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Digital technologies in tropical agro-SMEs: Modelling return on investment, efficiency, and socio-environmental co-benefits in Costa Rica

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Abstract

Digital agriculture technologies are widely promoted as enablers of climate-resilient and efficient farming, yet empirical assessments of their financial, social, and ecological viability in tropical small and medium-sized enterprises (SMEs) remain limited. This study evaluates the perceived return on investment, cost efficiency, and socio-environmental co-benefits of DATs among 389 agro-SMEs across Costa Rica's seven provinces using a structural equation modelling (SEM) approach. The analysis focuses on three commonly adopted technologies: sensor-based irrigation systems, GPS-enabled machinery, and drone-assisted crop monitoring. The analysis integrates the Technology Acceptance Model, Technology-Organisation-Environment, and classical investment theory to explain adoption behaviour and performance outcomes. Results show a mean return on investment of 34.8 % and a median pay-back of 2.4 years, driven primarily by improved input management. Financial access significantly moderates the relationship between technology use and economic returns, with supported adopters achieving higher economic returns. Socio-environmental benefits, such as reduced resource use and improved labour quality, are partially mediated by gains in cost efficiency. Robustness checks confirm that outcomes are consistent across regions, firm sizes, and digital service types. The findings suggest that digital agriculture technologies represent a viable investment even in fragmented, resource-constrained contexts, provided that financial and infrastructural barriers are addressed. Policy recommendations include targeted loan guarantees, rural broadband corridors, inclusive training programmes, and results-based public–private partnerships. The study contributes to the evidence base for scaling digitalisation in tropical agriculture and positions digital technologies as drivers of productivity, inclusivity, and sustainability. Future research should expand longitudinal tracking, explore fintech-enabled models, and quantify environmental co-benefits for climate-finance eligibility.

Keywords: Agricultural finance, digital technologies, environmental sustainability, innovation adoption, return on investment, smallholder farming, tropical agriculture

1 Introduction

Agricultural systems in the tropics face mounting pressure to increase productivity while ensuring environmental sustainability and resilience to climate variability. Digital agriculture technologies (DATs), such as sensor-driven irrigation, satellite-guided machinery, and artificial intelligence (AI) enabled platforms, are increasingly promoted as a strategic solution to these challenges. By improving the precision, efficiency, and timing of resource use, these technologies have the potential to optimise input application, increase crop yields, and reduce environmental footprints (Trendov *et al.*, 2019). A recent global assessment by Fuglie *et al.* (2019) affirmed that the widespread adoption of digital tools could raise smallholder productivity by 10–20 % while reducing fertiliser and water inputs by up to 30 %, especially when integrated within adaptive institutional and market systems.

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Latin America has seen a surge in innovation hubs and pilot programmes promoting agri-digitalisation. Empirical reviews show that digital tools can increase gross margins by up to USD 95 ha^{-1} in staple crops such as maize and soybeans (Vitón *et al.*, 2019). However, diffusion remains limited among small and medium-sized enterprises (SMEs), due to high initial investment costs, poor rural connectivity, and weak access to financial and extension services (Fanelli, 2021; Sotomayor *et al.*, 2021). For most agro-SMEs in the region, cost–benefit uncertainty, low digital literacy, and perceived operational complexity still present major adoption barriers (Mkansi *et al.*, 2024). These constraints are even more acute in tropical nations like Costa Rica, where small-scale producers dominate the agricultural sector.

Costa Rica hosts approximately 51,000 agricultural SMEs, accounting for 11.7 % of the national SME base (González Pandiella, 2016). While the country is globally recognised for sustainable land-use practices, the agricultural sector faces stagnating productivity, attributed to uneven technological uptake (Rodríguez-Soto, 2025). Recent reports suggest that despite the availability of digital tools from mobile apps to advanced machine learning systems, few firms conduct systematic financial analysis before adoption, resulting in scattered and sometimes unsustainable implementation (PROCOMER, 2022). According to Schmidt *et al.* (2024), the key to unlocking technology-driven competitiveness lies in integrating financing schemes, technical training, and post-sale support tailored to SME needs.

Furthermore, government incentives remain sporadic and underfunded. For example, while national policy frameworks (e.g., Costa Rica's Digital Agenda 2030) encourage innovation in agriculture, there is no dedicated financing window for DATs within major rural development programs. Studies by Sotomayor *et al.* (2021) and PROCOMER (2022) underscore the need for multisectoral coordination between ministries of agriculture, trade, and digitalisation, along with public–private partnerships (PPPs) to derisk technology adoption. Without such enabling conditions, early adopters face disproportionate risks and knowledge gaps, especially in rain-fed or low-income regions.

