” OR “precision livestock farming” OR farm OR agricult) AND (Sweden OR Scandinavia OR Europe)). Following this, we selected papers that met all inclusion criteria: release dates between 2015 and 2021, a direct or indirect focus on the agricultural domain, and a focus on single farms or farm clusters rather than large-scale views of nations or regions. Of the 87 search hits, 32 papers met the inclusion criteria and were fully reviewed.

Interview study

Afterward, qualitative data were collected through a semi-structured interview study that probed how different agricultural actors view intelligent farming technology. All interviews were carried out in the first half of 2021. In sum, 21 individuals were interviewed across diverse sectors of the Swedish agricultural sector. **Table 1** provides a synopsis of the respondents. The individuals were clustered by position: ten were self-employed farmers (F1-F10), seven were staff at commercial businesses and cooperatives in the agricultural field (C1-C7), two were investigators at Swedish research bodies (R1-R2), and the remaining two were employed at a public agency (A1-A2). Of the seven individuals from commercial businesses and cooperatives, four belong to organizations seen to hold some financial stake in the agricultural field, even though they also fulfill a cooperative role. Two other individuals in that same grouping are strictly cooperatives, one of which has links to the public realm. The last is a certification entity.

The investigators interviewed are employed by a Swedish university focused on agriculture, and the individuals from the public agency are likewise connected to various roles within a Swedish authority focused on agriculture. The question sets were crafted before the interviews and stayed unchanged. Separate question sets were utilized for farmers and for organizations, companies, governmental authorities, and researchers. For farmers, distinct sets of questions were applied to those already familiar with the intelligent farming concept and to those unfamiliar with it. For organizations, companies, governmental authorities, and researchers, a single question set was employed, as all were chosen based on their familiarity with intelligent farming. All interviews took place via digital conference platforms, and all but two were taped with each individual's consent. The codes listed in **Table 1** are used throughout this article to reference the corresponding interview respondents.

Table 1. Interview study participants were divided across groupings. On the horizontal axis, participants are split by their alignment with meat, dairy production, crop cultivation, or 'Interdisciplinary' for organizations with no such specified concentration. On the vertical axis, participants are split by occupation category.

		Meat	Dairy (milk)	Arable	Inter disciplinary
Farms	Large farms (> 500 ha or > 300 animals)	F9	F2	F8	
	Small/medium farms (< 500 ha and < 300 animals)	F6, F7	F4	F1, F3, F5, F10	
Organisations	Commercial cooperatives	C6	C2	C1, C3	C4, C5, C7
	Researchers		R2		R1
	Authorities				A1, A2

Outcomes Drawn from the Literature Review

The Web of Science database yielded 87 articles for our search term. Among these, 32 studies met all inclusion criteria and were fully examined. This segment relays the primary conclusions from the literature analysis. We separated our discoveries into two principal subjects, which appear in the subsections beneath: (1) approaches for capturing data within intelligent farming and (2) intelligent farming solutions deployed across agricultural branches.

Approaches for capturing data within intelligent farming

At its core, two classes of data-capture approaches are employed in intelligent farming: remote sensing and the Internet of Things (IoT). Either approach can be applied to any farming branch, depending on which activity the data is intended to inform as decision support.

Remote sensing

Remote sensing tools enable the recognition and tracking of terrain features across the planet. Information gathered through remote sensing is obtained from afar, most often through satellites and uncrewed aerial vehicles. The trio of attributes most commonly discussed for remote sensing data encompasses spatial, spectral, and temporal resolutions [7–19]. Spatial resolution refers to the pixel dimensions in an image, a feature that shapes the ability to distinguish items in visuals. Set apart from this, spectral resolution describes the breadth and count of spectral sampling windows, which determine how well sensors can perceive objects across the electromagnetic spectrum. Temporal resolution deals with the interval at which data is refreshed [13].

The matter of how obtainable and economically feasible remote sensing data collection is gets attention from Khanal et al. [13], who lay out remote sensing technology choices spanning both openly accessible sources (e.g., NASA's Landsat, the European Space Agency's Sentinel satellite constellation) and those carrying a price tag (e.g., RapidEye, GeoEye-1) [13]. Nevertheless, data granularity fluctuates, with mid-range-resolution data (≥ 10 m pixel size) offered at no charge, while the cost of high-resolution (≤ 5 m) and ultra-high-resolution (≤ 1 m) data increases with their increasing fidelity [13].

On the topic of data granularity, Meier et al. [19] argue that site-tailored intelligent farming hinges on fine resolution, as spotting deviations becomes unworkable or pointless when pixel dimensions are overly large. To be sure, the resolution requirement shifts depending on the analytical purpose the data is slated to serve. For example, projecting crop output within a plot can achieve notable precision despite a coarse resolution [13], whereas pinpointing crop disease through hyperspectral imaging requires fine-grained resolution [20].

Internet-of-Things (IoT)

The Internet of Things (IoT) is a broad term for devices with embedded circuitry and network connectivity that enable remote monitoring and data exchange. In agriculture, IoT primarily uses sensors to collect data. By subjecting this data to further processing, valuable insights can be extracted to guide decisions, for instance, by farmers [1]. Kamienski *et al.* [10] delineate four core difficulties confronting IoT progress in intelligent farming. Firstly, the IoT arrangement must show a substantial degree of flexibility. Given that farmers' demands often diverge significantly, the IoT setup needs to be tailored to local conditions without adding extra work for the farmer. Secondly, rolling out IoT must happen efficiently. As Kamienski *et al.* [10] phrase it, "there is no 'one size fits all' in IoT systems". Hence, every arrangement demands tuning; the web connectivity and farm framework must be trustworthy, and the farmer must commit adequate human and financial resources to this endeavor.

Furthermore, expandability is influenced by the earlier elements. Also, it depends on whether the system, along with its trained models, is meant to operate on a lone farm or an entire farming alliance. Finally, the intricacy inherent in the IoT system can be read as a balancing act between keeping the middleware broker elaborate while the software application stays straightforward, or the inverse [10].

One more dimension of IoT in intelligent farming concerns safeguarding. Given that the data often has value for the farmer and is classified as a commercial secret, Kleinschmidt *et al.* [14] outline the requirement for communication secured from one endpoint to the other, spanning from the sensor to the application. In concrete terms, this means the IoT sensor web must maintain a security posture aligned with the cloud store and any prospective fog computing layer [14]. By ensuring protection, the likelihood that the farmer will trust the IoT setup increases. Even so, faith in IoT setups does not rest solely on security but also on the accuracy of the sensors. Barring confirmation that systematic measurement drift is absent from the sensors, hardly any farmer would place confidence in the trained algorithm or the live sensor feed [21].

Intelligent farming solutions deployed across agricultural branches

Agriculture is a multifaceted sector, with its branches requiring a varied array of tools. Because the collected information varies across branches, certain data formats appear more frequently in some branches than others. Likewise, the tasks undertaken within the separate branches summon distinct application scenarios when bringing AI into farming businesses.

