Scientific African 29 (2025) e02848

Contents lists available at ScienceDirect

Scientific African

journal homepage: www.elsevier.com/locate/sciaf

Economic viability of mechanization service provision for rice cultivation: A case study of small and medium enterprises in Cote d'Ivoire

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A R T I C L E I N F O

Editor: DR B Gyampoh

Keywords:
Mechanization service provision
Break-even analysis
Agricultural SMEs
Rice value chain
Regional profitability
Cote d'Ivoire
Farm machinery economics

A B S T R A C T

Rice cultivation is integral to food security and economic development in Cote d'Ivoire; however, the widespread adoption of mechanization is constrained by high costs and logistical challenges in the country. This study evaluates the economic performance of Small and Medium Enterprises mechanization service providers involved in rice cultivation through a break-even analysis conducted across three distinct districts: Northern, Central, and Mountains. Utilizing real-world operational data, this study examined the profitability of various mechanization services, including plowing, harvesting, and threshing, under both optimal and actual working conditions. It assesses cost structures, including fixed and variable expenditures, effective field capacity, seasonal workday limitations, and regional service demand. The findings revealed significant variations in profitability by machinery type and location. Combine harvesters and tractors with rotovators, which are highly profitable in the central districts, have break-even points at 171.9 ha and 83.5 ha, respectively, achieving profit margins of 19 % and 8 %. Conversely, service providers in the northern districts encounter higher break-even thresholds, necessitating, for instance, a combine harvester and tractors with rotovators to service over 555.3 ha and 191.3 ha, respectively, to achieve profitability, which is hindered by dispersed demand and operational constraints. This study underscores the necessity of scale-appropriate mechanization, improved infrastructure, operator training, and supportive policies to enhance service viability. The policy recommendations, include subsidized leasing, shared-service models, and diversification of machinery, use beyond rice to ensure sustainable operations. These insights are crucial for informing the expansion of mechanization services through private sector engagement, offering a pathway to resilient and inclusive agricultural development in Cote d'Ivoire.

Introduction

Agricultural transformation in Sub-Saharan Africa is critically dependent on mechanization, particularly in nations such as Cote

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https://doi.org/10.1016/j.sciaf.2025.e02848
Received 10 January 2025; Received in revised form 4 July 2025; Accepted 8 July 2025
Available online 8 July 2025

d'Ivoire, where agriculture contributes approximately 23 % to the national Gross Domestic Product [1] and accounts for over two-thirds of export earnings [2,3]. Within this sector, rice holds strategic significance, functioning as both a staple food and a source of income for a substantial portion of the population [4,5], with rice cultivation employing approximately 8 % of the national labor force [6,7]. Despite this, Cote d'Ivoire remains reliant on rice imports to satisfy nearly half of its domestic demand, producing only 1.3 million tons in 2018 against a requirement of 1.8 million tons [8,9]. When effectively implemented, mechanization has been associated with notable increases in land productivity, reductions in manual labor burdens, and improvements in rural livelihoods [10–13]. However, these advantages are not without drawbacks. In several African contexts, large-scale mechanization has resulted in land dispossession, exacerbation of rural inequality, and displacement of labor, particularly among women and youth [10,14–16]. Mechanization can also heighten the dependency on imported equipment and spare parts, impose financial strain on service providers, and raise environmental concerns related to soil degradation and fuel use [17–19]. To address these challenges, the government of Cote d'Ivoire has initiated a new mechanization strategy under the National Rice Development Strategy (SNDR), implemented through the National Rice Development Agency (ADERIZ). This initiative targets agricultural Small and Medium Enterprises (SMEs) to provide mechanized services such as plowing, harrowing, seeding, harvesting, and threshing. Rather than promoting equipment ownership among individual farmers, this strategy supports a shared-service model, offering regulatory frameworks, technical support, access to finance, and skill development [20]. The key success factors include access to quality equipment, trained operators, financial sustainability, and proximity-based service delivery. While this approach reduces the upfront financial burden on smallholders, persistent barriers include delays in payment, maintenance logistics, and limited access to spare parts and technical expertise [14,21,22].

