

From Farm Records to a Digital Control Tower: Integrating Production, Harvest, Finance, Markets, and Traceability for Independent Oil Palm Smallholders — A Review

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ABSTRACT

Independent oil palm smallholders operate simultaneously as growers, employers, input purchasers, harvest managers, logistics coordinators, sellers, and increasingly as actors responsible for demonstrating legal and sustainability compliance. Yet these functions are often managed through fragmented records, informal communication, delayed information, and disconnected transactions. This qualitative literature review examines how an integrated digital farm-management architecture could transform those fragmented activities into a coherent management-control system. Recent literature published primarily between 2020 and 2026 was purposively reviewed across oil palm agronomy, farm management information systems, digital agriculture, precision technologies, agricultural marketing, certification, and supply-chain traceability. The thematic synthesis identifies seven interconnected domains: farm visibility and management control; harvest integrity and fresh-fruit-bunch quality; agronomic and input management; financial visibility; buyer and transaction management; legality and traceability; and digital adoption conditions. The review argues that the main opportunity is not simply to digitize farm records, but to establish a closed-loop system connecting measurement, verification, diagnosis, decision, action, transaction, reconciliation, and organizational learning. A conceptual Digital Smallholder Oil Palm Control Tower is consequently proposed to connect field-level data with managerial dashboards, farm-to-mill transactions, financial reconciliation, sustainability evidence, and decision support. The framework suggests that farmer-centred, mobile-first, interoperable, and progressively implemented systems may strengthen productivity, profitability, bargaining capacity, traceability, and resilience while limiting digital complexity and exclusion.

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Introduction

Oil palm smallholders occupy a strategically important yet managerially demanding position within the global palm oil economy. At the farm level, an owner must coordinate land, trees, fertilizer, labour, harvesting, transport, sales, cash receipts, maintenance, and documentation. In practice, these activities frequently occur through different workers, contractors, collectors, mills, cooperatives, input suppliers, and government or certification institutions. Consequently, the farm is not merely an agronomic production unit; it is also a small enterprise embedded in a complex value chain. Evidence from Indonesia shows that oil palm cultivation can improve household welfare, but outcomes vary substantially among growers, while farmers continue to face production, institutional, market, and resilience challenges

One of the most important findings of recent smallholder research is that low productivity cannot be explained solely by genetics, planting materials, or farm size using data from 977

independent-smallholder fields in Indonesia, found that average production represented only about 42% of attainable yield and identified nutrient management, harvest interval, weed control, and pruning among the important determinants of yield gaps. de Vos similarly showed that harvesting practices are governed not only by agronomic recommendations but also by labour availability, plantation accessibility, farm size, FFB prices, transport economics, and annual yield. These findings demonstrate that agronomic problems are inseparable from management and transaction constraints.

The challenge therefore extends beyond increasing production. A plantation may produce substantial FFB but lose value through late harvesting, uncollected loose fruits, delayed evacuation, quality deductions, weighing discrepancies, uncontrolled fertilizer usage, excessive transport costs, undocumented labour, unpaid receivables, or weak buyer selection. The relevant managerial variable is consequently not only tonnes of FFB harvested, but net economically recoverable value per hectare after operational and transaction losses. Better management practices can improve particular agronomic indicators, but their financial attractiveness depends on costs and farm circumstances. For example, found that implementing a package of better management practices improved several plant and nutrient indicators but did not produce a sufficiently rapid yield response to make the added fertilizer costs profitable during the experimental period, illustrating why

agronomic recommendations should be linked to farm economics rather than assessed independently.

Digital agriculture offers a potential mechanism for making these relationships visible. Farm Management Information Systems (FMIS) have evolved from electronic recordkeeping into platforms supporting planning, monitoring, inventory, quality assurance, finance, traceability, and decision support. The literature nevertheless shows that adoption cannot be interpreted as a simple decision to purchase technology because performance expectancy, perceived complexity, farm characteristics, organizational integration, competencies, infrastructure, affordability, and supply-chain relationships all influence actual use. Recent reviews further show that the transition to digital agriculture is constrained by interacting economic, infrastructural, knowledge, organizational, and privacy-related barriers, reinforcing the need for context-sensitive implementation rather than technology-led deployment [1-15]

This distinction is particularly important in smallholder agriculture. Sophisticated digital technologies may technically exist while remaining inaccessible, uneconomic, or difficult to integrate into everyday farm practices. Research on smallholder digital agriculture repeatedly identifies connectivity, digital literacy, affordability, organizational support, locally relevant design, and trusted advisory systems as critical conditions (Gumbi et al., 2023; Abdulai, 2022; Kudama et al., 2021; Miine et al., 2023). Digital services that provide actionable and personalized information can improve farm decision-making, but technology that merely increases the volume of data without improving decisions can generate additional administrative burdens rather than value (Rajkhowa and Qaim, 2021; Thompson et al., 2021).

Oil palm provides an especially suitable context for examining integrated digital management. FFB are perishable, harvesting occurs repeatedly throughout the year, maturity affects quality, loose-fruit losses can be significant, plantation blocks differ in age and productivity, inputs such as fertilizer represent large expenditures, and final payment depends on multiple stages between field collection and mill acceptance. Computer vision and deep learning are already capable of assisting FFB maturity classification, including through mobile devices, while UAV and machine-learning systems can support disease detection and plantation monitoring (Suharjito et al., 2021; Septiarini et al., 2021; Junior and Suharjito, 2023; Kent et al., 2023; Wong et al., 2023).