Intelligent farming in livestock operations

The promise of intelligent farming within livestock operations, covering dairy, beef, and fur production, rests substantially on raising productivity and economic returns through streamlining and automating tasks and information handling [4]. A considerable share of scholarship centers on techniques for observing and caring for animals using automated or semi-automated methods [3-5]. These publications argue that apparatus, spanning both body-mounted and stationary varieties, can be installed in animal housing and can harvest data that provide signals about animal health. The data that can be harvested from these pieces of equipment spans a wide range, yet body-mounted devices can measure temperature, hormone concentrations, heat cycles, and more. Stationary devices more commonly comprise 3D imagers for scoring body condition, infrared cameras, sensors for capturing environmental and climatic conditions, and automated weighing platforms and passageways [4, 5].

Intelligent crop cultivation

In crop cultivation, a central role of intelligent farming is computing vegetation indices for plots or zones to track when harvesting and other actions are due. This can be accomplished through remote sensing and IoT approaches. Viljanen *et al.* [22] develop a machine learning model aimed at striking the optimal "balance between the highest possible yield quantity and an adequately high digestibility for feeding". By employing an affordable drone setup that captures multispectral imagery from an RGB imager and an infrared imager, conventional physical instruments for projecting ley

harvest can be swapped out for smarter machine-learned models that deliver superior accuracy [22]. Beyond that, the scholarly work on projecting both the volume and the nutritional value of silage can also be carried out using satellite-derived data, as outlined by Griffiths *et al.* [8]. The investigation reveals that it is possible to detect grass-cutting events and, on that basis, profile land-use intensity by examining satellite imagery [8].

In relation to harvest projection, Feng *et al.* [6] underscore how vital it is to weave the crop's biophysical traits into machine learning algorithms. This indicates that to achieve high precision, mimicking the crop's developmental cycle is essential, enabling the model to capture its traits across different growth phases. Going further, Matos-Moreira *et al.* [17] introduce manual soil specimens to further refine their model. By coupling manual specimen collection and laboratory work with a range of pre-existing data streams, one may develop a model capable of projecting crop grade or the density of a particular substance at a chosen location and time.

A further deployment of precision farming involves detecting disease or pest infestations in crops. Torai *et al.* [20] explore how crop sickness can be recognized by sorting, or tagging, picture segments as “healthy”, “infected”, “diseased” or “aged”. Following that, tools such as hyperspectral imaging, Bayesian networks, and probabilistic latent semantic analysis are applied to identify the diseases [20]. This piece of research stands as a strong case for applying remote sensing technology to agriculture, calling for exceedingly fine data granularity, ideally down to the centimeter level.

One puzzle that arises when directing artificial intelligence toward crop-related problems concerns how to handle the diverse kinds of data at hand. Kerkow *et al.* [11] turn to fuzzy mathematical modeling to crack this problem. This tactic enables blending machine-learned climate simulations with wind records and expert landscape understanding to develop precise models [11].

Operationalizing smart farming

The body of literature surveyed also reveals several thought-provoking facets of bringing AI into the agricultural sphere. A command of both conceptual grounding and applied know-how around smart farming is underscored by Medvedev and Molodyakov [18] as indispensable for its fruitful adoption. The difficulty lies in the reality that growers seldom command the financial leeway or spare capacity to undertake lengthy educational programs in the area. As a remedy for the scarcity of technical education in smart farming, Medvedev and Molodyakov [18] advocate concise, model-centric training modules that encompass the technological, financial, and stewardship dimensions of the subject. An essential design feature is the on-demand nature of the offerings, so that time-strapped growers can tap into the material at times that fit their schedules [18].

Viable business rationales together with unmistakable impetus are both singled out as vital building blocks for accelerating the societal diffusion of smart farming tools [7, 15, 16]. The countervailing forces that brake the momentum toward smart farming get sorted under the headings of economic, institutional-behavioral, and structural obstacles [15], with market-related friction also playing a role [7]. The scholars further flag social and ethical motivations as exerting considerable influence in cultivating broad-based demand for smart farming. Their conclusion holds that, shorn of endorsement from the wider public, novel solutions will not gain a foothold among pivotal actors [15].

A separate strand of scholarly effort attempts to map out what exactly stands in the way of rolling out and propagating smart farming technologies. Kernecker *et al.* [12] detail how growers orient themselves toward such tools in markedly different fashions, shaped by the extent to which they have already embraced them. Among the group labelled adopters, the perceived roadblocks to further uptake are formed by burdensome initial capital outlay, struggles with drawing meaning from collected figures, shortcomings in how devices mesh together or in their accuracy, an inability to discern the novel technology's extra payoff or its edge over existing setups, coupled with an absence of impartial counsel from extension agents and other intermediaries. The non-adopters similarly zero in on heavy capital commitments and on the obscured extra payoff as obstacles. Layered on top, they point to daunting intricacy in everyday use, a poor fit between the technology and their own context or scale of operation, and the unavailability of neutral proof-of-concept demonstrations, as further hindrances [12].

Wrapping up the literature review, the matter of how information gets laid out and visually rendered earns strong emphasis, spanning both crop cultivation and livestock management. Moving beyond mere identification of viable technological uses in agriculture, several investigative teams [13, 21] argue that machine learning and AI pipelines require decision-aid interfaces that present the underlying figures in an intuitively digestible manner.

Outcomes Drawn from the Interview Study

This part draws forward the core takeaways from the interview investigation. The findings are separated into technical and non-technical dimensions of introducing AI into agricultural practice. We conclude by presenting the findings grouped by respondent type (farmers, companies/corporations, research institutes, and governmental authorities).

Technical dimensions of introducing AI

Rolling out AI inside the agricultural arena does not amount to a single, uniform undertaking, precisely because the arena itself is marked by deep variety. One recurring sentiment, articulated by a farmer participant, is that growers in any given agricultural branch almost always believe that smart farming adoption has made greater strides in every branch except their own (int. F4). The branch most commonly flagged by growers as the present-day leader in technological maturity is dairy production. Robotic milking units made their commercial debut several decades ago. Alongside these units, the diet of each animal can be fine-tuned to improve its health markers and productive output. It is precisely these robotic milking units that have earned the dairy branch its reputation as noticeably data-infused (int. C4).

A consideration of central importance when sizing up the achievements of robotic milking units is the tightly wound feedback loop. Because the cows are fed and milked daily, the apparatus can adjust its parameters quickly in response to the most recent data stream (int. C4). Compounding this, Sweden's dairy farmers boast a long history of systematic record-keeping through their participation in Kokontrollen, a bovine data aggregation platform run by Växa Sverige. Even if Kokontrollen has now migrated to a web-based format, dairy farmers on Swedish soil have been filing reports into the system for longer than a century. In earlier eras, the entire record-keeping was done by hand, whereas today virtually all information linked to milk output is automatically recorded straight from the robotic milking units (int. C6).

