

International Journal of Agriculture Extension and Social Development

Volume 9; Issue 7; July 2026; Page No. 332-337

Received: 02-04-2026
Accepted: 08-05-2026

Indexed Journal
Peer Reviewed Journal

Bridging the digital divide in Rural Agro-Enterprises: Extension pathways for industry 4.0 adoption among micro-manufacturing units

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DOI: <https://www.doi.org/10.33545/26180723.2026.v9.i7e.3870>

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Abstract

While the digitisation of agriculture has become a familiar theme in extension discourse, the rural micro-manufacturing enterprises that process agricultural produce have been left at its margins. Oil expellers, millers, food-drying and leaf-plate units continue to operate much as they did a generation ago, largely untouched by the Fourth Industrial Revolution. This paper asks what Industry 4.0 technologies, chiefly sensor-based process monitoring, predictive maintenance and digital inventory management, can realistically offer such enterprises in eastern India, and what it would take to deliver them. The analysis draws on field documentation of twelve agro-processing micro-enterprises in Odisha between 2021 and 2024, supplemented by secondary data from national development-finance, agricultural-engineering and small-enterprise agencies. A mixed descriptive approach is used to examine adoption patterns, cost-benefit horizons and the socio-institutional conditions that shape uptake. Unplanned equipment downtime was found to consume 18–25% of production hours, while modest sensing interventions costing ₹8,000–15,000 per machine reduced that downtime by 25–40% over three years. The study's central finding, however, is that adoption turned less on affordability than on the presence of a supporting extension ecosystem of Krishi Vigyan Kendras, district agricultural technology management agencies, self-help groups and farmer producer organizations, and on whether delivery was gender-sensitive and participatory. A barrier-mitigation matrix and a three-phase adoption roadmap are offered as working tools for extension functionaries. Digital transformation of rural agro-enterprises, it is argued, must be pursued *with* the enterprises concerned rather than merely *for* them.

Keywords: Agricultural extension, rural micro-manufacturing, technology adoption, internet of things, agro-processing, women empowerment

1. Introduction

Rural micro-manufacturing enterprises (RMMEs) occupy an odd position in the rural economy of developing countries: they are almost everywhere, yet they are rarely studied. Engaged in agro-processing such as oil expelling, paddy and millet milling, food drying and leaf-plate moulding, they anchor local value chains and absorb labour that agriculture alone cannot. In India the unorganised manufacturing sector accounts for more than 80% of manufacturing employment and roughly 45% of industrial output by volume, much of it concentrated in agro-processing and food technology^[1]. For all this weight, these enterprises have stayed on the far side of the transformation now called Industry 4.0, the coming together of cyber-physical systems, the Internet of Things (IoT), data analytics and automation^[2].

Agricultural extension has historically been the institution through which new technology reaches rural producers^[3]. The lesson of decades of adoption research is that whether a technology is taken up depends on far more than its profitability. Information, access to credit, attitudes to risk and the human capital of the producer all bear on the decision^[4]. Extension once carried improved seeds, agronomic practice and mechanisation into the countryside; it is now being asked to carry digital and Industry 4.0 tools into the rural non-farm economy. The difficulty is that the

Indian extension system has struggled to meet even the information needs of small and marginal producers, and the non-farm and value-addition segments have been served least of all^[5]. For RMMEs, then, the obstacles to digital adoption are not simply a matter of cost. They are social and institutional in character, arising from low digital literacy, unreliable last-mile connectivity, thin advisory support and, not least, unequal access along lines of gender^[6].

Four concerns run through the paper. It begins by setting out the IoT, predictive-maintenance and digital-inventory technologies that are realistic for low-capital agro-processing units, rather than those imported wholesale from formal manufacturing. It then weighs their costs and benefits against field evidence. Its main emphasis, though, falls on the extension and social-development conditions that decide whether adoption actually happens: capacity building, peer learning, engagement with SHGs and FPOs, and attention to gender. Finally, it offers a barrier-mitigation matrix and a phased roadmap meant to be of practical use to extension functionaries, development agencies and policymakers.

2. Materials and Methods

2.1 Study Area and Approach

The study follows a mixed descriptive design, combining

first-hand field documentation with a synthesis of secondary data. The primary material comes from twelve agro-processing micro-enterprises in the Angul, Kendrapara and Dhenkanal districts of Odisha, documented over the period 2021–2024. These units, comprising oil expellers, paddy threshers, mini granulators, sev-namkeen makers and leaf-plate moulding machines, were chosen purposively to reflect the range of low-capital agro-processing activity common in the region.