A parallel challenge concerns market governance and sustainability. Independent smallholders may have incomplete price information, weak negotiating positions and dependence on intermediaries. Meanwhile, sustainability certification requires evidence concerning legal status, farm organization, production practices, input usage and FFB origins. Research on Indonesian certification has documented barriers involving land legality, cost, institutional organization, knowledge, dependence on facilitators, and uneven incentives (Apriani et al., 2020; Ernah et al., 2020; Degli Innocenti and Oosterveer, 2020; de Vos et al., 2023b; Renner et al., 2024).

Against this background, the present article asks seven questions. First, what operational, financial, commercial, agronomic, and compliance-management problems could be addressed through integrated digital farm management? Second, how can digital dashboards improve production visibility and managerial control? Third, how can harvest-to-mill monitoring protect FFB quantity and quality? Fourth, how could digitalization improve buyer selection, price transparency, transaction reconciliation, and bargaining?

Fifth, how can routine farm data support agronomy, legality, traceability and certification? Sixth, what constraints determine adoption? Finally, what conceptual architecture can connect these functions into a practical farmer-centred management system?

The article makes three main contributions. Conceptually, it moves beyond studies of individual technologies by treating the smallholder farm as an integrated information-and-control system. Managerially, it proposes a practical architecture connecting production, costs, harvesting, fertilizer, logistics, sales, receivables, and traceability. Analytically, it advances a distinction between a **digitized farm**, where records are electronic, and a **digitally managed farm**, where data continuously inform verification, decisions, transactions, reconciliation, and learning.

Literature Review

Independent Oil Palm Smallholders as Enterprises

Independent oil palm farms are highly heterogeneous. Differences in land area, planting material, palm age, location, knowledge, access to labour, capital, infrastructure, institutions and markets translate into substantial performance variation. Technical efficiency remains uneven, suggesting considerable scope for improving performance without automatically expanding cultivated land. At the same time, better efficiency can change incentives concerning future land use, illustrating that productivity improvement should be considered together with governance and sustainability.

Agronomic management is central. Monzon demonstrate that nutrient management, harvest frequency, weed control, and pruning are important in explaining yield gaps. Thoumazeau show that fertilizer management, particularly potassium, and understory management can influence oil palm performance and soil health, while Essono warn that insufficient nutrient replenishment can create longer-term sustainability problems in low-input oil palm systems. Recent panel evidence from Indonesian independent smallholders further indicates that land-management practices such as composting, manual weeding, and selected soil amendments can shape yield dynamics, although adoption and effects remain heterogeneous across farms. The implication is that digital fertilizer and field-management records should not merely document purchases; they should connect recommendations, inventories, application timing, quantities, blocks, workers, agronomic responses, and cost outcomes.

Recent Indonesian research reinforces the economic importance of context-sensitive input management. de Vos found that fertilizer use among smallholders is constrained by interacting agronomic and socioeconomic factors, including finance and farm conditions. Replanting creates another information-intensive decision because farmers must evaluate age profiles, declining yields, planting materials, cash-flow interruptions, financing and technical knowledge. These findings suggest that long-term digital farm histories can have value extending well beyond daily monitoring by creating evidence for rehabilitation, credit, replanting and investment decisions.

Digital Agriculture and FMIS

Digital agriculture encompasses mobile applications, sensors, satellite data, UAVs, machine vision, Internet of Things devices, cloud systems, artificial intelligence and decision-support tools. Agriculture 4.0 literature describes their potential to connect physical activities with digital information, but also emphasizes that many applications remain experimental or difficult to scale. Precision-agriculture reviews similarly show strong technical

potential while identifying affordability, skills, infrastructure and adaptation to small-farm realities as important constraints.

FMIS are especially relevant because they bridge technology and managerial processes. Giua identify farmer characteristics, farm characteristics, technological properties and adoption theories as major strands in FMIS research. Actual commercial use indicates strong farmer demand for quality assurance, inventory, financial management and traceability functions Thompson further conceptualize farm information as a lifecycle in which data collection creates value only when data are subsequently organized, interpreted and used. This is directly applicable to oil palm: a harvest record is valuable not because it exists digitally, but because it can be compared with block productivity, transporter records, mill weight, sales invoices and payments.

Adoption research also cautions against technological determinism. Giua find that performance expectations and social influence shape intentions, while actual adoption depends additionally on farm structure and organizational conditions. Gabriel and Gandorfer show that small-scale contexts have distinctive adoption patterns, and Brazilian evidence similarly suggests that FMIS adoption is shaped by structural and human-capital characteristics. A recent synthesis of digital-agriculture adoption studies likewise identifies economic capacity, technological infrastructure, technical knowledge, age, organizational affiliation, system reliability, and concerns about security and privacy as recurrent determinants (Dibbern et al., 2024). Thus, the relevant question is not whether a technology is theoretically useful, but whether its expected decision value exceeds the monetary, cognitive, organizational, and connectivity costs of using it.

Smallholder Digital Inclusion

Smallholder-oriented digitalization requires a different design philosophy from technology developed for large commercial estates. Gumbi identify digital infrastructure, affordability, skills, and immature digital ecosystems as recurring barriers, while Abdulai argues that digitalization becomes embedded only when material access, competencies, and socially meaningful practices develop together. Kudama likewise identify affordability, literacy, gender and age differences, infrastructure, and public policy as determinants of inclusive digital agricultural development. A more recent scoping review confirms that connectivity, digital literacy, affordability, infrastructure, and gender disparities continue to constrain the use of digital tools among smallholder farmers, even where potential benefits for market access and decision-making are substantial.