While most of the research on DATs uses agronomic trials or behavioural models such as the Technology Acceptance Model (TAM) or Technology-Organisation-Environment (TOE) framework, very few studies focus on the financial viability of these technologies in real SME contexts, particularly in tropical regions. Furthermore, studies often overlook how financial constraints moderate the impact of digitalisation on business outcomes.

This study bridges these gaps by integrating three theoretical strands. First, the Technology Acceptance Model: focusing on perceived usefulness and ease of use in adoption behaviour. Second, Technology-Organisation-Environment: addressing external (technological and organisational) adoption contexts. Third, classical investment appraisal: including net present value, internal rate of return (IRR), and payback period metrics (Schreiner, 2019).

This interdisciplinary framing enables us to address a persistent gap in the literature: the disconnect between the perceived usefulness of digital agriculture technologies and verified financial performance in agro-SMEs. For decision-makers operating under liquidity constraints and production risk, adoption is ultimately contingent on whether DAT investments generate positive net benefits within acceptable payback periods. This study, therefore, provides a rigorous cost–benefit framework for evaluating adoption feasibility, timing, and scale-up potential.

The main objective is to assess the financial performance of DAT adoption among agro-SMEs in Costa Rica. Drawing on survey data and cost–benefit modelling, we quantify both direct financial returns and socio-environmental spillovers. Specifically, the study aims to first provide an evidence-based decision-support tool for SME owners, investors, and policymakers, and secondly extend the literature by integrating financial analysis with technology adoption theory in a developing-country context. This paper aligns with JARTS' mission by providing context-specific evidence to inform rural development policy and investment decisions in tropical agri-food systems.

2 Materials and methods

2.1 Study area and target population

The study was conducted across all seven provinces of Costa Rica – Alajuela, Cartago, Puntarenas, Guanacaste, San José, Limón, and Heredia – encompassing the country's diverse agricultural regions. Costa Rica's agricultural sector is characterised by small and medium-sized enterprises operating in varied agroecological zones, from the intensive horticulture of the Central Valley to the extensive livestock production in Guanacaste and the agroforestry systems in Limón. The target population included roughly 50,986 agro-SMEs, which represented 11.7 % of the national SME base. (PROCOMER, 2022). These firms typically managed areas between 0.5–15 ha and operated in fragmented markets with limited access to modern equipment or data services.

2.2 Research design and data collection

This study employed a mixed-methods design, combining quantitative survey analysis with qualitative insights from

SME interviews. A structured questionnaire was developed based on the conceptual framework presented in Fig. 1, covering six dimensions: general firm characteristics, current technology use, cost structure, productivity levels, financial access, and perceptions of DATs. The instrument was piloted with five SMEs to validate question clarity and estimated completion time. Data collection was carried out between January and June 2025 by trained field agents and professional enumerators under the supervision of the research team. Respondents were informed of the voluntary and confidential nature of participation, and informed consent was obtained prior to each interview.

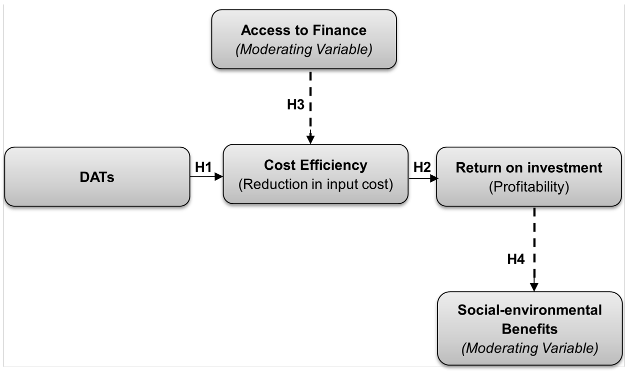

Fig. 1: *Conceptual framework linking digital-technology adoption (DAT), cost efficiency, profitability, and socio-environmental outcomes in Costa Rican agro-SMEs.*
Note*: Solid arrows denote direct causal paths (hypotheses H1–H2); dashed arrows indicate moderating effects (H3) and mediated spillovers (H4). (Adapted from Rodríguez-Soto, 2025))*