Set in stark contrast to dairy production, crop cultivation is marked by heterogeneity, with dissimilar crops requiring distinct implements and technical solutions. For this reason, any single piece of machinery that proves effective is tricky to transplant into the crop farming branch as a whole, rendering its pathway of technological change more tangled. That said, developing potent technology for specific crop types remains entirely within reach. As a rough heuristic, crops that require heavy manual input, exemplified by vegetables, tend to require a great deal of technology because they are grown in smaller, more tightly regulated plots (int. C3). In these kinds of settings, for instance, in greenhouse environments, the feedback loop runs tighter, and the number of variables outside the operator's command, such as weather or wild boar incursions, shrinks, which simplifies the task of bringing in new technology and AI (int. C3, F3).

Among the trio of agricultural branches examined in this investigation, beef production is viewed by the study's participants as trailing furthest behind in technological development. Despite this, one participant embedded in a sizable corporation expresses confidence that meat production will play a pivotal role in the forward trajectory of Sweden's core food production system (int. C4). The roster of conceivable breakthroughs features digitizing the supply chain end-to-end by transmitting details ahead to slaughterhouses concerning the attributes of the livestock they are about to receive. Given that every head of cattle is obliged to carry an RFID tag, the participant sees an extraordinary reservoir of untapped potential, as the animals' development could be continuously monitored along the entire chain. With an infrastructure of this kind, a slaughterhouse could plan its intake of meat by quality and quantity far in advance. In parallel, a retail grocery outlet could channel data back to primary producers on the shifting popularity of distinct meat categories, thereby equipping producers to tune their output to live consumer signals (int. C4). Building further, if one succeeded in weighing cattle autonomously and without manual intervention, their growth trajectories would become predictable, opening the

door to perfectly timed dispatch for slaughter. Through such fine-tuning, the scenario of holding fully mature animals that simultaneously drain financial resources and emit climate-damaging methane could be sidestepped (int. C4).

Data capture within smart farming

Shifting the lens to data and the practices surrounding its capture, the feedback gathered through the interviews paints a picture of divergent day-to-day realities across the agricultural landscape. From one vantage point, a subset of participants holds that growers are broadly receptive to capturing data across their operations (int. C3, F6, F8). From the opposite vantage point, certain growers who took part in the study report that they capture hardly any data across their holdings, even as they freely admit they understand how data could generate extra value for them (int. F1, F3, F5). Occupying the ground between these poles sits a whole spectrum of postures regarding data capture and the embedding of technology into farm routines. Several participants drawn from the ranks of the bigger firms and cooperatives floated the idea that these postures could be colored by the sense of hassle that data capture seems to entail. They are united in their conviction that a greater share of growers would warm to the practice were the task of capturing data rendered significantly less cumbersome. Beyond that, there is also a palpable feeling that the data already captured gets put to suboptimal use, partly attributable to its residence inside mutually isolated database silos (int. C3, C4, C5). The accounts furnished by the participants suggest that the manner of data capture varies considerably across the agricultural branches examined. To illustrate, a large share of participants from the dairy segment report that a substantial volume of data is captured, often down to the individual-animal level, across the livestock herd (int. C6, F2). Standing in contrast, crop growers, too, capture data on practically all holdings, but that data does not routinely exhibit the same level of granularity. A crop grower may well capture remote sensing satellite imagery of their land. Yet, occasionally that capture occurs not at a resolution measured in square meters but rather at the scale of a discrete field or even the aggregated farm level. The applied inputs, meaning the materials deliberately introduced into the soil, represent the element for which the grower would find decision-aid support most intriguing, provided a meaningful and profitable chain could be drawn linking applied inputs to resulting outputs (int. F4).

One grower who took part and has a professional history in the technology sector thinks that the central stumbling block in directing AI in crop cultivation is the limited volume of available data (int. F10). The full data chain, they observe, is not stitched together in the current landscape. What this means concretely is that the input figures logged during events like crop sowing stay inadequately linked to the harvest's output metrics. What makes matters worse is that the intelligence drawn from the harvest never circles back to serve as a foundation for steering choices about the following season's sowing. Hence, the data loop remains open, a situation that needs to be rectified before AI can operate effectively (int. F10). This data void, layered atop the multitude of hard-to-forecast variables such as fickle weather, forms a technical roadblock to training AI models.

Striking a balance between wide-ranging utility and pinpoint accuracy

A fundamental tension that sits at the heart of AI and machine learning work is the unavoidable tug-of-war between underfitting and overfitting. The study participants voiced a range of perspectives on where the emphasis should fall. When broaching this subject during the conversations, we steered clear of specialist jargon, framing the discussion instead around the notions of 'wide-ranging utility' and 'pinpoint accuracy'. A camp of participants holds the firm position that pinpoint accuracy reigns supreme, reasoning that a technological offering that correctly forecasts or flags something on only every other attempt is effectively worthless in the field (int. A1, C6, R2). Arrayed on the opposite side, a different set of voices makes the case that, provided the model's predictive or detection performance clears the bar of human capability, even if only by a slim margin, then favoring wide-ranging utility presents no problem whatsoever. To press the point further, quite a few participants insist that the commercial pull for one-size-fits-all, standardized products dwarfs the niche demand for offerings meticulously sculpted around hyperlocal requirements (int. C4, F4, F5, F8). An observable split emerges in which operators in the cropping sector, together with corporate players, signal a greater willingness to accept a heavier tilt toward wide-ranging utility, whereas those managing livestock voice a stronger insistence on pinpoint accuracy (int. C1, C4, C6, F4, F5, F8). One voice from the livestock world underscores that an enterprise would harvest essentially zero practical upside from a setup that correctly identifies heat cycles in the herd on just one of every three

tries. The same participant doubles down on the absolute necessity for tightly calibrated models whenever the target domain encompasses biological systems and sentient creatures (int. C6). Predictably, numerous participants circle back to the observation that discovering a sweet spot between wide-ranging utility and pinpoint accuracy is what truly counts. The dream scenario would bake in a degree of user-controlled tuning along this very axis, empowering each deployment to be shaped around the unique contours of each holding (int. C3, C5, F4, F5, F8).

Full autonomy contrasted with advisory tools

When the conversation turns toward the ideal configuration of farm technology, getting to the bottom of how growers actually want their digital implements and mechanical aids engineered, along with the precise flavor of assistance they seek, becomes paramount. Scanning the pool of grower participants, a solitary voice steps forward to champion a future in which smart farming systems assume total command over farm operations through full autonomy (int. F10). Swinging hard in the opposite direction, a hefty majority of growers gravitate either toward setups that digest the amassed data and then push forward a concrete recommended course of action (int. F1, F5, F6), or toward more restrained interfaces that confine themselves strictly to surfacing the data, leaving the grower entirely in the driver's seat when it comes to concluding (int. F2, F4, F9). Advisory support and analytic outputs synthesized from aggregated data streams already enjoy modest traction in practice. However, their deployment frequency and impact are poised to rise substantially should the foundational data become both more readily accessible and demonstrably more faithful. A dairy operator among those interviewed notes that while the installed system does indeed pipe out a stream of suggestions derived from the ongoing, aggregated data inflow, the actual steering decisions made on the property continue to be anchored wholly in the untouched raw data feed (int. F2).