2.2 Data Collection

Data at the enterprise level were gathered through structured observation, interviews with operators and the logging of process performance. Among the variables recorded were the frequency of equipment downtime, raw-material wastage, inventory-holding patterns, the use of digital tools, and access to institutional credit and extension support. In three of the enterprises, low-cost vibration and thermal monitoring kits costing ₹6,000–12,000 were installed and their readings tracked over fourteen months against a pre-monitoring baseline. All participating operators were informed of the purpose of the documentation and took part voluntarily after giving verbal consent; no personally identifying information was recorded, and enterprise identities have been withheld to preserve confidentiality.

2.3 Secondary Data and Analytical Framework

Secondary data were drawn from NABARD field reports, ICAR-CIAE technology-deployment reviews, successive MSME Annual Reports and the peer-reviewed literature on smart farming and rural digitisation [7]. The interpretation is guided by the diffusion-of-innovations perspective [3], which situates adoption within a social system and draws attention to change agents, opinion leaders and the channels through which information travels, concerns that map closely onto the work of extension. Cost-benefit parameters were arranged across short-, medium- and long-term horizons, and the barriers identified in the field were grouped by category and severity to yield the mitigation matrix presented below.

3. Results and Discussion

3.1 IoT-Enabled Process Monitoring and Connectivity

The Internet of Things describes networked sensor–actuator systems that gather, transmit and act upon operational data in real time [8]. In the enterprises studied, the applications that mattered most were unglamorous: monitoring process temperature in oil expellers and pelletisers, tracking energy use, logging how long machines actually ran, and viewing all of this on a dashboard through an ordinary smartphone. Even at this level the shift was significant, because it replaced the operator's intuition with a documented record of how a process behaved. That record was itself an asset, since it could later support quality certification or an application for institutional credit [9].

Connectivity was the recurring constraint. Mobile-data coverage has widened under the BharatNet programme, but latency and inconsistent bandwidth still made real-time transmission unreliable. The workable compromise was edge computing, in which data are processed locally on low-power microcontrollers such as Arduino, Raspberry Pi or the ESP32 and synchronised with the cloud only selectively.

This cut bandwidth demand, let the system keep working offline, and cost 60–70% less than industrial IoT hardware [7]. Low-power wide-area protocols such as LoRa and NB-IoT stretched coverage across 2–15 km at power levels suited to solar-powered sites. That information technology can lower the cost of reaching dispersed rural users is by now well documented in the extension literature [10]. The more striking observation from the field concerned *peer learning*. One early adopter showing a neighbour what the technology did moved adoption along more effectively than any top-down training, a pattern familiar from the older tradition of farmer-to-farmer diffusion [3]. Where several units shared a single gateway, the cost of basic monitoring fell below ₹15,000 per enterprise.

3.2 Predictive Maintenance and Downtime Reduction

Few things hurt a micro-enterprise more than an unplanned breakdown. With a single operator doubling as technician, a failure does not stop at the machine: production halts, perishable inputs spoil, deliveries slip, and repairs are arranged at short notice and high cost through informal channels. The field data put unplanned downtime at 18–25% of annual production hours, and the combined loss from idle time, spoilage and forgone orders reached 12–17% of annual revenue [11].

A stripped-down, three-tier approach to predictive maintenance (PdM) proved workable in this setting: vibration and thermal sensors on the main drive motors and gearboxes; a local microcontroller to flag readings that crossed a threshold; and a simple SMS or WhatsApp alert to the operator. At ₹8,000–15,000 per machine, the arrangement brought unplanned downtime down by 25–40% within three years. The three units that piloted vibration monitoring recorded no unplanned breakdowns at all across fourteen months, against a baseline of 3.2 per year. And because the sensors kept accumulating data, machine-learning models could later be trained on the same stream without any further outlay on hardware [12].

3.3 Digital Inventory Management and Market Linkage

Inventory was handled almost entirely by hand, through physical counts, informal ledgers and the operator's memory, an arrangement that managed the odd feat of over-stocking raw materials and under-stocking essential consumables at the same time. For units handling perishables, the cost of that imprecision was spoilage. A structured mobile application such as Vyapar, Khatabook or OkCredit changed the picture, offering real-time visibility of stock, automatic reorder prompts, material-yield tracking and a simple record of demand over time. Within the documented enterprises, units that took up even a basic digital ledger reported 10–20% less working capital tied up in surplus stock within six months of adoption.