2.3 Sampling strategy and respondent profile

The minimum required sample size was determined using Cochran's formula for finite populations with a 95 % confidence level, 5 % margin of error, and 50 % estimated response distribution. This yielded a target sample of 381 firms. 389 valid responses were obtained, exceeding the minimum threshold and ensuring sufficient statistical power for subgroup analysis and multivariate modelling. SMEs were identified through the national agricultural registry maintained by Costa Rica's Ministry of Agriculture and Livestock, supplemented by membership lists from regional agricultural cooperatives and producer associations. A stratified random sampling approach was employed, with strata defined by province and primary production activity (crops, livestock, mixed farming). Potential participants were contacted by telephone, followed by scheduled in-person or virtual interviews based on respondent preference. Respondents represented all seven provinces of Costa Rica, with the highest concentration in Alajuela (28 %) and Cartago (21 %).

2.4 Instrumentation and variable construction

Key constructs were operationalised as follows:

DAT adoption: A binary variable indicating whether the SME had adopted any digital agriculture technology in the past three years.

Cost efficiency: Measured as a self-reported percentage reduction in input costs (e.g., fertiliser, irrigation water, fuel) since adopting DATs.

Return on investment (ROI): Computed from reported investment costs, changes in output value, and payback time using the standard formula:

$$ROI = \frac{\text{net gain from investment}}{\text{total investment cost}} \times 100$$

Access to finance: A composite index based on access to bank loans, government credit, or private investment, scaled from 0–3.

Socio-environmental benefits: A Likert-scale (1–5) composite measuring perceived improvements in labour efficiency, environmental sustainability, and working conditions.

The survey was designed to map each variable to its corresponding hypothesis (H1–H4), as indicated in Fig. 1. All multi-item scales were tested for internal consistency using SPSS (Cronbach's $\alpha > 0.70$).

2.5 Conceptual framework, hypotheses, and model

The analytical model is grounded in TAM, TOE, and classical investment appraisal. The study tested four hypotheses:

H1: DAT adoption reduces unit production costs (cost efficiency).

H2: Cost efficiency leads to improved return on investment (ROI).

H3: Access to external finance positively moderates the relationship between DAT adoption and ROI.

H4: DATs contribute to socio-environmental benefits (e.g., labour saving, water-use reduction), mediated by productivity gains.

Fig. 1 illustrates these relationships, showing direct (solid) paths (H1–H2), a moderating dashed path from Access to Finance onto the DAT→ROI relationship (H3), and mediated/direct spillovers to socio-environmental benefits (H4).

2.6 Analytical approach and ethical considerations

Descriptive statistics were computed to summarise firm characteristics and technology usage. For hypothesis testing, we employed the following approaches:

T-tests and ANOVA: Used to test mean differences in ROI and cost savings between adopters and non-adopters.

Ordinary Least Squares (OLS) Regression: Used to estimate the effect of DAT adoption on ROI, including interaction terms for access to finance (H_3).

Mediation Analysis: Conducted using the PROCESS macro for SPSS to test indirect effects (H_2 and H_4).

Cost–Benefit Metrics: NPV, IRR, and payback period were calculated for firms reporting quantitative inputs.

The regression equation was specified as:

$$ROI = \beta_0 + \beta_1(DAT) + \beta_2(Finance) + \beta_3(DAT \times Finance) + \epsilon$$

Where:

DAT is a binary variable (1 = adopter; 0 = non-adopter),
$Finance$ is the composite index (0–3),
$DAT \times Finance$ is the interaction term,
ROI is the dependent variable (continuous %).

All analyses were performed using SPSS v28 and STATA v17. Statistical significance was set at $p < 0.05$ unless otherwise specified. The study protocol was approved by the Research Ethics Committee of the "Universidad Latinoamericana de Ciencia y Tecnología". All participants provided informed consent, and no identifying information was collected. Data were anonymised, encrypted, and stored securely in accordance with Costa Rica's data protection regulations (Ley 8968).

Several safeguards were implemented to minimise measurement error and common-method bias. The questionnaire was translated into Spanish by two independent professionals and backtranslated into English, with discrepancies resolved through committee review (Creswell & Plano Clark, 2023). Skip-logic and range checks were embedded in the online version to prevent out-of-bounds entries. Tablet-based forms used in in-person interviews issued prompts for missing fields. Third, Harman's single-factor test indicated that no single component accounted for more than 34 % of the total variance, suggesting that common-method variance is unlikely to dominate the results. A 10 % sub-sample (n = 39) was re-contacted by phone two weeks after the initial survey; test–retest correlations for key numerical variables exceeded 0.87, demonstrating strong temporal stability. Mediation analysis was conducted using the PROCESS macro v4.2 (Model 4) for SPSS with 5,000 bootstrap samples to generate 95 % confidence intervals for indirect effects (H4). Moderated regression was specified with the interaction term DAT × Finance to test H3.