The data ownership and sharing puzzle

Looming large among the preoccupations surrounding the maturation of smart farming technologies is the question of who ultimately claims the information generated. The overwhelming majority of smart farming platforms are deliberately architected as proprietary, walled-off digital enclaves, affording only the slimmest of passageways for data to cross their boundaries. This engineered fragmentation chokes off the ability of different platforms to converse with one another. It thus stands squarely as a blockade to the knitting together of a seamless digital fabric. Rooted in the cutthroat maneuvering among the globe-spanning agricultural equipment behemoths, a dynamic fueled equally by the drive to cement customer entrapment inside each firm's branded ecosystem and by the defensive reflex to deny adversaries any foothold from which to craft rival offerings, this entrenched architecture resists easy dismantling (int. C3, F10). Even so, a pair of study participants (int. C4, F10) pick up on the early signals of a directional pivot among these same multinational titans, a slow turn away from technologies whose design philosophy centers on customer lock-in and a tentative shuffle toward regimes of far greater data fluidity. The bet underpinning this pivot is that such fluidity can unlock superior value for both corporations and end users tethered to their platforms. A downstream implication of this shift, should it gather steam, is that an expanding slice of agricultural data looks set to be structured around open, interoperable standards (int. C4, F10).

Even if the equipment manufacturers supplying the foundational technology make some progress toward openness, a small cluster of parallel initiatives has sprouted up to tackle data compatibility friction head-on. GigaCow, an investigative venture housed within the agricultural university SLU and focused squarely on the information output of dairy enterprises, pursues the objective of making data portability a reality by orchestrating the automated extraction of records from a diverse fleet of robotic milking installations captured over time. Endeavors of this stripe garner a warm reception across much of the grower community. Still, the arrangement remains a bolt-on fix stitched together by an outside player and cannot rival the elegance of a world in which every piece of hardware ships natively ready to share data from the moment it powers on (int. R2).

Cyber threats and digital vulnerability

A segment of the study's participants draws attention to the lurking menace of hostile acts targeting online information systems, casting this as a tangible hazard entangled with the wider push to embed novel smart farming technology (int.

A1, C4, C5, F1, F2, F8). The specter of a successful breach imperils growers individually and society collectively. Narrowing the lens to the societal dimension, an official embedded within a public authority casts the cybersecurity dimension of farming's digital turn as an issue meriting particular gravity (int. A2). The official's working assumption is that any such consolidated data repository would almost certainly attract a designation signaling the most stringent imaginable protective and confidentiality mandates and would land under the oversight umbrella of Sweden's Security Service, SÄPO. Framed in this light, the cybersecurity hurdle can plausibly be read as a formidable brake on any timeline toward a unified data infrastructure. That said, the same official tacks on the qualifier that, were hostile cyber activity to actualize, a reality in which the data resides inside a collectively stewarded fortress would be markedly less perilous than the current patchwork where data sits scattered across countless individual farms, precisely because the former scenario would see the repository subjected to a regime of round-the-clock professional guarding that far outstrips the ad-hoc precautions most growers currently wrap around their own holdings (int. A2). While the conversation around cyber risk is most often initiated by the bigger institutional players and public-sector bodies, the threat has not escaped the notice of some within the grower community itself. These growers articulate a conviction that networked data hubs underpinned by flimsy defenses render a farming operation acutely naked before potential adversaries (int. F1, F2, F8). That said, one grower offered the quip that "it is not worse than having all money in a bank account, and that I trust today." (int. F1). Other voices in the study, straddling both public agencies and the grower cohort, acknowledge that information systems likely harbor points of weakness but refuse to elevate this into a source of active anxiety. Rather, they push back squarely against the suggestion that fragile cybersecurity would place the agricultural domain in a uniquely precarious position relative to any other corner of the modern societal fabric (int. A2, F5, F10).

Dimensions of AI deployment that lie beyond technology

AI, along with the broader smart farming toolkit, commands a seat of considerable importance within the strategic planning horizons of the lion's share of the agricultural organizations and cooperatives whose representatives sat for these interviews (int. A1, C1, C2, C4, C5). Inside one of Sweden's foremost agricultural enterprises, AI is ranked among the most potent levers for squaring the circle between a more ecologically sound production model and an upward-trending output curve (int. C1). A further participant, positioned within a Swedish agricultural business, recounts that their organization's chosen angle of attack on the sector's digital metamorphosis will center on pouring capital into the software-mediated orchestration of separate tools, the aim being to strip complexity away from smart farming technologies so that growers can maintain a clear line of sight across their operations and land on well-founded operational choices (int. C2). The overarching drive toward digitization and the wringing of maximal intelligence from data is placed on a higher rung than directing fresh investment toward tangible physical assets, such as purpose-built server halls, as one ready illustration. The logic underpinning this ordering is the belief that channeling resources into the software layer channels benefits to growers along a more immediate and perceptible pathway (int. C2, C4).

Political momentum and the drive toward intelligent farming

When the subject becomes the digital re-engineering of a societal pillar as foundational as the food production system, a host of directional choices inevitably carry resonance and consequence far beyond the farm gate, touching the national interest. A number of the study participants operating within the orbits of large organizations and public bodies voice the sentiment that a genuine, widely shared appetite to see the farming sector take a decisive leap toward greater intelligence does exist (int. A1, A2, C7). The burden of actually undertaking this technological metamorphosis, however, lands squarely on the shoulders of the growers themselves. A pair of participants advances the critique that what is conspicuously missing is any sustained drumbeat of organized initiatives, whether emanating from the apparatus of the state or from the large institutional players, designed to propel the expansion of digitization forward along anything resembling a coherent roadmap (int. A1, C7). One study participant, whose professional home is a governmental authority, wades into the discussion of whether a genuinely national-level eagerness exists to digitally overhaul the farming sector (int. A2) and stakes out the position that the infusion of AI into agriculture marks the next logical chapter in the sector's unfolding story. This participant shares that animated, ongoing debates are coursing through the corridors of public agencies, centered on the twin questions of whether and precisely how these bodies should adopt a more

muscular, front-footed leadership stance to steer Sweden's digital transformation of its agricultural landscape. The civil servant confesses to a personal assessment that Sweden, measured against peer nations grappling with tighter fiscal circumstances and thinner agricultural budgets, has allowed itself to slip to the rear of the pack in digital advancement (int. A2). The most natural opening maneuver, in this participant's estimation, would be the establishment of a singular, nationally scoped data commons into which the totality of agricultural information streams could be pooled. That said, this very same participant scans the horizon and detects no crisply defined political will animating such a project, even while the emergence of that will could act as a powerful accelerant to the entire digital transition. While there exists no undercurrent of desire to 'strong-arm' growers into embracing agricultural technologies and digitizing their enterprises, such a trajectory becomes a thoroughly plausible outcome if a nationally endorsed, politically charged current of interest in steering toward that precise destination begins to flow (int. A2).