The value of digital inventory did not stop at the enterprise gate. Once micro-manufacturers could share live stock data with FPOs and input suppliers, procurement lead times shortened and their hand in price negotiation strengthened. Digitisation also created something these enterprises had always lacked, a paper trail, and with it the documentation needed for institutional credit, GST registration and entry into formal markets, benefits that outran the immediate operational gains [9]. Decentralised, demand-led advisory

structures such as the district-level Agricultural Technology Management Agency (ATMA) have been shown to widen the reach of such services to smallholders and micro-entrepreneurs ^[13]. It was telling that the two women-managed units showed the strongest uptake of digital inventory tools, a pattern that seemed to follow from their closer involvement with FPO- and SHG-level coordination, where digital records are increasingly a condition of membership and price bargaining ^[14].

3.4 Cost-Benefit Horizons

Table 1 sets out a parametric cost-benefit framework built

from the twelve documented enterprises. It carries a lesson that matters a good deal for extension planning: the financial case for Industry 4.0 does not announce itself early. In the first years, returns are negative, absorbed by the initial outlay and the disruption of learning. Break-even arrives somewhere between the third and fifth year, after which efficiency gains begin to compound into clearly positive returns. The escalating operational gains that underlie this pattern, namely falling downtime and wastage alongside improving energy efficiency, are plotted in Fig 1.

Table 1: Cost-Benefit Parameters for Industry 4.0 Adoption in Rural Agro-Processing Micro-Enterprises

Parameter	Short-Term (0–2 yrs)	Medium-Term (3–5 yrs)	Long-Term (6–10 yrs)
Initial Investment	₹2–5 lakhs (IoT + sensors)	₹1–2 lakhs (upgrades)	Minimal
Equipment Downtime Reduction	10–15%	25–35%	40–50%
Inventory Wastage Savings	5–8%	12–18%	20–25%
Energy Efficiency Gain	Negligible	8–12%	15–20%
Estimated ROI	Negative (–10 to –20%)	Break-even to +15%	+30–50%

This timeline sits awkwardly against the finance actually available to micro-enterprises, whether informal moneylenders charging 24–48%, microfinance at 22–36%, or even MSME schemes built around 12–18 month

repayment cycles. Closing that gap, through extension-linked credit facilitation, SHG revolving funds and the convergence of existing subsidies, is the single most important lever for accelerating adoption.

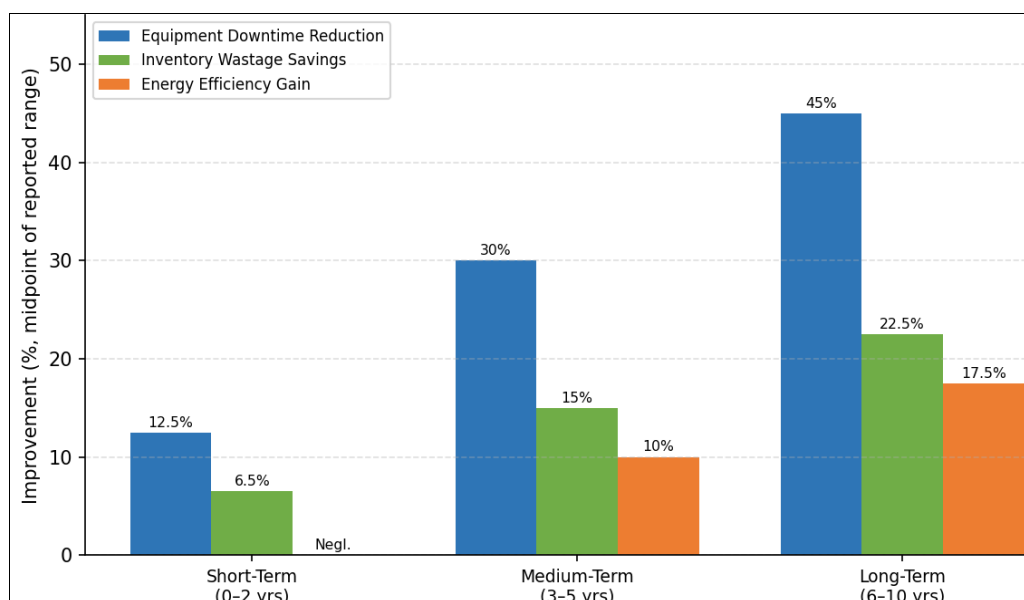


Fig 1: Operational Gains from Industry 4.0 Adoption across Investment Horizons (derived from Table 1)