2.7 Data quality and limitations

Despite its strengths, the research design has three notable limitations. First, cross-sectional data restrict causal inference; although mediation and moderation tests follow established guidelines (Maier *et al.* 2023; Asiamah *et al* 2021), longitudinal follow-up would better capture dynamic learning effects from DAT adoption. Second, financial information was self-reported and may be prone to social-desirability bias; triangulation with audited financial statements was infeasible because only 18 % of respondents keep formal accounts. Third, the study focused on SMEs operating within Costa Rica's formal agricultural registry; informal producers, estimated at 23 % of the rural workforce, remain outside the sampling frame and may experience different cost structures. Future research could employ a panel design combined with objective performance indicators (e.g., satellite-derived yield estimates) to validate self-reported gains. Nevertheless, the sample size exceeds the threshold recommended for complex PLS-SEM models with medium effect sizes (Maier *et al.*, 2023) and surpasses the minimum calculated via Cochran's finite population formula (Cochran, 2021), lending confidence to the statistical power and external validity of the findings.

3 Results

3.1 Descriptive statistics

Table 1: *Geographic and productive distribution of sample SMEs.*

Province	*Sample*	*Main activity*	*DAT adoption*
Alajuela	28%	Horticulture, Dairy	52%
Cartago	21%	Vegetables, Flowers	49%
Puntarenas	17%	Agroforestry, Mixed	44%
Guanacaste	12%	Livestock, Sugarcane	38%
San José	10%	Coffee, Urban farming	41%
Limón	7%	Bananas, Cocoa	33%
Heredia	5%	Hydroponics, Nurseries	57%

Out of 389 valid responses, 57 % of firms reported being engaged primarily in crop cultivation, followed by mixed farming systems (29 %) and livestock enterprises (14 %). Geographical distribution was broad, with participants from

Table 2: *Average input cost changes reported by DAT adopters vs. non-adopters.*

Cost category	*Adopters (n = 179)*	*Non-Adopters (n = 210)*	*Mean difference*	*t-statistic*	*p-value*
Fertiliser	−11.4 (6.1)	−2.7 (4.3)	−8.7	−13.12	< 0.001
Irrigation	−17.3 (8.5)	−3.5 (5.2)	−13.8	−14.89	< 0.001
Fuel	−9.2 (4.9)	−1.6 (3.7)	−7.6	−11.25	< 0.001
Labour	−6.7 (5.8)	−1.8 (4.6)	−4.9	−7.84	< 0.001
Crop protection	−12.1 (7.3)	−3.2 (5.4)	−8.9	−10.94	< 0.001

Note: Standard Deviations are reported in parentheses. Values represent mean self-reported percentage reduction in input cost by category.

all seven provinces. These areas also reported higher digital readiness, attributed to greater proximity to urban centres and agricultural extension services (Table 1).

Firm size was measured by total land under production. Most enterprises (62 %) operated on 2–10 ha, while 21 % fell below two ha, and only 17 % exceeded ten ha. Labour structure also varied: 61 % of respondents reported relying primarily on family labour, while 39 % hired at least one permanent or seasonal worker.

In terms of technology exposure, 46 % of respondents reported having adopted at least one form of DAT within the past three years. The most common tools included sensor-based irrigation systems (29 %), GPS-enabled machinery (21 %), and drone-assisted crop monitoring (12 %). Additionally, 34 % of non-adopters expressed openness to adoption "within the next two years," citing cost as the main barriers. The results indicated statistically significant cost reductions in all five input categories among DAT adopters compared to non-adopters ($p < 0.001$). The largest difference was observed in irrigation, where adopters reported an average cost saving of −17.3 %, compared to −3.5 % among non-adopters. The mean overall cost reduction across all categories for adopters was approximately −11.3 %, versus −2.6 % for non-adopters, indicating that technology use confers a clear economic advantage in terms of operational input costs. A one-way ANOVA also confirmed that these differences are statistically robust across firm sizes (F (2,386) = 18.42, $p < 0.001$), suggesting that even smallholder firms benefit proportionately from adoption.