Empirical studies nevertheless show significant opportunities. Mobile-phone use for agricultural purposes has been positively associated with productivity and perceived reductions in farming costs and time in Tanzania. while personalized digital extension in India was positively associated with productivity, input use, and agricultural income. In Ghana, membership in farmer organizations, access to credit, and agronomic training increased the probability and intensity of digital agricultural service adoption, and more recent evidence links agricultural digitalization with improved livelihood assets and outcomes where farmers also have access to reliable electricity, internet connectivity, and mobile-money services. Evidence from Vietnam similarly shows that training, organizational membership, extension contact, education, and farm characteristics shape smallholder adoption of mobile applications, connectivity tools, and digital platforms. Together, these findings show that digitalization can connect production management,

extension, finance, and markets rather than operating as a stand-alone information service.

Agricultural-market digitalization adds a further dimension. Abate observe that digital tools can address price information, buyer–seller matching, coordination and transaction frictions, but many pilot systems have failed to reach scale. Their findings are relevant to palm oil because independent growers frequently need market information that is timely, localized and net of logistics and quality costs rather than merely headline prices.

Digital Technologies Specifically Relevant to Oil Palm

Oil palm digitalization increasingly extends from landscape monitoring to individual harvest decisions. Lim show how Industry 4.0 technologies may contribute to palm-oil sustainability and operational improvement. Mobile deep-learning models can classify FFB maturity with relatively modest computational requirements, while machine-vision systems have demonstrated high classification performance using colour and texture information Video-based real-time models further demonstrate the possibility of bringing automated classification closer to actual harvesting environments

At plantation scale, UAV imagery can support sustainability assessment and spatial monitoring, and deep learning can assist early identification of basal stem rot symptoms. These technologies should not be interpreted as substitutes for agronomy or human judgment. Their value lies in increasing observation frequency, consistency and spatial coverage, thereby directing scarce management attention toward anomalies requiring intervention.

Traceability, Certification and Information Governance

Traceability research provides an important conceptual bridge between farm records and downstream sustainability requirements. Blockchain and related distributed systems can increase transparency, immutability and visibility, yet studies repeatedly warn that technology does not guarantee truthful source data and cannot compensate for weak governance or poor incentives

More broadly, traceability implementation depends on collaboration, technology maturity, governance and organizational capability. Supply-chain systems may complement existing technologies rather than replacing them, while interoperability, privacy, scalability, cost and knowledge remain persistent challenges

Evidence from smallholder cocoa is particularly instructive. Steinke find that digital sustainability tracing can face high setup costs, questionable returns to farmers, and risks arising from inaccurate or strategically distorted farmer-supplied information. Strong supply-chain cooperation and appropriate incentives are therefore necessary. The lesson for palm oil is clear: digital traceability should be designed as an outcome of useful everyday farm-management records, rather than imposed as a separate reporting burden whose benefits accrue primarily downstream.

Method

Review Design

This study adopts a qualitative literature review, not a systematic literature review. A qualitative review is appropriate because the objective is conceptual integration across multiple bodies of literature rather than exhaustive estimation of a narrowly defined effect. Narrative and qualitative methodological reviews can combine heterogeneous evidence while retaining analytical

rigor when the logic of selection, interpretation, comparison and synthesis is transparent

The study consequently did not apply PRISMA screening, meta-analysis, formal risk-of-bias scoring or a claim of exhaustive database coverage. Instead, literature was selected purposively and iteratively to develop an interdisciplinary explanation of how digital management could integrate oil palm production, harvesting, financial control, marketing, transactions, traceability and certification.

Sources and Selection Strategy

The principal literature window was 2020–September 2026. Searches were oriented toward peer-reviewed articles accessible through Scopus- and Web of Science-indexed journal ecosystems and major scholarly platforms including ScienceDirect, SpringerLink, Wiley, Taylor & Francis, Emerald, IEEE-related databases and reputable open-access journal platforms.

Search concepts included combinations of oil palm smallholder, yield gap, harvest interval, fertilizer, FFB quality, farm management information system, digital agriculture, precision agriculture, mobile agriculture, agricultural market information, traceability, blockchain, RSPO, ISPO, certification, UAV, computer vision, and smallholder technology adoption. The initial practitioner-oriented infographic supplied with this study was used only as a sensitizing input for identifying operational functions—such as production dashboards, cost control, harvest monitoring, buyer management, fertilizer auditing and legality. It was not treated as scholarly evidence.

Peer-reviewed sources were included where they provided either direct evidence from oil palm systems or conceptually transferable evidence concerning smallholder digitalization, FMIS, agricultural marketing, traceability or technology adoption. Technical studies were retained where they had an identifiable management application. Sources were excluded when they were purely promotional, duplicated existing evidence, or had insufficient relevance to the integrated management question.

Thematic Analysis

The literature was coded iteratively around recurring managerial problems, technological functions, implementation conditions and

outcomes. Reflexive thematic analysis treats themes as analytically developed patterns rather than mechanically discovered categories; accordingly, coding moved between source-level findings and the emerging conceptual architecture

Seven final themes emerged: (1) farm visibility and management control; (2) harvest integrity and FFB quality; (3) agronomic input and asset productivity; (4) financial visibility; (5) buyer and transaction management; (6) legality, traceability and certification; and (7) conditions for adoption and scaling. Cross-theme synthesis then generated the proposed Digital Smallholder Oil Palm Control Tower.