3.5 Non-Financial and Social Returns

To read the case in purely financial terms is to miss much of what adoption achieves. The less tangible gains were real enough: more consistent product quality, which opened the door to food-safety certification and regulated markets; a lighter physical burden, especially for the women who do much of the repetitive sorting, grading and packaging ^[14]; greater credibility with lenders; and the quiet spread of know-how to neighbouring units through simple demonstration. Frameworks that evaluate women-centric agricultural technology make a point of scoring these ergonomic and social dimensions alongside the financial ones, which gives a fuller measure of what a rural technology investment is worth ^[14]. Where women operate

30–40% of agro-processing units, that fuller measure matters, and digital adoption becomes as much a question of women's economic empowerment as of productivity, an aim that sits at the heart of agricultural extension and social development.

3.6 Barriers and Extension-Led Mitigation

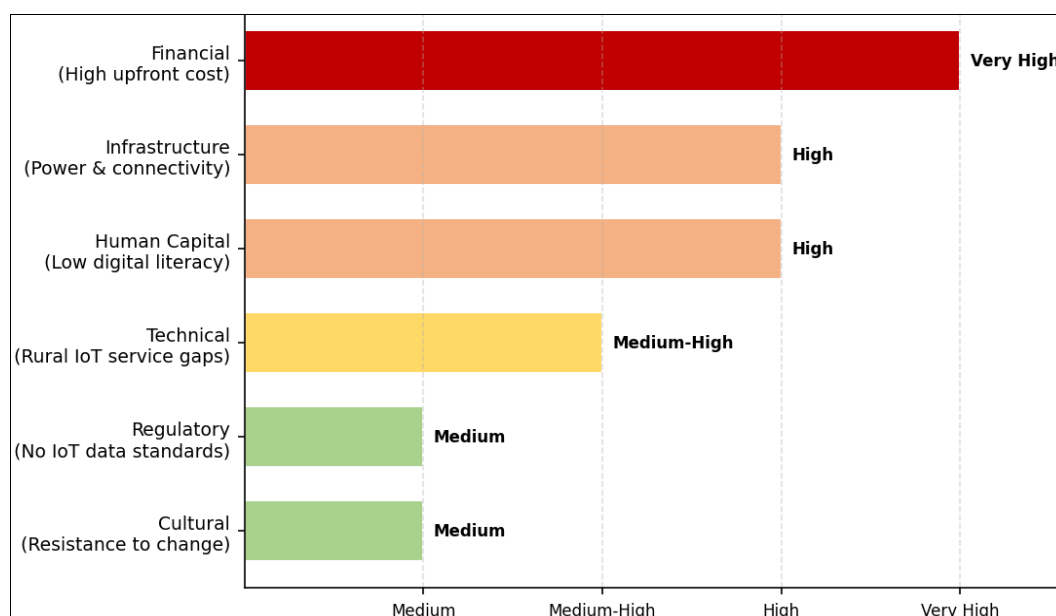
Table 2 gathers the barriers observed across 35 agro-processing enterprises, together with supporting secondary evidence, into a single matrix, and pairs each with a mitigation strategy framed in extension terms. The pairing is deliberate: it restates the paper's argument that diffusion depends as much on how a technology is delivered as on the technology itself ^[5, 6].

Table 2: Barrier–Mitigation Matrix for Digital Technology Adoption in Rural Agro-Enterprises

Barrier Category	Specific Challenge	Severity (RMMEs)	Extension / Mitigation Strategy
Infrastructure	Unreliable power supply and internet connectivity	High	Solar + edge computing; PM-WANI cluster Wi-Fi
Financial	High upfront cost relative to capital base	Very High	TUFS subsidy, NABARD credit, SHG revolving funds
Human Capital	Low digital literacy among operators	High	Vernacular on-site training via KVKs and ATMA
Technical	Absence of rural IoT service networks	Medium-High	District Technology Support Centres
Regulatory	No MSME-specific IoT data standards	Medium	Open-standard policy mandate (BIS)
Socio-cultural	Resistance to change; gendered access gaps	Medium	Demonstration models; women SHG-led adoption

Read across, the matrix places financial constraints and digital-literacy deficits at the top of the list, as the severity ranking in Fig 2 makes clear. Infrastructure gaps, though serious, are gradually being narrowed by BharatNet and PM-KUSUM; the socio-cultural and regulatory barriers, rated medium, tend to give way to demonstration effects and

to open-standard policy. The human-capital barrier is the instructive one. It is not met by generic digital-literacy drives but by vernacular, enterprise-specific training of the kind that pluralistic, best-fit advisory arrangements, delivered through Krishi Vigyan Kendras (KVKs) and the ATMA architecture, are well placed to provide^[15].