Agricultural mechanization is widely acknowledged as a catalyst for productivity enhancement and rural transformation in sub-Saharan Africa; however, its economic impacts remain inconsistent and context-specific [9,10]. While recent policies in countries such as Cote d'Ivoire have shifted towards promoting private-sector mechanization service provision, most empirical studies have focused on large-scale mechanization schemes or optimal, model-based scenarios that do not accurately reflect the practical realities of smallholder-dominated rice systems [11,13]. Specifically, there is a paucity of evidence regarding the economic performance, break-even thresholds, and operational constraints faced by Small and Medium Enterprises (SMEs) mechanization service providers under the diverse agroecological and market conditions that characterize West African rice value chains [5,12]. Existing research frequently neglects critical district-level variations in demand density, farm structure, seasonal labor bottlenecks, and the impact of infrastructure on service delivery [14,27]. Furthermore, most economic analyses adopt generalized or single-approach frameworks (e.g., total cost or income approaches) and rarely integrate empirical cost structures with actual field data on SMEs operations [34]. Consequently, there is a significant gap in understanding the real-world viability and profitability of SMEs-driven mechanization services for rice cultivation, particularly in countries like Cote d'Ivoire, where government strategies increasingly rely on such models to drive inclusive agricultural transformation [23,29]. No comprehensive district-level economic analysis has systematically assessed the fixed and variable cost structures, break-even points, and context-specific barriers faced by SMEs mechanization providers across different agro-ecological zones in the country.

In this context, the present study conducts a district-level economic evaluation of mechanization services provided by Small and Medium Enterprises (SMEs) in rice cultivation across the Northern, Central, and Mountains districts of Cote d'Ivoire. It addresses existing empirical gaps by incorporating operational data from 26 service providers, along with detailed cost structures, regional constraints, and observed work capacities. The objectives of this study are to (i) identify and quantify the fixed and variable costs associated with various types of rice cultivation machinery utilized by mechanization service providers in Cote d'Ivoire; (ii) calculate the break-even points and maximum profit margins for tractors, harvesters, and threshers under both optimal and actual field conditions across three agro-ecological districts; (iii) assess the viability of current mechanization models and offer policy recommendations tailored to the economic realities and agro-ecological characteristics of each district; and (v) analyze economic and operational performance over a one-year agricultural cycle [26,30]. Beyond providing empirical insights, this study contributes to the broader discourse on inclusive agricultural mechanization by examining the implications of service delivery constraints, governance bottlenecks, and regional differences in farm structure. Ultimately, this study addresses the following critical question: Can Small and Medium Enterprises mechanization providers maintain profitability without substantial subsidies or land consolidation? What scale of machinery and service models are appropriate for each agro-ecological region? Furthermore, how can policy interventions enhance private sector participation without replicating the failures of the past?

Methodology

Study area and mechanization strategy

Study area

Cote d'Ivoire, located in West Africa, encompasses a diverse agro-ecological spectrum ranging from coastal plains to savannah and forest zones. It shares borders with Ghana, Burkina Faso, Mali, Guinea, Liberia, and the Atlantic Ocean, covering an area of approximately 322,462 square kilometers. The nation experiences a tropical climate characterized by high temperatures and humidity, with two rainy seasons in the south and one in the north of the country. Rainfall varies from approximately 1000 mm in the northern savannahs to over 2500 mm in the southern forests [4,6,27]. The soils are varied, with rich lateritic types in the south that support intensive rice cultivation and sandy and loamy soils in the northern regions [4,6,25]. These climatic and soil conditions render Cote d'Ivoire highly suitable for rice farming. To capture this agro-ecological diversity, the study selected three representative districts: Mountains District: This district includes areas such as Man and Danané. It features a humid subtropical climate with high annual rainfall (1800–2500 mm) and cooler temperatures, supporting terraced upland fields and valley lowlands conducive to both upland

and irrigated rice cultivation. Central districts: Represented by Bouaké, Yamoussoukro, Daloa, Gagnoa, and Bouaflé, this transitional zone experiences bimodal rainfall (March–July and September–November). Fertile soils and seasonal rainfall support mixed lowland and upland rice systems, making them favorable sites for diverse mechanized interventions. Northern districts: Encompassing Korhogo, Touba, Odienne, and Ferkessédougou, this area has distinct dry (November–April) and wet (May–October) seasons. Irrigation is essential for sustaining productivity in predominantly lowland systems. Its expansive flatlands are particularly suitable for mechanized farming operations.