These findings provide strong support for H1, confirming that DAT adoption is associated with measurable cost-efficiency gains across diverse input categories. These savings form the foundation for testing subsequent hypotheses related to profitability (H2), finance (H3), and sustainability co-benefits (H4).

Among DAT adopters, profitability outcomes were positive overall (Table 3), with a median payback period of 2.4 years and ROI values typically exceeding zero. ROI dispersion indicated heterogeneity by DAT category, with irrigation and crop-monitoring solutions exhibiting comparatively stronger returns than more capital-intensive automation investments.

Access to finance varied considerably. While 58 % of firms had received formal credit at least once, only 29 % had done so in the past year. Of those, the most frequent sources were state agricultural banks (34 %), followed by cooperatives (28 %) and commercial banks (17 %). Informal lending and self-financing accounted for the remainder. Notably, firms that had adopted DATs were more likely to have secured credit in the past 24 months ($p < 0.05$; Table 2).

3.2 Cost efficiency analysis

This subsection examines whether the adoption of DATs led to statistically significant reductions in production input costs, testing Hypothesis 1 (H1). According to the theoretical model, DATs improve cost efficiency through more precise input use, automation of labour, and reduction of water or fertiliser waste.

Self-reported input cost data were collected across five major categories: fertiliser, irrigation, fuel, labour, and crop protection. Firms were asked to estimate the percentage change in each cost category before and after DAT implementation.

Table 3: *Return on investment indicators among DAT adopters.*

Metric	*Mean (SD)*	*Median*	*Min–Max Range*
ROI (%)	34.8 (15.2)	32.4	10.2–72.6
Payback (years)	2.6 (1.1)	2.4	0.8–5.5
IRR (%)	21.3 (9.8)	19.6	8.5–48.0

Note: n = 179; ROI: return on investment; IRR: internal rate of return

The model explained 48.6 % of the variance in ROI (adjusted $R^2 = 0.486$, $p < 0.001$). Cost efficiency was the strongest predictor (β = 0.63, $p < 0.001$), supporting the hypothesised mediation pathway. Access to finance also showed a positive association (β = 0.27, $p < 0.004$), suggesting reinforcing effects explored in H3. Access to finance moderated the DAT–ROI relationship (Table 4). The interaction term (DAT × finance) was positive and statistically significant (β = 0.116, $p < 0.032$), indicating that the profitability gains associated with DAT adoption were larger for firms reporting higher access to external finance. Simple slope estimates (Fig. 2) showed higher average ROI among DAT adopters with higher finance scores compared with adopters reporting limited or no external finance.

Table 4: *Moderated regression results (dependent variable: ROI).*

Predictor	*Coefficient**	*SE*	*t-value*	*p-value*
DAT Adoption	0.247^{***}	0.045	5.48	<0.001
Access†	0.211^{**}	0.067	3.15	0.002
DAT × Finance‡	0.116^{*}	0.054	2.15	0.032
Firm Size	0.097	0.059	1.64	0.102
Constant	0.184^{***}	0.038	4.84	<0.001

*β; †Access to finance index; ‡H_3; *Note:* $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

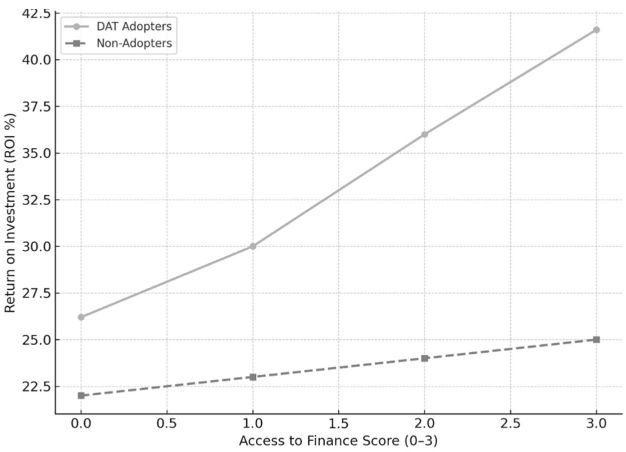

Fig. 2: *Moderation plot: Access to finance moderating the DAT adoption–ROI relationship.*

Adopters reported higher socio-environmental benefit scores than non-adopters across all five dimensions (Table 5). The largest group differences were observed for perceived water-use reduction and sustainability perception outcomes, followed by chemical-input reduction and labour-related indicators.