Monetary drivers

Just as holds in every other sphere of commerce, the farming domain marches to the beat of chasing higher earnings. The lure of financial reward acts as an engine, not exclusively for sprawling agribusiness operations but also for the individual cultivator (int. F3, F5). Precisely for this reason, the chronically thin revenue streams that characterize farming pose a towering challenge. The art of wringing out efficiencies looms especially large for the frequently loss-making Swedish agricultural units striving to stay in the ring against global competitors (int. A2, F3). Amid the labyrinth of subsidy instruments that envelop food production within the European farming framework, no cultivator participating in the study could identify any scheme designed to cushion the financial blow of adopting novel technologies at the individual farm scale. The upshot is that the technological leapfrog, meant to deliver either greener production footprints or fatter harvests, is bankrolled entirely from each cultivator's pocket (int. R2).

Cultivators do not line up uniformly behind a single set of financial calculations that might nudge them toward weaving smart farming instruments into their everyday practice. Roughly drawn, one cluster of cultivators feels a far weaker tug to invest in technological renewal, given that their existing architecture reliably delivers revenue regardless of such choices. This cluster tends to be populated by those who hold outright ownership of both their land and the structures on it. Arrayed on the other side stand those cultivators who operate on leased acreage and who, by virtue of that arrangement, find themselves trapped in an unending imperative to ratchet up their efficiency year after year (int. C3, F4, F5). The ownership question is not the whole story; however, the sheer scale of the enterprise also tilts the odds in favor of whether smart farming instruments will actually fatten the bottom line. Among cultivator participants, a settled belief holds that running a compact operation makes it exceedingly difficult to achieve a meaningful payback from smart farming methods (int. F1, F5). One cultivator steering a modestly sized farm reports that his financial headroom does not stretch to purchasing new capital equipment, a new tractor being the textbook example. Yet rejuvenating the stable of machinery constitutes a non-negotiable stepping stone if smart farming instruments are to amass data of sufficient density and worth (int. F1). This strand of the discussion can be hitched directly to the dominant macro-scale current of farm amalgamation. At its core, this phenomenon encodes the brutal arithmetic that outfits below a certain dimensional floor simply cannot mount a credible competitive challenge against their larger counterparts, who can convert sheer bulk into formidable defensive moats. The blunt reality is that the surplus thrown off by running the majority of small units is too slender to sustain the enterprise, a vise that compels scores of cultivators to fuse their operations with those of adjacent properties (int. C7, F4).

The migration toward software-as-a-service

One more wave, presently remodeling the contours of the agricultural sector, touches on commercial packaging through which technologies are retailed and disseminated. According to the reigning orthodoxy, the preponderance of technology changes hands as discrete pieces of physical equipment, a transaction class that habitually lands as an eye-watering capital blow for the cultivator. The landscape is, nonetheless, inching toward a different configuration. A pivot is steadily gaining traction, one in which functionality is accessed through 'Software as a Service' (SaaS) constructs. This unlocks commercial blueprints in which the material apparatus itself lands at a radically depressed initial price point, or is even delivered to the cultivator's possession for no upfront charge, while the cultivator shoulders a periodic subscription fee in

exchange for the privilege of operating the conjoined hardware-software bundle. One informant embedded inside an agricultural cooperative hazards the prediction that the shockwaves from this reconfiguration will be profound and speculates aloud that, in a mere ten years, tractors could be vended purely as a leased utility rather than as a capital good. Underpinning such a re-engineering of the commercial model will be an insatiable appetite for mammoth datasets (int. C4).

Entanglement with and confidence in engineered systems

A disquiet that surfaced repeatedly and was subjected to extended examination during the dialogues centers on the state of thoroughgoing entanglement that smart farming instruments threaten to spin between the cultivator and the technological layer. Entanglement with technology denotes a configuration in which the day-to-day pulse of the farm is suspended upon processes that run in either fully automatic or partly automatic mode, steered by software routines whose inner mechanics often stay impenetrable, upon a flow of electric current that never falters, or upon a tether to the internet that remains continuously alive. The system, envisioned in its flawless operational state, stirred no opposition from any corner of the participant pool. Discomfort flares; however, at the moment, the conversation turns to episodes in which such a system collapses. A participant housed within an organization expresses concern that the entire utility of the setup would dissolve into nothing should the connectivity fabric upon which it is draped be rent apart (int. C6). This current of anxiety manifests through a spectrum of emotional registers and with a gradient of felt urgency. Those who steward herds of living animals give voice to a particular flavor of distress, one rooted in the bedrock fact that their entire enterprise revolves around breathing creatures whose ease and bodily integrity are pinned entirely to the uninterrupted hum of the technological apparatus (int. C5, F2). Adding yet another layer, multiple participants tug at a thread woven into the wider fabric of technological entanglement: the haunting possibility that entire reservoirs of hard-earned, practical intuition currently carried by cultivators and their trusted advisors might evaporate into the ether of obsolescence (int. A1, F1). One cultivator who joined the study confesses to a private foreboding that, were he to drape too thick a quilt of technology over his land, he would run the risk of watching some fraction of the intimate, geographically bound, wordless familiarity with his particular terrain dissolve through his grasp. He fixates in particular on certain micro-scale quirks of his fields that he experiences as fiercely stubborn in their refusal to be faithfully transcribed into any digital dataset. Confronted with the staggering tangle of interwoven parameters that collectively decree how a plant in one unique patch of earth will unfold, he nurses a quiet unease that a piece of software could blunder straight past some variable of decisive weight (int. F1). This queasiness can be traced to a wider, at times explicitly articulated, undercurrent of guardedness toward technology, a persistent itch that its outputs must forever be subjected to a second set of eyes to assure that it is indeed performing faithfully while left to hum along in autonomous mode (int. F1, F4).

The shape of everyday labor

Panning across the attitudinal terrain, the dominant stance toward smart farming and the metamorphoses it could set in motion, both across the sector as a whole and for cultivators on the ground, is strongly affirmative. Braiding smart farming instruments into the everyday weave of operations could translate into pared-back time burdens and clipped expenses for routines like distributing water and applying soil amendments. The corollary is that cultivators can regain a stronger command over their own schedules once they are equipped with dependable, thoughtfully crafted technology (int. C3, C5, C6, F7, F8, R2). One happy spillover from this pivot is a detectable improvement in the day-to-day working climate for the people employed on the holding (int. F8). Holding this sunnier picture in the foreground, researcher respondent R2 delivers a bracing counterpoint, noting that, as a general trait, cultivators exhibit a curious inability to affix a proper price tag to the hours they sink into the work relative to the economic yield they claw back. Farming units find themselves locked in a ferocious squeeze to extract a return on invested capital that justifies the entire enterprise, a crucible that, during the seasonal flashpoints when the workload reaches its fever pitch, drives cultivators to subsist on a sleep ration bordering on starvation (int. R2). A cultivator confirms the grim math, remarking that the sheer tonnage of hours he clocks pushes some of those hours effectively into the territory of unpaid labor (int. F7). Funneling AI into the agricultural theater could, in principle, sand down some of the jagged edges of these savage seasonal workload spikes, and in so doing, restore to cultivators a measure of something that carries immeasurable social and human weight.