Results: Thematic Findings

Theme I: From Fragmented Records to Farm Visibility

The first theme concerns the transformation of scattered farm observations into managerial visibility. Smallholder information frequently exists across notebooks, workers' recollections, messaging applications, weighbridge tickets, fertilizer receipts, mill documents and bank transactions. Each data source may be individually accurate yet collectively ineffective because records cannot easily be reconciled. An FMIS architecture can integrate these data around common identifiers—farm, block, date, activity, worker, delivery, buyer and payment.

A practical dashboard should not maximize the number of indicators. It should highlight deviations requiring managerial attention. Examples include actual versus expected FFB per block; harvest intervals above a threshold; fertilizer issued but not confirmed as applied; fuel consumption above normal; transport delays; repeated grading penalties; receivables exceeding agreed payment terms; or unusually large discrepancies between field weights and mill weights. This principle is consistent with evidence that FMIS value comes from planning, monitoring, control and decision support rather than electronic recordkeeping alone [11-19].

Figure 1 presents the integrated management architecture developed from the thematic synthesis. It emphasizes that digital transformation should connect operational and transactional functions rather than deploy isolated applications that generate separate data silos.

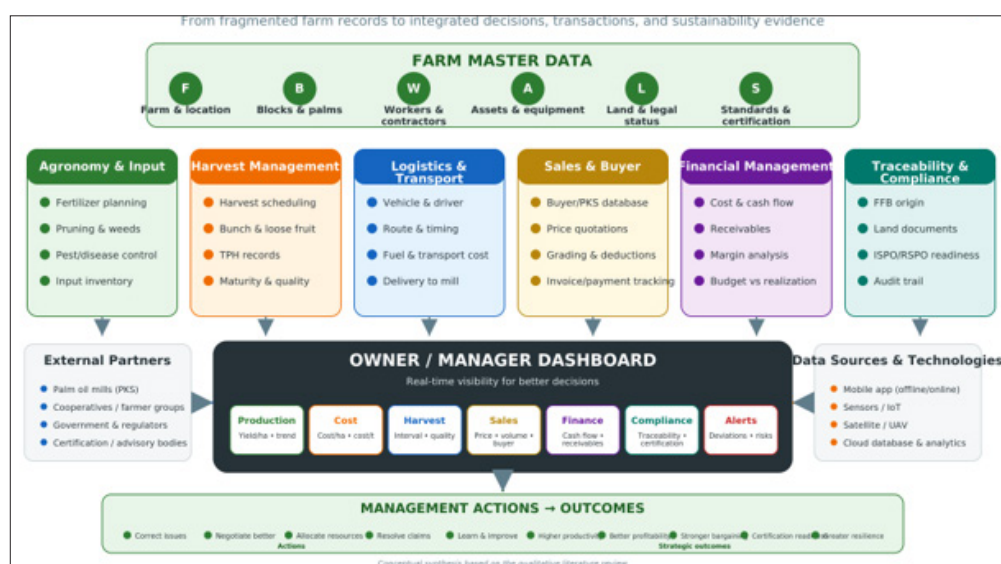


Figure 1: Integrated Digital Oil Palm Smallholder Management Architecture

Figure 1 illustrates that the architecture begins with stable master data and progressively incorporates operational events. Its distinctive feature is reconciliation. A harvest record is connected to transport and mill delivery; fertilizer purchases are connected to stocks and applications; sales invoices are connected to receivables and payments. In this model, the dashboard is not the digital system itself. It is the visible interface of a deeper data architecture linking field activities to financial and supply-chain outcomes.

Theme II: Harvest Discipline, FFB Quality and Logistics

Harvest management is one of the clearest cases in which agronomy and economics intersect. de Vos et al. (2023a) demonstrate that long harvest intervals among Indonesian smallholders reflect not simple ignorance but trade-offs involving yield, labour productivity, accessibility and transport costs. Long intervals can increase loose-fruit losses and overripe bunches, yet harvesting more frequently may be uneconomic where yield is low or transport is poorly coordinated.

Digitalization can make these trade-offs measurable. Each block can have a scheduled harvest interval based on previous harvest date, yield profile and labour availability. Harvesters can record bunch numbers, estimated weight and loose fruits. TPH collection can receive time stamps, while dispatch records connect vehicle, driver, load and destination. The system can then calculate time from harvest to delivery, compare estimated and accepted weight, and record mill grading.

Computer vision introduces an additional quality-control layer. Mobile FFB classification has demonstrated technically feasible maturity recognition on relatively low-resource devices, while image-based and video-based systems can distinguish maturity classes and support more standardized assessment. Such tools are unlikely to eliminate human judgment immediately, but they can create photographic evidence and reduce inconsistency in harvest decisions.

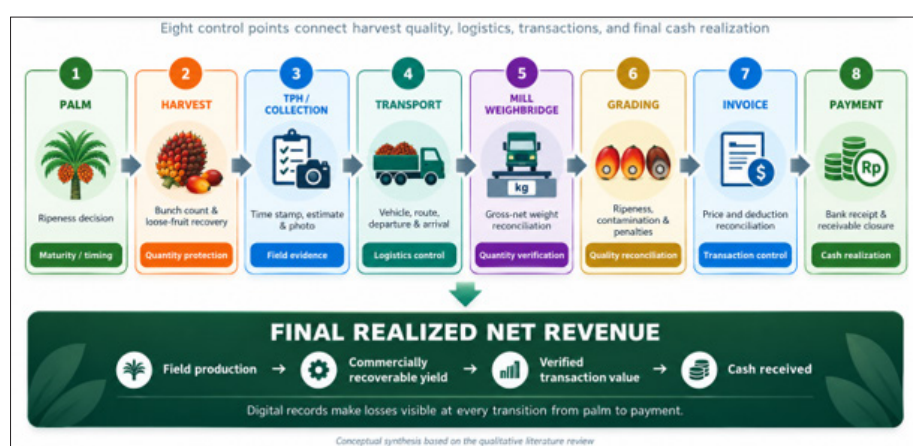


Figure 2: Digital Farm-to-Mill FFB Flow and Loss-Control Points

Figure 2 illustrates that the important unit of analysis is the complete harvest-to-cash chain. A farm can lose economic value at every transition. Digital records make those transition points observable, allowing the owner to distinguish biological production loss from harvest loss, logistics loss, grading deductions, weighing discrepancies and payment problems.