The selected districts were identified because of their substantial contributions to national rice production and their role as hosts to agricultural SMEs that are actively involved in the provision of mechanization services. However, these districts do not possess equal levels of machinery and equipment. The regions of Gbêkê and Bélier, located in the central districts, along with the prefectures of Katiola and Touba in the northern districts exhibit the highest power tiller concentration. While the distribution of tractors is relatively uniform across all regions, the central and northern districts demonstrate a higher level of equipment use. There is a noted deficiency in machinery for the mechanization of other agricultural operations, such as sowing, spraying, harvesting, and threshing [31]. These districts provide a solid foundation for evaluating service models across diverse topographical and climatic contexts (Fig. 1).

Mechanization strategy

The government of Cote d'Ivoire, through its National Rice Development Strategy (SNDR) and the National Rice Development Agency (ADERIZ), is actively promoting Agricultural Small and Medium Enterprises (SMEs) to provide mechanization services to smallholder rice farmers. This strategy prioritizes affordability, scale appropriateness, and engagement with the private sector. Agricultural SMEs are selected through a competitive process based on criteria such as operational capacity, legal status, technical capability, and economic viability. ADERIZ supplies machinery under a concession model, with ownership transferred after 3–5 years upon loan repayment. SMEs operate within a 75 km radius and adhere to service pricing models regulated by ADERIZ.

Agricultural calendar and operational framework

Mechanized operations within the study districts adhere to a structured agricultural calendar that corresponds with both irrigated