Viewing the landscape from a somewhat tilted angle, the matter of sinking capital into and bedding down novel technology in agriculture is freighted with an additional subtext: outlays of this kind are frequently categorized by cultivators not as operational imperatives but rather as beguiling playthings, entities perched somewhere on the spectrum between the genuinely useful and the merely stylish. In this vein, expenditures of this nature are described with a wink as being debited from the “amusement account” (int. C3, F5). A cultivator lends flesh to this portrait, divulging that the lion’s share of the technological acquisitions that have landed on his farm owes its presence to his private captivation with and enchantment by gadgetry (int. F8). Respondent C4 observes that a great many cultivators derive authentic satisfaction from handing over currency in return for gleaming new implements and machines, with tractors serving as the quintessential emblem. Extrapolating from these narrative threads, it would appear that a considerable slice of the cultivator community perceives the very magnetism of operating a farming concern as lying in the liberty to continually tinker with and adjust the operation until it mirrors one’s own idiosyncratic preferences. While one participant derives deep fulfillment from keeping operations staunchly manual (int. F9), another takes delight in perpetually reimagining the work process through the incremental stacking of new technological strata (int. F10).

Gravitational pull of the marketplace and the scholarly sphere

Echoing the recognized necessity of stitching end-users into the very fabric of the design process, a separate obstruction that stymies pilot ventures and academic research undertakings from successfully vaulting the chasm into commercial traction is the elementary disconnect that their foundational ideas often lack any mooring in the authentic, voiced requirements of the agricultural marketplace (int. C6, R1, R2). A trio of participants advances the analysis that this mismatch may well be the progeny of researchers and product fabricators operating at a persistent remove from those who would ultimately use the tools, compounded by a neglect of disciplined market reconnaissance aimed at zeroing in on the specific pain points around which remedies deserve to be clustered. The tableau they sketch instead is one in which agricultural technology is birthed into existence either as a sandbox for technical virtuosity pursued as an end in itself, or, flipping to the opposite pole, as a mere incidental exhaust fume of inquiries whose fundamental character is agronomic rather than technical (int. C6, R2, A1). One denizen of the research community recounts that, over a lengthy stretch of years, the institutional energies of Swedish academia were deliberately channeled toward facets of agriculture located at a considerable distance from the technological sphere (int. R2). The currents have, however, commenced a slow pivot over the past decade, with Swedish universities beginning to recognize the pivotal role that nascent technologies are fated to play in farming’s unfolding story and to steer resources in that direction.

Condensation of outcomes grouped by participant cluster

To braid together the various filaments unspooled over the course of this interview-driven inquiry, the recurring leitmotifs and thematic knots are sorted into those that present themselves as the articulated longings or gleaming openings for AI in the agricultural space, arranged in counterpoint to the barricades or friction surfaces that put a drag on its broader embrace. Building further on this scaffold, the sharply contrasting rejoinders and observational stances offered by the separate clusters of participants make it possible to tease the identified longings and barricades apart along the seams that mark the distinct functions each grouping performs within the wider agricultural ecosystem. **Table 2** offers a distilled cartography of the most resonant signals plucked from the interviews, parsed across the distinct participant clusters.

Table 2. Distilled cartography of the principal signals plucked from the interview study, parsed by distinct participant clusters.

Stakeholder	Demands and opportunities	Barriers and challenges
Farmers	• Higher profitability	• High investment costs
	• Better working conditions in terms of time efficiency and comfort	• Limited technical knowledge and education

	• Greater sustainability	• Lack of integration between technical systems
	• Social benefits	• Challenges in interpreting and utilizing data
	• Entertainment and enjoyment aspect	• Uncertain consumer market conditions
		• Insufficient cybersecurity measures
Companies	• Enhanced collaboration	• Unclear ownership of data
	• Inclusion of end users during the development stage	• Weak cybersecurity protection
	• Shift toward Software as a Service (SaaS)	
	• More efficient logistics	
Research institutes	• Faster and more effective research processes	• Research outcomes not aligned with market needs
	• Improved data sharing	
Governmental authorities	• Increased competitiveness in the global market	• Undefined role in the transition process
	• Ability to provide EU innovation subsidies	• Lack of cybersecurity preparedness

Opening the analysis, the feedback gathered from the grower participants reveals that a wealth of promising opportunities surrounds the deployment of AI and smart farming technologies in the agricultural sphere. Standing at the forefront, in their assessment, novel smart farming instruments have the capacity to improve their financial returns, either by boosting incoming revenues or by freeing up hours otherwise consumed by monotonous chores. Flipping the coin, the hefty upfront capital requirements to put these technologies in place are singled out as a formidable barrier. That said, should the financial wherewithal exist to underwrite such outlays, growers hold the conviction that these investments will ultimately reward them through enhanced margins and a sharper competitive edge. Additional currents that feed the appetite for smart farming instruments include their promise of improved ecological stewardship and the simple fact that they inject a greater sense of enjoyment into farming. Further roadblocks, as perceived by growers, include overly complex systems, a lack of cross-platform compatibility, inadequate foundations and scarce avenues for ongoing technical education tailored to the agricultural context. Compounding matters, the volatile nature of commodity markets renders sinking capital into smart farming a gamble from the grower's standpoint.

Surveying the terrain from the vantage point of commercial firms, a landscape of plentiful openings tied to smart farming comes into view. Yet, these are shadowed by a set of decisive obstacles that demand attention. The voices within this cluster spy potential in deepened collaborative ties stretching both between firms and outward toward growers, in viable commercial models built around delivering Software as a Service, and in the opportunity to bring sharper efficiency to the logistical arteries that feed agriculture. Nonetheless, the sharing of data and the specter of cyber vulnerabilities are seen as towering impediments to the wider embrace of these technologies.

Participants drawn from the research community likewise project an affirmative stance toward an accelerated infusion of AI into farming. They anticipate that such an evolution would yield a richer stream of data captured directly by growers, thereby reducing the time investigators must personally devote to gathering raw material. This, the researcher participants contend, would translate into swifter, more impactful scientific inquiry focused on agriculture. Yet the friction around data sharing once again throws sand in the gears of scholarly progress, as rapid-cycle research proves exceedingly difficult to pursue without reliable conduits for data flowing from disparate sources. One further roadblock flagged for smart farming is the skeptical undercurrent among growers, a nagging doubt that solutions born in scientific

circles genuinely address real-world agricultural needs rather than merely serve as exercises in technological invention for its own sake.