Theme III: Fertilizer, Crop Maintenance and Asset Productivity

Nutrient management represents one of the largest opportunities and risks in oil palm farming. The evidence indicates that nutrient limitations are strongly associated with productivity gaps, while fertilizer expenditure can represent a major financial burden. Monzon Thoumazeau de Vos and Essono collectively demonstrate why nutrient management must balance yield response, soil conditions, affordability and long-term nutrient sustainability.

A digital fertilizer-control system should therefore include four separate records: **recommendation, issue, application and verification**. A recommendation specifies product, dose, block and timing. Stock issue identifies how much fertilizer leaves storage. Application records confirm the worker, date and actual block treated. Verification compares applied quantities with recommendations and remaining stock. This separation creates an audit trail and reduces the risk that fertilizer accounting is based only on purchase invoices.

Similar logic applies to pruning, circle and path maintenance, weed management, pests, disease and drainage. GPS-tagged photographs

or simple field inspection records can document condition and completion. UAV imagery and remote-sensing applications may eventually automate some monitoring, particularly in detecting disease or spatially heterogeneous plantation conditions

Yet the literature also cautions against assuming that more inputs always improve profitability. Woittiez et al. (2024) found cases where better practices improved plant indicators but additional costs were not compensated by sufficient short-term yield increases. Digitalization therefore has a valuable analytical role: it can calculate marginal cost and marginal output over time so that an owner can distinguish agronomically desirable practices from economically justified investment under particular farm conditions.

Theme IV: Financial Visibility and the Shift from Yield to Margin

Many small farms measure performance through tonnes harvested or total sales received. These indicators can be misleading. Higher output can coincide with declining profitability if fertilizer, labour, fuel, repairs, harvesting or transport costs increase faster than revenue. The digital dashboard should therefore calculate at least cost per hectare, cost per tonne FFB, gross revenue per hectare, realized net price, operating margin and cash conversion.

Cost allocation should occur at the lowest level that remains practical. Highly detailed accounting can discourage data entry, while aggregate annual totals cannot diagnose problems.

Block-level yield and selected cost categories offer a workable compromise. Labour should be linked to task and block where possible; fertilizer to application block; harvesting and transport to delivered quantities; while overheads can be allocated periodically.

Cash-flow visibility is equally important because accounting profit does not ensure liquidity. Receivables should be matched against specific deliveries and invoices. Digital financial inclusion research suggests that mobile transactions and financial services can influence agricultural input use and output by lowering transaction friction and improving access to financial services

The result should be an owner dashboard capable of answering questions that are difficult to answer from paper records: Which block produces the highest net margin? What proportion of fertilizer expenditure is recoverable through higher production? Which buyer consistently pays late? How much revenue is lost through grading deductions? Has transport cost per tonne increased? Which harvest contractor delivers the most complete loose-fruit recovery? Such questions convert financial records into management instruments.

Theme V: Buyer Selection, Price Discovery and Payment Integrity

Agricultural marketing literature shows that digital tools can reduce some forms of information asymmetry, connect market actors and support price discovery, but successful scaling is far from automatic (Abate et al., 2023). For independent oil palm

smallholders, simply displaying a PKS quotation is inadequate. A commercially useful system must estimate the effective net farm-gate value after transport cost, commissions, quality deductions, weighing outcomes, waiting time, payment delays and default risk.

This creates a different approach to buyer selection. The highest nominal price may not be the highest realized price. A more distant mill may quote more but impose larger transportation costs. Another may offer lower nominal prices but pay reliably and apply fewer deductions. A digital buyer history can record quotation, accepted quantity, grading, deductions, invoice date, due date, actual payment date and disputes.

The commercial relationships can be stated as transparent accounting identities: Effective Net FFB Price = Quoted FFB Price - Transaction and Quality Costs; Realized Farm Revenue = Effective Net FFB Price × Accepted Tonnes; and Operating Margin = Realized Farm Revenue - Farm Operating Costs. These expressions are conceptual management equations rather than econometric models, and they clarify why buyer comparison should be based on realized net value rather than the posted price alone.