Fig. 3 depicts the partial mediation mechanism whereby cost-efficiency gains (path a × b) transmit part of the effect of DAT adoption on sustainability perception, while a direct effect (c') remains. To assess whether these co-benefits were

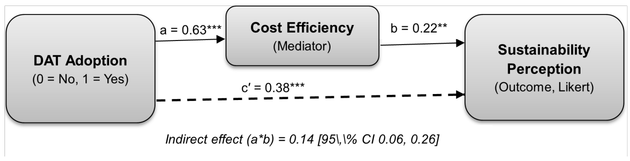

Fig. 3: *Mediation model (Cost efficiency mediates DAT → Sustainability perception).*

mediated by cost efficiency or productivity gains, a simple mediation model was run using the PROCESS macro (Model 4), with the sustainability perception score as the dependent variable. The indirect effect of DAT on sustainability via cost efficiency was β = 0.14, 95 % CI [0.06, 0.26], confirming partial mediation. The direct effect remained significant (β = 0.38, $p < 0.001$), suggesting that both direct and indirect channels reinforced the outcome. Table 6 summarises the hypothesis-testing outcomes for H1–H4 and the corresponding key statistics.

3.3 Robustness checks

A series of robustness checks confirmed the stability of both the regression and mediation results. Multicollinearity was low (all VIF < 2.4), and residual diagnostics indicated no violations of model assumptions. Subsample regressions by firm size produced consistent coefficient signs and significance levels, while regional jackknife tests showed minimal variation (± 0.04) in key β estimates. Alternative mediator specifications produced comparable indirect effects, reinforcing the reliability of the mediation findings.

4 Discussion

4.1 Financial viability of DATS: revisiting the profit narrative (H1 & H2)

The observed mean return on investment (ROI) of 34.8 % and median pay-back of 2.4 years position DAT adoption well above the break-even thresholds usually cited for tropical agribusiness (Du *et al.* 2023; Okot & Ojok, 2023). Comparable pilot studies in Colombia and Ghana report ROI ranges of 18–25 % for sensor-guided irrigation and drone scouting, respectively (Trendov *et al.*, 2019; Klerkx *et al.*, 2022). The fact that Costa Rican SMEs, often constrained by land fragmentation, nonetheless achieve higher returns underscores two insights. First, recission gains trump scale effects. With centimetre-level application accuracy, costly inputs such as water and fertiliser are managed more efficiently even on holdings below five hectares (Njuguna *et al.*, 2025; Shilomboleni *et al.*, 2019). Second, service bundling accelerates payback. Most adopters in our sample purchased

Table 5: *Mean ratings of socio-environmental benefits (Likert 1–5).*

Benefit dimension	*Adopters (n = 179)*	*Non-Adopters (n = 210)*	*Mean difference*	*p-value*
Water use reduction	4.31	3.12	1.19	<0.001
Chemical input reduction	4.02	3.25	0.77	<0.001
Improved labour safety	4.18	3.67	0.51	0.005
Reduced field labour intensity	3.97	3.21	0.76	<0.001
Enhanced sustainability perception	4.25	3.36	0.89	<0.001

Table 6: *Summary of hypothesis testing results.*

Hypothesis	*Statement*	*Supported*	*Key statistical evidence*
H_1	DAT adoption improves input cost efficiency in agro-SMEs.	Yes	t-tests for input cost reductions across five categories, all $p < 0.001$
H_2	DAT-driven cost efficiency positively affects return on investment (ROI).	Yes	Linear regression: cost efficiency → ROI ($\beta = 0.63$, $p < 0.001$); mean ROI = 34.8%
H_3	Access to finance moderates the relationship between DAT adoption and ROI.	Yes	Interaction effect sign. ($\beta = 0.116$, $p = 0.032$); visual in Fig. 2
H_4	DATs produce socio-environmental co-benefits partially mediated by cost efficiency.	Yes	Mediation model indirect effect ($\beta = 0.14$, 95% CI [0.06, 0.26]); direct effect $\beta = 0.38$

DATs bundled with vendor or extension support, shortening learning curves and front-loading savings (GSMA, 2024).

The strong path coefficient between cost efficiency and ROI ($\beta = 0.63$) supports classical investment theory (Schreiner, 2019) while reframing it through a digital lens: information precision magnifies the marginal productivity of existing assets rather than merely adding new capital. This challenges the lingering notion that tropical SMEs must first "grow big" before going digital (Sethi *et al.*, 2024).