Bringing up the rear, the voices within public agencies maintain that a considerable appetite and a clear pull exist to accelerate the spread of smart farming instruments, driven by considerations of national competitive standing and a broader suite of economic rationales. Even so, these actors confess to a lingering uncertainty about how to situate themselves within this unfolding shift. This hesitation puts the brakes on the broader digitization of the farming domain. This cluster of participants views the twin challenges of cybersecurity and data sharing as pivotal barriers that must be overcome.

Conclusion

This article provides a survey of the principal opportunities and challenges associated with directing AI toward agricultural enterprises. By undertaking a methodical literature review alongside an interview study encompassing 21 participants pulled from assorted corners of the agricultural industry, material has been amassed to construct a rounded portrait of intelligent technology's role in farming. The breadth of the investigation is, by design, extensive, focused on three agricultural branches: crop cultivation, milk harvesting, and beef rearing. Beyond this, participants are grouped by the roles they play within the sector, spanning public agencies, commercial firms, investigators, and growers. This spacious vantage point enables insights that cut across multiple production branches and organizational forms, each with its own distinct lens on the agricultural domain.

The overwhelming majority of actors consulted in this inquiry express a shared hunger to steer AI into the agricultural arena. Propelling growers toward smart farming tools are the cravings for fatter profit margins, a lighter workload, and, quite often, an authentic fascination with novel gadgetry. Tellingly, the full spectrum of these impulses does not find a complete mirror inside the body of literature surveyed. By way of illustration, scholarly work exists that probes the imprint smart farming can leave on the bond between humans and animals on a working farm [9], yet such studies failed to surface in the literature search parameters employed. Running in the opposite direction, certain anticipated wellsprings of momentum for smart farming found no echo among the participants, such as the favorable environmental ripple effects it can unleash through reduced nutrient runoff. In their place, the pursuit of profit emerges as the single most potent force, elevating a lucid commercial rationale into a non-negotiable prerequisite for the wider diffusion of smart farming instruments. With an expanding catalog of agricultural products now materializing under the SaaS banner, a development that opens the door to pooled access and leased equipment, the underlying economic calculus is undergoing a metamorphosis for growers and machinery fabricators alike, cracking open fresh possibilities. That said, for smart farming to genuinely reforge the agricultural sector, public agencies and commercial firms may be called upon to adopt a more muscular, front-footed posture during the transition. Such ambitions carry particular weight to guarantee that the governmental and societal hunger for pared-back emissions and a thicker weave of sustainability finds concrete fulfillment inside the technological pivot.

For this metamorphosis to bear fruit, it is absolutely vital that the scaffolding that enables growers to deploy smart farming instruments is itself brought up to modern standards. One linchpin requirement is that growers have seamless, ongoing pathways to access current knowledge on the practical application of smart farming. Consequently, a pressing need exists to secure agricultural schooling of a technical stripe that is readily accessible, delivered, for example, through elastic, on-demand instructional formats. Beyond this, the smart farming methods themselves must offer sufficient built-in flexibility to accommodate the divergent appetites for openness and configurability that growers bring to the table.

Turning to the question of how the embedding and spread of AI within agriculture might be derailed, this inquiry identifies a clutch of factors that act as drag forces. The most towering of these revolves around data stewardship. This knot can be further teased apart into the threads of data sharing and proprietorship, together with the safeguarding of digital assets. This tangle constitutes a multilayered puzzle for which, at the present juncture, no tidy resolution exists, whether on the technical or legal plane. Herein lies a vital arena of engagement for both the research community and public bodies. Even

so, a shared conviction runs through the participant pool that, to successfully steer the agricultural domain into a more data-soaked, digitally wired operating environment, the supporting technical skeleton must be rendered fortress-like. The remedy must ensure that sensitive information remains beyond the reach of hostile actors while preventing legitimate users from encountering any barrier to entry. Furthermore, for the eventual beneficiaries at the end of the chain to truly harvest the fruits of the sector's digital pivot, the underlying data models must exhibit a generous measure of suppleness. This imperative flows directly from the staggering assortment of machinery scattered across working farms, not to mention the wildly uneven distribution of technological enthusiasm and digital literacy among the grower population.

Layered on top of this, a dimension that meaningfully gums up the machinery of rolling out smart farming instruments and AI in agriculture is the economic reality to which the participants give voice. A sizable slice of this is, without question, the towering upfront capital demands, yet additional economic threads also weave themselves into this barricade. To take a few, the skittishness of market demand signals, the structurally anemic profitability that pervades the sector, and the powerful undertow pulling toward farm consolidation all conspire to steep any investment outlay in a heavy broth of risk. Additional barricades identified as putting the brakes on the spread of AI in farming include a range of social dynamics, among them anxieties about sliding into an overreliance on technology and a lack of end-user trust in the tools themselves. The thin reserve of trust appears to trace its origins to a pattern of overhyped claims peddled by technology builders, as well as to a stubborn gap between the tools fabricated in the laboratory and the genuine pull of the marketplace.

As for the technical pathways that hold the promise of answering the hunger for AI and smart farming instruments, the menu of options is long. Within this inquiry, the findings indicate that the bulk of the necessary data streams and sensor types are already available. The riddle that lingers to be cracked is the stitching together of input data with output data through the deliberate cultivation of rich datasets, thereby snapping the data loop shut. At the present moment, the dairy branch, taken as a whole, operates with a closed and finely knurled data loop, whereas, in broad strokes, the meat and cropping branches lag in the sophistication of their data capture, and consequently command less finely honed decision-support instruments. This contrast is thrown into relief by both the interview material and the surveyed literature, as fine-grained, high-resolution data unlocks the door to more precise and more richly textured decision support. That said, following a painstaking journey of data accumulation stretching from the initial inputs through to the final outputs, one gains the ability to construct models and sift through them, judging which rise to the top against a chosen set of evaluative yardsticks. Tacked onto this, a generic headache and stumbling block in the enterprise of constructing machine learning models is the tendency of models to attempt to swallow an excessive number of variables in a single gulp. The findings drive home the wisdom of 'starting lean' during the model-building phase: begin with a sparse set of input variables and subsequently refine the model by introducing additional variables, strictly one at a time.

A further discovery is that every conceivable use case and technical remedy calls for a high degree of exactness in the outputs of classification models, matched by tightly compressed prediction errors in regression models. Decision support in the agricultural theater steers and leaves its fingerprints on the innermost workings of the farming enterprise; for this reason, projections and estimates must land close to the mark. Curiously, voices drawn from the cropping branch let on that, for the time being, they are prepared to tolerate a more generous helping of aggregate error within their models. Looking further down the road, however, toward future applications and toward solutions whose tangled complexity will only deepen, the aggregate error will be forced to shrink, a development that is all but certain to rattle the familiar bias-variance balancing act. A precondition for arriving at tightly calibrated supervised machine learning models sculpted to the idiosyncrasies of the local holding will be the availability of straightforward data-preprocessing pipelines. What this means in practice is that the chore of data labeling must either be stripped of its complexity by the tool builders themselves or else be packaged and delivered to growers as a paid service through consultancy channels.