**Fig 2:** Severity of Adoption Barriers in Rural Agro-Processing Enterprises (derived from Table 2)

3.7 Phased Implementation Roadmap

Given the financial and learning-curve constraints already described, a phased approach recommends itself over any attempt at wholesale deployment, in keeping with staged

models of Industry 4.0 implementation^[16]. Table 3 sets out three such phases, each calibrated so that its investment is matched by demonstrated returns and, so far as possible, funded from the gains of the phase before it.

Table 3: Phased Adoption Roadmap for Rural Agro-Processing Micro-Enterprises

Phase	Timeline	Technologies Introduced	Expected Outcomes
Phase 1 (Foundation)	Year 1–2	Digital ledgers, basic IoT sensors, smartphone-based monitoring	Improved record-keeping; 10–15% downtime reduction
Phase 2 (Integration)	Year 3–4	Predictive maintenance alerts, cloud-linked inventory, FPO data sharing	Break-even ROI; 20–30% wastage reduction
Phase 3 (Optimization)	Year 5+	AI-assisted scheduling, automated reordering, market linkage platforms	30–50% ROI; institutional market access

Phase 1 (Years 1–2) digitises records and installs basic sensors. These are the cheapest and most visible steps, and the ones that build an operator's confidence with digital tools. Phase 2 (Years 3–4) adds predictive-maintenance alerts and cloud-linked inventory, and with them a connection to FPOs and aggregators. Phase 3 (Year 5 onward) introduces AI-assisted scheduling and market-linkage platforms, drawing on the operational data accumulated over the preceding years^[12]. One condition

cuts across all three phases. In the present documentation, enterprises with a technical mentor within reach, whether an extension coordinator, an ICAR field officer or an MSME facilitator, adopted and sustained digital tools at roughly three to four times the rate of those left to manage alone, whatever the financial incentives on offer. The projected downtime reduction and returns across the three phases are plotted in Fig 3. It is a finding that points to the extension functionary as the indispensable figure in this transition.

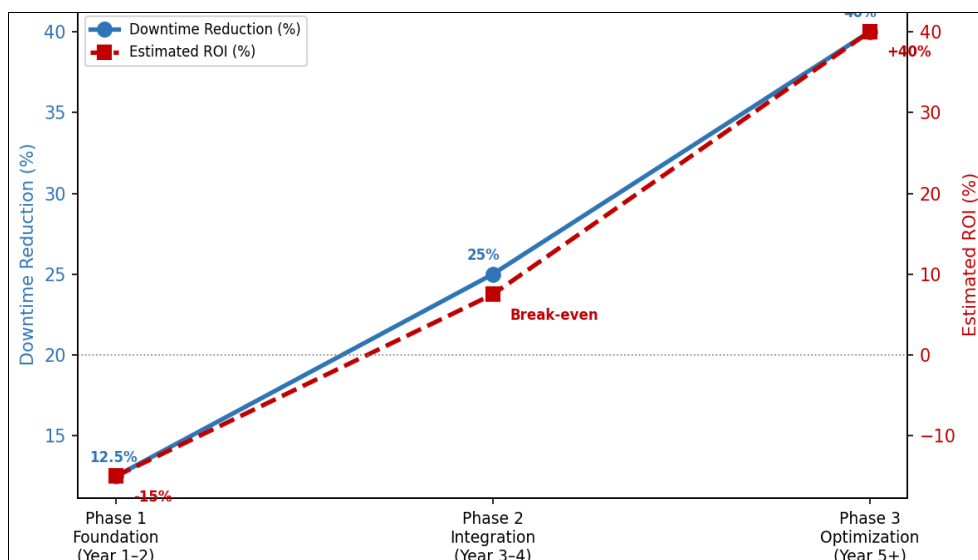


Fig 3: Projected Downtime Reduction and ROI across the Phased Roadmap (derived from Table 3)

4. Conclusion

For rural agro-processing enterprises, Industry 4.0 is best understood not as a single leap but as a set of selective, staged possibilities. Used judiciously, IoT monitoring, threshold-based predictive maintenance and digital inventory can sharpen competitiveness, cut waste and open routes into institutional markets. The economics work over the medium and long term rather than the short, and only where financing, capacity building and technical support are in place to make them work.