Digital market tools are particularly valuable when they change actual transactions rather than merely supplying information. Evidence on smallholder digital agriculture indicates that information, markets, credit and organizational participation often work as complementary services rather than isolated interventions

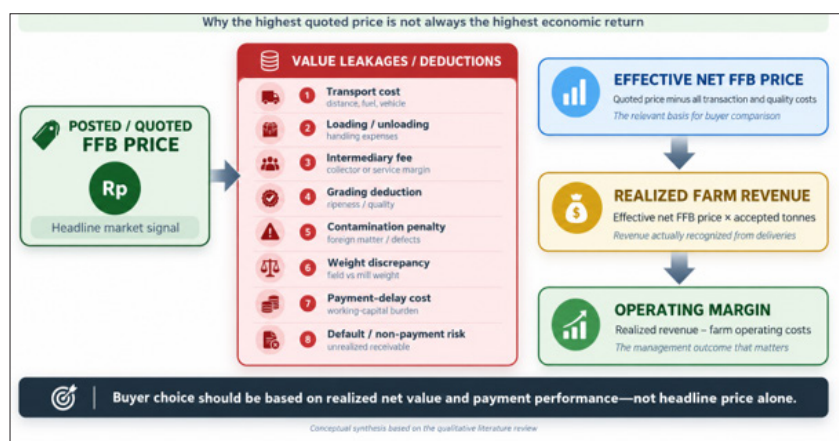


Figure 3: From Posted FFB Price to Realized Net Farm-Gate Revenue

Figure 3 separates headline price from economic realization. A digital sales tracker should consequently rank transaction outcomes using realized historical data, not only published prices. Such information can improve negotiation and help producer groups determine whether collective transport or direct mill access produces measurable economic benefits.

Theme VI: Legality, Traceability and Sustainability Readiness

Sustainability certification poses particular challenges for independent farmers because evidence requirements are layered on top of already demanding farm operations. Apriani show the importance of external facilitation and farmer organization, while Ernah demonstrate that training and extension strategy affect the economics of sustainability-standard adoption. Degli Innocenti and Oosterveer identify knowledge-transfer bottlenecks within certified palm-oil value chains.

de Vos et al. (2023b) find that land legality, prior group organization, costs, and access to facilitators strongly shape independent-smallholder certification prospects. Renner et al. (2024), meanwhile, report positive associations between certification, land productivity, and profits but caution against interpreting observational differences as causal effects and find no price premium in their sample. More recent evidence from Indonesia indicates that training and financial incentives can materially influence smallholder willingness to enter certification schemes, while risk preferences and perceived burdens remain important constraints (Reich and Musshoff, 2025). These findings imply that certification value may arise partly through better management and market access rather than solely through premium prices.

The most efficient approach is therefore compliance by design. Parcel identity, farmer identity, land documentation, input records, harvest dates and delivery records should be captured once during ordinary business processes. The same records can subsequently support traceability or audit requirements, subject to appropriate data governance.

Traceability technologies can improve transparency, but blockchain literature emphasizes that digital ledgers cannot determine whether inaccurate data were entered initially. Successful traceability depends on governance, collaboration, incentives and verification.

Interoperability is another critical requirement. Agricultural traceability systems increasingly combine IoT devices, digital records and distributed databases, but scalability, privacy, security and cross-platform compatibility remain challenges

Steinke provide an especially important warning: if digital sustainability systems create substantial farmer-side costs without corresponding economic benefits, adoption and data quality may suffer. Thus, traceability should not be built as surveillance imposed on producers. It should return value to farmers through improved management, market access, reduced duplication and credible transaction records.

Theme VII: Adoption, Usability and Digital Inclusion

The final theme is that technological sophistication does not equal successful implementation. Smallholder digitalization studies repeatedly identify affordability, device ownership, connectivity, digital skills, trust, institutional organization, perceived usefulness, and social context as adoption determinants. Recent evidence also highlights the importance of economic capacity, infrastructure, training, organizational affiliation, privacy concerns, and farmers' perceptions of usefulness and risk.

A smallholder system should consequently be mobile-first but not mobile-only, operate under intermittent connectivity, minimize repetitive typing, use icons and local-language labels, allow voice or photograph evidence where useful, and synchronize when connectivity becomes available. The farm owner should not need to understand database architecture to obtain value. The interface should answer recurring decisions.

Organizational structures can further reduce adoption costs. Miine et al. (2023) show the relevance of farmer-group membership for digital-service adoption. Raharja et al. (2020) similarly emphasize cooperatives, farmer organizations, mills and supporting institutions in strengthening independent oil palm smallholders. Thus, a promising architecture may involve individual farm data ownership combined with shared services at cooperative or association level for analytics, aggregation, training, buyer relationships and certification.

Discussion and Analysis

The Fundamental Problem Is Fragmented Management

The literature suggests that the central digitalization problem is not an absence of technology. Individual technologies already exist for farm records, machine vision, UAV monitoring, mobile payments, traceability, price information and decision support. The larger problem is **fragmentation between operational domains**.

The independent grower may know the fertilizer purchased but not fertilizer cost by productive block; know total FFB sales but not recoverable losses between harvesting and mill acceptance; know the PKS quotation but not net realized price; and possess legal

documents but lack a structured linkage between farm identity, FFB origin and transactions. A Digital Control Tower addresses this problem by using common data identifiers so that previously separate records can be reconciled.

This interpretation is consistent with the broader Agriculture 4.0 literature, which emphasizes data integration and cyber-physical connections rather than individual technologies. It also reinforces the article's central claim that value is created when digital components are integrated into a coherent management process rather than operated as isolated tools.

A Dashboard Creates Value Only Through Closed-Loop Management

A frequent risk in digital projects is dashboard proliferation. Attractive visualizations can create the appearance of managerial sophistication without changing decisions. The useful analytical unit is therefore a closed management loop in which information moves through a recurring sequence of measure, verify, compare, diagnose, decide, act, reconcile, and learn. This sequence converts monitoring from a passive reporting activity into an adaptive management process [20-30].

Suppose a block's FFB output falls below expectation. The dashboard should lead the manager toward potential explanations—harvest interval, fertilizer history, palm age, pruning, flooding, disease or incomplete collection—rather than simply display a lower bar on a graph. The resulting intervention should subsequently be recorded so that future performance can be compared against the action.