From a technological standpoint, the agricultural domain has been on an evolutionary arc stretching back many decades. Yet, the pivot toward smart farming methods and a data-steeped mode of agriculture may well rank among the most far-reaching transformations it has ever witnessed. AI, once embedded in the agricultural context, carries the latent power to fine-tune and streamline operations across every branch of farming. Through data-fueled decision assistance, and even

through activities executed in fully autonomous fashion, growers harbor hopes of lifting their output along the twin axes of volume and grade, of putting a dent in carbon emissions, of clawing back working hours, and of fattening their balance sheets. For commercial firms and public agencies, the transformation opens the door to revamped supply chains and refreshed planning frameworks, lifting the agricultural industry's performance when viewed through a wide-angle, macro-level lens. For all that, a suite of stubborn challenges remains untackled, placing the tempo of the transition in jeopardy. It is here that weighty assignments await corporate actors, public bodies, and research institutions alike. Nonetheless, animated by such formidable tailwinds, the long arc of the trend bending toward an expanding role for AI in agriculture is unmistakable. The question is no longer whether smart farming will continue to evolve. It has become instead a matter of how the roadblocks will be dismantled and which players in this sprawling ecosystem will manage to harvest the gains from its radically disruptive force.

Acknowledgements

This study was partly funded by Peltarion. The authors would like to thank all interview respondents for their time and willingness to participate in this study.

Conflict of interest

None

Financial support

None

Ethics statement

None

Received: 04 Feb 2025

Revised: 01 Apr 2025

Accepted: 15 May 2025

Published online: 15 September 2025

Rights and permissions

Open Access The author(s) retain copyright. This article is licensed under the Creative Commons Attribution-NonCommercial-ShareAlike 4.0 International License. It may be shared and adapted for non-commercial purposes with appropriate attribution, an indication of changes, and distribution of adaptations under the same license. Third-party material may be subject to separate terms identified in its credit line. View the license at <https://creativecommons.org/licenses/by-nc-sa/4.0/>.

References

- Atzori L, Iera A, Morabito G. Understanding the Internet of Things: definition, potentials, and societal role of a fast evolving paradigm. *Ad Hoc Netw.* 2017;56:122-40.
- Berrang-Ford L, Pearce T, Ford JD. Systematic review approaches for climate change adaptation research. *Reg Environ Chang.* 2015;15(5):755-69.

Bhole A, Falzon O, Biehl M, Azzopardi G. A computer vision pipeline that uses thermal and RGB images for the recognition of Holstein cattle. In: *Computer Analysis of Images and Patterns*. Cham; 2019.

Buller H, Blokhuis H, Lokhorst K, Silberberg M, Veissier I. Animal welfare management in a digital world. *Animals*. 2020;10(10):1779.

Caja G, Castro-Costa A, Salama AAK, Oliver J, Baratta M, Ferrer C, et al. Sensing solutions for improving the performance, health and wellbeing of small ruminants. *J Dairy Res*. 2020;87(S1):34-46.

Feng P, Wang B, De Li Liu CW, Xiao D, Shi L, Yu Q. Dynamic wheat yield forecasts are improved by a hybrid approach using a biophysical model and machine learning technique. *Agric For Meteorol*. 2020;285-286:107922.

Fusco G, Melgiovanni M, Porrini D, Ricciardo TM. How to improve the diffusion of climate-smart agriculture: what the literature tells us. *Sustainability*. 2020;12(12):5168.

Griffiths P, Nendel C, Pickert J, Hostert P. Towards national-scale characterization of grassland use intensity from integrated Sentinel-2 and Landsat time series. *Remote Sens Environ*. 2020;238:111124.

Hostiou N, Fagon J, Chauvat S, Turlot A, Kling-Eveillard F, Boivin X, et al. Impact of precision livestock farming on work and human-animal interactions on dairy farms. A review. *Biotechnol Agron Soc Environ*. 2017;21(4):268-75.

Kamienski C, Soininen JP, Taumberger M, Dantas R, Toscano A, Salmon Cinotti T, et al. Smart water management platform: IoT-based precision irrigation for agriculture. *Sensors*. 2019;19(2):276.

Kerkow A, Wieland R, Koban MB, Hölker F, Jeschke JM, Werner D, et al. What makes the Asian bush mosquito *Aedes japonicus japonicus* feel comfortable in Germany? A fuzzy modelling approach. *Parasites Vectors*. 2019;12(1):106.

Kernecker M, Knierim A, Wurbs A, Kraus T, Borges F. Experience versus expectation: farmers' perceptions of smart farming technologies for cropping systems across Europe. *Precis Agric*. 2020;21(1):34-50.

Khanal S, Kushal KC, Fulton JP, Shearer S, Ozkan E. Remote sensing in agriculture—accomplishments, limitations, and opportunities. *Remote Sens*. 2020;12(22):3783.

Kleinschmidt JH, Kamienski C, Prati RC, Kolehmainen K, Aguzzi C. End-to-end security in the IoT computing continuum: perspectives in the SWAMP project. In: *Proceedings of the 9th Latin-American Symposium on Dependable Computing (LADC)*. 2019 Nov; p. 19-21.

Long TB, Blok V, Coninx I. The diffusion of climate-smart agricultural innovations: systems level factors that inhibit sustainable entrepreneurial action. *J Clean Prod*. 2019;232:993-1004.

Long TB, Blok V, Poldner K. Business models for maximising the diffusion of technological innovations for climate-smart agriculture. *Int Food Agribus Manag Rev*. 2016;20(1):5-23.

Matos-Moreira M, Lemercier B, Dupas R, Michot D, Viaud V, Akkal-Corfini N, et al. High-resolution mapping of soil phosphorus concentration in agricultural landscapes with readily available or detailed survey data. *Eur J Soil Sci*. 2017;68(3):281-94.

Medvedev B, Molodyakov S. Internet of Things for farmers: educational issues. In: *Proceedings of the 18th International Scientific Conference "Engineering for Rural Development"*. Jelgava, Latvia; 2019 May 22-24.

Meier J, Mauser W, Hank T, Bach H. Assessments on the impact of high-resolution-sensor pixel sizes for common agricultural policy and smart farming services in European regions. *Comput Electron Agric*. 2020;169:105205.

Torai S, Chiyoda S, Ohara K. Application of AI technology to smart agriculture: detection of plant diseases. In: *Proceedings of the 59th Annual Conference of the Society of Instrument and Control Engineers of Japan (SICE)*. 2020 Sept 23-26.

Van Hertem T, Rooijakkers L, Berckmans D, Peña Fernández A, Norton T, Berckmans D, et al. Appropriate data visualisation is key to Precision Livestock Farming acceptance. *Comput Electron Agric.* 2017;138:1-10.

Viljanen N, Honkavaara E, Näsi R, Hakala T, Niemeläinen O, Kaivosoja J. A novel machine learning method for estimating biomass of grass swards using a photogrammetric canopy height model, images and vegetation indices captured by a drone. *Agriculture.* 2018;8(5):70.