The evidence returns, in the end, to a single point for extension and social-development practice: what decides adoption is not the price of the technology but the strength of the institutions around it, the KVKs, ATMA structures, SHGs, FPOs and the presence of someone who can help when a sensor fails. Rural micro-manufacturers are not waiting passively to receive technology; they are practised problem-solvers who understand their own processes intimately. Digital transformation therefore has to be designed *with* them rather than *for* them. The barrier-mitigation matrix and phased roadmap set out here are offered in that spirit, as starting points for extension agencies and development-finance institutions trying to make inclusive, gender-aware digital development a reality in the rural non-farm economy.

5. Acknowledgement

The author is grateful to the enterprises engaged in agricultural machinery manufacturing, supply, and distribution whose participation forms the empirical basis of this study, and to all SME participants from different parts of the state and the country for generously sharing their valuable information and insights. The author also extends sincere thanks to the field officers of the Department of Agriculture, Government of Odisha, for their support throughout the study.

References

1. Ministry of Micro, Small and Medium Enterprises, Government of India. Annual report 2022-23. New Delhi: Ministry of Micro, Small and Medium Enterprises; 2023.
2. Schwab K. The Fourth Industrial Revolution. Geneva: World Economic Forum; 2016.
3. Rogers EM. Diffusion of innovations. 5th ed. New York: Free Press; 2003.
4. Feder G, Just RE, Zilberman D. Adoption of agricultural innovations in developing countries: a survey. *Economic Development and Cultural Change*. 1985;33(2):255-298.
5. Glendenning CJ, Babu S, Asenso-Okyere K. Review of agricultural extension in India: are farmers' information needs being met. IFPRI Discussion Paper 01048. Washington (DC): International Food Policy Research Institute; 2010.
6. Luthra S, Mangla SK. Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies. *Process Safety and Environmental Protection*. 2018;117:168-179.
7. Bacco M, Barsocchi P, Ferro E, Gotta A, Ruggeri M. The digitisation of agriculture: a survey of research activities on smart farming. *Array*. 2019;3-4:100009.
8. Kumar R, Singh RK, Dwivedi YK. Application of Industry 4.0 technologies in SMEs for ethical and sustainable operations: analysis of challenges. *Journal of Cleaner Production*. 2020;275:124063.
9. Fosso Wamba S, Akter S, Edwards A, Chopin G, Gnanzou D. How 'big data' can make big impact: findings from a systematic review and a longitudinal case study. *International Journal of Production Economics*. 2015;165:234-246.
10. Aker JC. Dial 'A' for agriculture: a review of information and communication technologies for agricultural extension in developing countries. *Agricultural Economics*. 2011;42(6):631-647.
11. Singh M, Rathi R. Investigation and modeling of lean six sigma barriers in small and medium-sized industries using hybrid ISM-SEM approach. *International Journal of Lean Six Sigma*. 2021;12(6):1115-1145.
12. Carvalho TP, Soares FAAMN, Vita R, Francisco RP, Basto JP, Alcalá SGS. A systematic literature review of machine learning methods applied to predictive maintenance. *Computers and Industrial Engineering*. 2019;137:106024.

13. Babu SC, Glendenning CJ. Decentralization of public-sector agricultural extension in India: the case of the district-level Agricultural Technology Management Agency (ATMA). IFPRI Discussion Paper 01067. Washington (DC): International Food Policy Research Institute; 2011.
14. Food and Agriculture Organization of the United Nations. The state of food and agriculture 2022: leveraging automation in agriculture for transforming agrifood systems. Rome: FAO; 2022.
15. Birner R, Davis K, Pender J, Nkonya E, Anandajayasekeram P, Ekboir J, *et al.* From best practice to best fit: a framework for designing and analyzing pluralistic agricultural advisory services worldwide. *Journal of Agricultural Education and Extension*. 2009;15(4):341-355.
16. Kagermann H, Wahlster W, Helbig J. Recommendations for implementing the strategic initiative INDUSTRIE 4.0. Frankfurt: Acatech - National Academy of Science and Engineering; 2013.