This logic is consistent with the farm-data lifecycle concept and FMIS literature, where data create value only when they are converted into decisions and performance improvement. The implication is that dashboard design should be evaluated by the quality and timeliness of management responses it enables, not by the number of indicators it displays.

Protecting Commercial Yield Is as Important as Raising Biological Yield

Agronomic productivity typically focuses on FFB produced per hectare. For the owner, however, commercially recoverable yield matters equally. Losses occur when ripe bunches remain unharvested, loose fruit is not collected, loads are delayed, weight is disputed, quality is downgraded or deductions cannot be reconciled.

de Vos et al. (2023a) demonstrate why harvest frequency depends on both agronomic and socioeconomic conditions. Monzon et al. (2023) show that harvest interval contributes to yield gaps. Together, these findings support treating harvest management as an integrated scheduling and logistics problem rather than merely a field-operation problem.

Digital technologies can improve this process in layers. The simplest level is a dated harvest calendar. The next records bunches, loose fruits and TPH. GPS and photographs can add verification. Mobile computer vision can assist maturity classification. Vehicle records can monitor transport. Mill tickets can close the quantity loop. The point is not to deploy every technology immediately; it is to preserve continuity of evidence from palm to payment.

Digitalization can Strengthen Commercial Governance

Independent smallholder digitalization is often framed as an agronomic project, but the literature supports an equally important

commercial interpretation. Agricultural digital services can reduce information frictions, facilitate market links and improve access to financial services, although effects depend strongly on context and institutional arrangements

For palm oil, the most useful commercial innovation may be mundane rather than technologically spectacular: reliable reconciliation. Each delivery should generate an identifiable chain linking load, weight, grading, agreed price, invoice, deductions, due date and payment. This system directly addresses owner concerns regarding receivables, payment matching and disputes.

Digital records can also strengthen collective bargaining. Farmer groups could aggregate anonymized transaction statistics—such as realized net prices, payment delays and average deductions—to compare buyers. Such evidence is potentially more useful than informal claims that one mill offers "better prices."

Sustainability Data Should Emerge from Normal Farm Management

Certification is often burdensome because documentation is collected specifically for audit purposes. This creates parallel systems: one for running the plantation and another for proving compliance. The proposed framework replaces this separation with **one-time capture, multiple-use data**.

For example, a fertilizer-application record serves at least four functions: operational confirmation, inventory control, cost accounting and sustainability evidence. A harvest record supports labour management, yield calculation, traceability and sales reconciliation. A mapped parcel supports field planning, land documentation, traceability and potentially remote monitoring.

This approach may lower marginal certification costs, although technology cannot resolve underlying legality or institutional barriers. Evidence from Indonesian certification research makes clear that land rights, organizations, facilitation, learning, financing and standards remain substantive challenges independent of software.

Digitalization Also Creates New Risks

The literature strongly cautions against treating digital systems as neutral. Data collection can redistribute power. A mill or platform possessing detailed farm data may gain advantages that farmers do not. Traceability can reduce anonymity while increasing compliance burdens. Proprietary platforms can produce lock-in. Automated grading can reproduce errors systematically. Poor connectivity can exclude remote farmers. Older or less digitally literate growers may become dependent on intermediaries to use ostensibly empowering technology.

Agricultural digitalization research therefore emphasizes inclusive design and context-specific capabilities. Traceability research likewise emphasizes governance, privacy, interoperability, and incentive alignment, while participatory research on smart farm networks shows that farmers' willingness to share data depends strongly on trust, perceived data validity, privacy protection, and the identity of the organizations managing the network (Bekee et al., 2024).

Accordingly, farmer data governance should contain minimum principles: farmers should know what data are collected; commercially sensitive information should not automatically be visible to every downstream actor; data should be exportable; farmer identity should not be unnecessarily exposed; and aggregation should be used when individual-level disclosure is unnecessary. Clear governance rules are therefore a functional requirement for adoption rather than a secondary legal consideration, particularly when multiple mills, cooperatives, technology providers, or public agencies exchange data [31-40].

The Proposed Digital Smallholder Oil Palm Control Tower

The preceding synthesis is consolidated into a seven-layer Digital Smallholder Oil Palm Control Tower. As shown in Figure 4, each layer transforms raw farm and transaction data into increasingly decision-relevant information, feedback, and strategic outcomes.



Figure 4: Digital Smallholder Oil Palm Control Tower

Figure 4: Illustrates that the framework deliberately places technology below decision and outcome layers. Technologies are enabling infrastructure; management value occurs higher in the architecture. This avoids defining success as the number of sensors installed or records digitized. The relevant outcomes are improved productivity, lower avoidable loss, stronger margin, better bargaining information, credible traceability and greater resilience.

A Progressive Digital Maturity Pathway

Immediate implementation of the complete architecture would be unrealistic for many independent farmers. The literature on adoption and smallholder digital ecosystems supports progressive implementation rather than a 'big-bang' digital transformation because barriers arise simultaneously from affordability, connectivity, skills, trust, and organizational capacity. Accordingly, the proposed maturity pathway begins with low-complexity functions that generate immediate management value before adding more advanced analytics and traceability.

Stage A focuses on digital records. Farm identity, block data, harvest quantities, major expenses, and sales are captured in a consistent format so that the enterprise has a reliable baseline dataset for later analysis.

Stage B focuses on dashboard visibility. Basic records are converted into yield, cost, harvest-interval, inventory, realized-price, and receivable indicators so that deviations can be detected quickly and discussed with workers or service providers.