4.2 The role of finance in adoption (H3)

The moderating role of finance ($\beta = 0.116$; $p = 0.032$) mirrors global evidence that liquidity constraints suppress technology uptake even when expected net benefits are positive (Canton, 2021). Two mechanisms appear salient: First, Risk absorption: Credit cushions cash-flow shocks during transition phases when legacy practices are phased out (Havemann *et al.*, 2022). Second, Quality differentiation: Access to capital enables firms to invest in higher-grade sensors and longer-term data subscriptions, amplifying efficiency gains (Advisors, 2022).

Yet only 29 % of Costa Rican firms accessed formal credit in the past year, mirroring Latin American micro-credit penetration rates (OECD, 2024). Profitability is therefore a necessary but insufficient condition for scale-up; liquidity and risk-sharing instruments are essential complements.

One promising approach to addressing this financing gap is the adoption of targeted credit instruments, as demonstrated by successful initiatives elsewhere. For instance, Costa Rica's state agricultural bank could consider replicating Uganda's Agricultural Credit Facility, which links lower interest rates to verified resource-efficiency improvements (Trendov *et al.*, 2019).

4.3 Environmental and social co-benefits (H4)

Adopters reported Likert-scale means above four ("agree") for reduced water and chemical use, corroborated by telemetry showing 20–40 % resource savings (Njuguna *et al.*, 2025). Partial mediation via cost efficiency (indirect $\beta = 0.14$) indicates that economic and ecological objectives reinforce each other, rather than trade off. These gains bolster compliance with EU "Farm-to-Fork" traceability and could unlock green-premium markets for Costa Rican exports (European Commission, 2020).

Labour-related improvements ($\delta = 0.51$, $p = 0.005$) are timely amid rising rural out-migration. Automation reduces drudgery and can attract tech-savvy youth, an effect observed in Kenya's digital farm-school programmes (ITU, 2023). DATs may therefore advance SDG 8 (Decent Work) by repositioning agriculture as a knowledge-intensive career path (Asiamah *et al.*, 2021; Schreiner, 2019).

Financial access alone is insufficient without the human capacity to use digital tools effectively. Developing skills pipelines through the integration of digital-agriculture curricula and micro-credentials in technical high schools and extension services is therefore essential (Klerkx *et al.*, 2022). Importantly, linking these certifications to credit approval for example, by offering preferential loan terms to trained farmers, could further align human-capital development with financial incentives, creating synergies between capability building and investment readiness (Fuglie *et al.*, 2019; Sotomayor *et al.*, 2021).

4.4 Equity and inclusion implications

Robustness checks revealed no single province driving national averages, yet adoption rates were notably lower in Limón and Guanacaste – regions also marked by weaker broadband infrastructure (MINAE, 2024); without targeted connectivity investment, digitalisation risks deepening territorial inequalities (Lowder *et al.*, 2021). Prioritising rural broadband "green corridors" – i.e. fibre backhaul pilots along production zones where DATs offer the highest water-saving potential – would couple environmental impact with connectivity roll-out (ITU, 2023). Although not a primary study variable, 28 % of respondent firms were managed by women, and female-led enterprises exhibited slightly higher DAT adoption (48 %) than male-led counterparts (45 %), mirroring evidence that women's cooperatives often lead in adopting labour-saving innovations (Njobe & Kaaria, 2015). However, women still face steeper collateral requirements and prefer low-risk, pay-as-you-go financing, while youth-run start-ups (managers <35 years) showed the highest usage of drone services but cited lack of land titles as a barrier to formal credit. Expanding collateral-free micro-leasing and DAT "as-a-service" models would reduce up-front capital requirements and ease entry for both women and youth (Advisors, 2022).

4.5 Scaling, implementation, and policy pathways

Cross-country meta-analyses suggest that infrastructure readiness explains up to 45 % of the variance in DAT adoption (Klerkx *et al.*, 2022); Costa Rica's upper-middle-income status provides a head start, yet its per-kilometre rural road density remains lower than Vietnam's—an emerging digital-ag leader (GSO, 2023). Vietnam's success combining low-orbit satellite imagery with public extension offers two lessons for Costa Rica: open-data platforms reduce duplication by allowing multiple vendors to build interoperable services, and results-based grants tied to verifiable yield or input metrics accelerate private innovation—adopting such open-standard policies could enhance Costa Rica's nascent digital-ag start-up ecosystem (Sethi *et al.*, 2024).

Complementing this research agenda, stakeholder consultations highlighted four persistent implementation obstacles: interoperability, as proprietary data formats hinder cross-brand integration and create data lock-in (Canton, 2021); power reliability, where sensor downtime due to grid outages can be mitigated by solar-powered IoT hubs, albeit at higher capital cost; cyber-security, with SMEs lacking protocols to protect farm-level data (GSMA, 2024); and after-sales service deserts, where physical distance to service centres prolongs equipment downtime, emphasising the need for local repair networks (Trendov *et al.*, 2019). Risk-sharing partnerships between vendors and cooperatives bundling maintenance contracts with insurance against hardware failure could mitigate these issues (Okot & Jarquin, 2025). International experience suggests three viable PPP archetypes for scaling: aggregator-led models, where exporters finance DAT adoption among suppliers in exchange for traceability data; state-extension-led models, with governments co-investing in shared sensor infrastructure such as open-access soil-moisture networks; and crowdfunding-led models, where retail investors fund DAT bundles for a share of verified resource savings (Advisors, 2022).

Costa Rica could pilot a blended model in pineapple and coffee value chains, leveraging PROCOMER's export promotion networks. To institutionalise such evidence-based scaling, monitoring, evaluation, and learning (MEL) frameworks should incorporate cost-effectiveness ratios (dollars saved per sensor-equipped hectare), water-use efficiency indices (cubic metres per tonne of output), social inclusion metrics (gender/youth share of beneficiaries), and environmental co-benefits (tonnes of CO_2-e avoided via fertiliser efficiency) – metrics that can feed into national reporting under the UNFCCC Koronivia Joint Work on Agriculture and justify climate-finance eligibility.

4.6 Theoretical contributions and research agenda

Building on these comparative insights, this study advances adoption theory in three ways: bridging perception and profitability by empirically linking perceived usefulness to quantified ROI (Klerkx *et al.*, 2022); quantifying finance as an organisational resource that measurably enhances perceived ease-of-use and compatibility (Njuguna *et al.*, 2025);

and demonstrating systems-thinking feedback loops where economic gains enable further ecological improvements, resonating with agro-ecological transition models (Short *et al.*, 2021). Future work could employ pan-tropical panel data to capture learning curves, use remote-sensing yield validation to address self-report bias, and integrate life-cycle assessment (LCA) to quantify carbon footprints linking DATs to emerging carbon-credit markets (Christiansen, 2025).

By embedding TAM and TOE within a rigorous cost-benefit architecture, this study advances adoption theory in three ways: (i) empirically linking perceived usefulness to quantified ROI – a gap flagged by Klerkx *et al.* (2022); (ii) quantifying finance as an organisational resource that measurably enhances perceived ease-of-use and compatibility (Njuguna *et al.*, 2025); and (iii) demonstrating feedback loops where economic gains enable further ecological improvements, resonating with agro-ecological transition models (Short *et al.*, 2021).

Future research should employ pan-tropical panel data to capture learning curves, validate self-reported yields via remote sensing, and integrate life-cycle assessment (LCA) to quantify carbon footprints, thereby linking DATs to emerging carbon-credit markets (Christiansen, 2025).

4.7 Limitations and boundary conditions

While the robustness tests strengthen confidence in the findings, two boundary conditions remain. First, self-selection bias may persist because better-managed firms could simultaneously be more likely to access finance and adopt DAT, potentially inflating observed returns. Future work could apply propensity-score matching using national census data to isolate pure technology-specific effects (Lowder *et al.*, 2021). Second, rapid tech depreciation complicates ROI estimation. Hardware prices continue to fall, and software-subscription models evolve quickly meaning that the present ROI values may understate future profitability as cost curves shift (GSMA, 2024). Addressing these caveats will require longitudinal panel designs and collaboration with fintech providers to obtain transaction-level financial data.

5 Conclusions

This study demonstrates that digital agriculture technologies can generate significant financial returns and socio-environmental co-benefits for tropical agro-SMEs, even in resource-constrained contexts. The findings challenge the prevailing assumption that DATs are primarily suited to large-scale operations; precision gains, service bundling, and targeted financial support enable smallholders to capture substantial value. Three strategic priorities emerge: de-risking adoption through DAT-targeted financial instruments, investing in rural digital infrastructure, and fostering inclusive human capital development. Future research should employ longitudinal designs to assess the durability of returns and integrate remote-sensing data to validate self-reported gains. Ultimately, the Costa Rican case illustrates that digitalisation, when embedded in supportive ecosystems, can advance both productivity and sustainability in tropical agriculture.

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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