Stage C focuses on reconciliation. Fertilizer issues are linked with field applications, harvest estimates are matched with mill weights, and invoices are matched with payments so that leakage and unexplained differences become visible.

Stage D adds decision support. Alerts, trend analysis, agronomic recommendations, buyer comparisons, and anomaly detection are introduced only after the underlying records are sufficiently reliable to support higher-level interpretation.

Stage E integrates traceability and external interfaces. Farm records are connected, subject to appropriate consent and governance, with cooperatives, mills, certification evidence, and other authorized supply-chain users so that data collected for management can also support market and compliance functions.

This progression can substantially reduce implementation risk because each stage provides measurable value before the next layer of complexity is introduced. It also allows farmers and supporting organizations to learn from early use, correct data-quality problems, and refine incentives before committing to more advanced technologies.

Managerial and Policy Implications

For farmers, priority should be placed on functions that have an immediate economic logic. Harvest records, cost visibility, fertilizer control, sales reconciliation and receivables are likely to produce clearer short-term value than advanced predictive analytics. Early benefits can strengthen willingness to maintain accurate data.

For cooperatives and farmer associations, digital platforms can create economies of scale. Shared systems can support input procurement, extension, buyer databases, transportation

coordination, certification documentation and aggregated bargaining without requiring each smallholder to operate sophisticated infrastructure independently. Raharja emphasize the importance of farmer organizations and interinstitutional cooperation, while certification research similarly demonstrates the importance of group organization and facilitation.

For mills, integration with smallholder records could improve delivery scheduling, traceability and supplier development. However, information exchange should be reciprocal. If farmers provide traceability information, mills should return transparent grading, weighing, pricing and payment data in machine-readable form.

For government and extension agencies, policy should avoid equating digitalization with application development. More valuable interventions may include interoperability standards, farmer digital skills, rural connectivity, shared identifiers, training, data-governance rules and incentives for systems that demonstrably reduce duplication.

For technology providers, the market opportunity lies in integration rather than feature abundance. Smallholders require systems that tolerate offline operation, work on affordable smartphones, minimize duplicate entries, generate simple reports and allow gradual adoption. Evidence from both FMIS and smallholder-digitalization literature consistently suggests that perceived usefulness and fit with existing work routines are critical for sustained use.

Research Agenda

Several empirical gaps remain. First, future research should measure the causal effect of integrated digital farm management on net profit rather than only technology adoption. Randomized, quasi-experimental or longitudinal comparisons could distinguish the effect of digital information from farmer self-selection.

Second, research should estimate where value is actually generated. Does digital harvest monitoring increase recoverable FFB? Does fertilizer reconciliation reduce input leakage? Does buyer comparison raise realized net prices? Does payment tracking reduce overdue receivables? These questions can be tested using transaction-level data.

Third, farmer willingness to pay requires careful analysis. Digital services may have social value yet fail commercially when benefits accrue mainly to mills, regulators or downstream buyers. Cost-sharing arrangements should therefore reflect the distribution of benefits.

Fourth, interoperability needs technical and institutional research. Agricultural blockchain literature demonstrates that adding another data architecture does not automatically solve fragmentation; systems require shared standards, governance and credible source data.

Fifth, inclusion should be evaluated explicitly. Age, farm size, education, gender, remoteness, organization and connectivity may determine who captures benefits. The distributional consequences of digitalization could therefore be as important as average productivity effects.

Finally, AI-assisted decision support warrants further investigation. Computer-vision technologies already demonstrate technical

capability in FFB classification and disease detection, but their field-level economic value, reliability across cultivars and lighting conditions, maintenance requirements and consequences for worker decision-making remain underexplored [41-49].

Conclusion

The digital transformation of independent oil palm farming should not begin with the question, **"Which technology should farmers adopt?"** It should begin with the question, **"Which management decisions currently suffer from missing, delayed, fragmented or unverifiable information?"** This change in perspective has significant implications for the design of digital agriculture.

The synthesis presented in this article identifies a connected set of managerial functions extending from the palm to the bank account: agronomic inputs, labour, harvesting, loose fruits, collection points, transport, grading, weighing, buyer selection, invoicing, receivables, payment, legality, traceability and sustainability documentation. Managing these functions independently creates data fragmentation and makes operational leakage difficult to detect.

The proposed Digital Smallholder Oil Palm Control Tower addresses this fragmentation through a layered architecture connecting primary farm records, reconciliation, analytics, decision support, supply-chain interfaces, performance feedback and strategic outcomes. Its fundamental innovation is therefore organizational rather than technological. The same trusted record should support multiple managerial purposes.

The article consequently distinguishes **digitization** from **digital management**. Digitization converts paper into electronic information. Digital management establishes a recurring cycle of measurement, verification, diagnosis, decision, action, transaction reconciliation and learning. Only the latter is expected to create sustained managerial value [50-60].

Implementation should nevertheless be progressive. Basic harvest, cost, sales and payment records should precede advanced analytics. Offline-capable mobile systems should precede technology-dependent architectures requiring continuous connectivity. Farmer-side value should precede downstream demands for increasingly detailed data. Traceability should ideally emerge from routine management information rather than duplicate it.

An inclusive digital future for independent oil palm smallholders therefore depends on combining three elements: **useful farm economics, credible data architecture and supportive institutions**. When those elements are aligned, digitalization can potentially strengthen not only yield, but also profitability, commercial transparency, farmer bargaining capacity, sustainability evidence and long-term resilience.

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