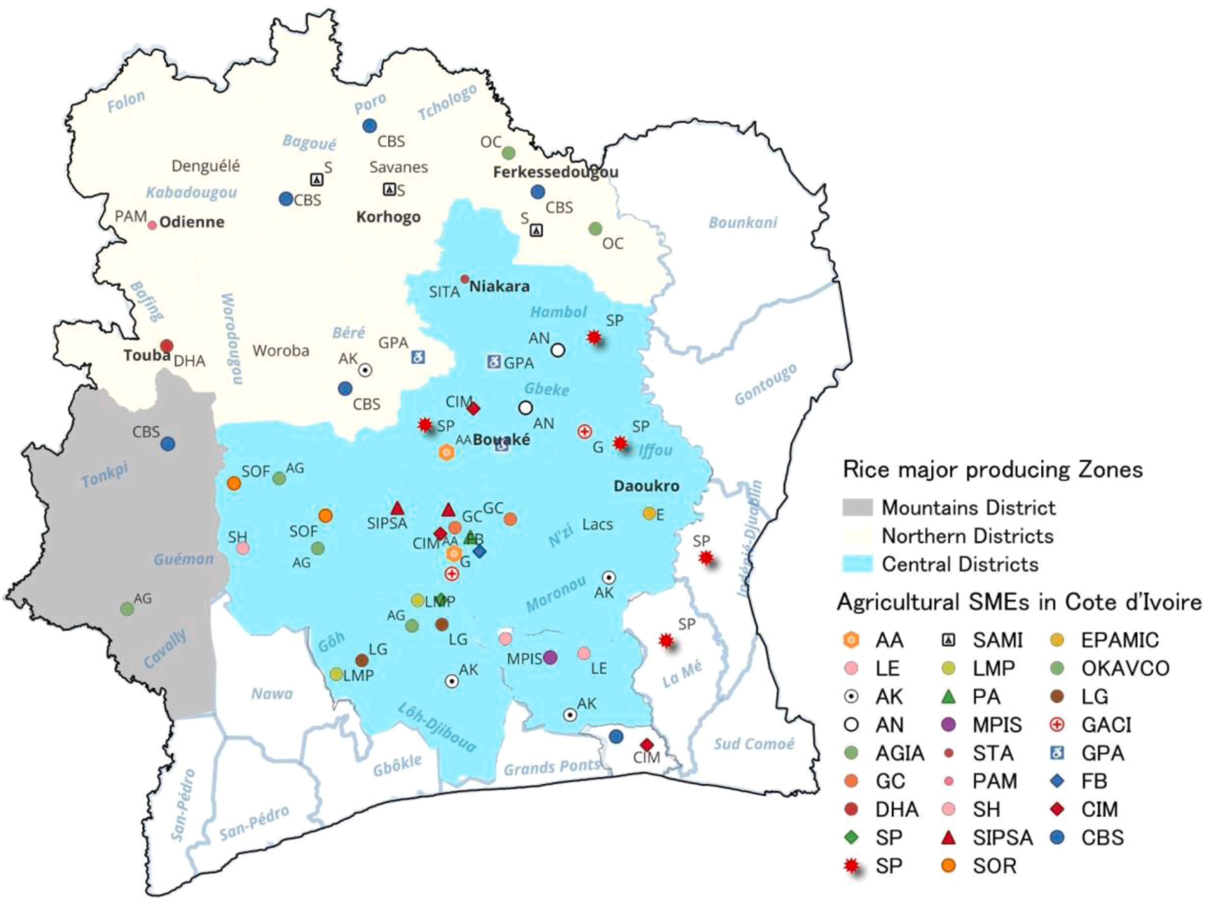

Fig. 1. Geographical distribution of the 26 agricultural SMEs providing mechanization services across Cote d'Ivoire's agro-climatic and soil conditions.

and upland rice cultivation cycles, thereby ensuring optimal utilization of machinery throughout the year (Supplementary material Cost_Calculations.xlsx, Worksheet_10). Farmers in Cote d'Ivoire typically do not conform to a standardized working week, as observed in formal employment sectors. Their labor patterns are highly seasonal and influenced by agricultural cycles, climatic conditions, and crop-specific demands. During critical periods, such as land preparation, planting, or harvesting, farmers frequently work six days per week. In the Mountains District, where there is a single annual crop cycle, mechanization is limited because of the presence of terraced fields. For irrigated lowland rice, land preparation commences between February and April, utilizing small tractors for plowing and puddling (power tillers). Harvesting operations, which employ handheld tools, occur between September and October, followed by threshing (threshers) until November. Upland rice in this region follows a similar pattern but relies more heavily on manual land preparation than lowland rice.

In the Central districts, where two annual cropping cycles are practiced, irrigated lowland fields employ high levels of mechanization. The cycles commence with land preparation, utilizing power tillers or tractors equipped with rotary cultivators, during November-December and May. Harvesting and threshing are conducted using combine harvesters or reapers in April and October-November, with threshers employed following reaper usage in April-May and October-December. In contrast, rainy upland fields rely on manual land preparation in April-May, whereas rainy lowland fields are partially mechanized, employing tractors with plows and disk harrows in May. For harvesting, combine harvesters or reapers are utilized in rainy lowland fields during October-November, whereas handheld methods are employed in rainy upland fields. Threshing occurs between October and December. Two annual cropping cycles were also observed in the northern districts. Irrigated lowland fields are fully mechanized. The cycles begin with land preparation using power tillers or tractors with rotary cultivators in November-December and May-June. Harvesting and threshing are executed using combine harvesters or reapers in April and October-November, with threshers following reaper usage in April-May and October-December. Rainy upland fields utilize ox-drawn plows in April-May, whereas rainy lowland fields are mechanized with tractors equipped with plows and disk harrows in May. For harvesting, combine harvesters or reapers are employed in rainy lowland fields during October-November, whereas handheld methods are used in rainy upland fields. Threshing is conducted between October and December.

Sampling frame

The sampling frame for this study consisted of a comprehensive list of all agricultural SMEs officially registered and supported by the National Rice Development Agency (ADERIZ) as of 2023. This list, provided by ADERIZ, included detailed information on each SME's location, operational capacity, and machinery inventory, serving as the definitive population for our selection process.

Sample selection

Selection of SMEs locations

From the sampling frame, a purposive sampling method was employed to select 26 agricultural SMEs located across key rice-producing districts, including the Northern, Central, and Mountains districts. A significant concentration of these SMEs is found in the central districts, attributed to their favorable agroclimatic conditions for rice cultivation (Fig. 1). The selection process was informed by ADERIZ's operational records and insights from the PRORIL Project. These SMEs encompass a range of agroecological and

Table 1
Custom Charge per hectare for various mechanization services in the districts of Cote d'Ivoire.

District	Operation	Machine	Applied Custom Charge ($/ha)
Northern District	Plow	Tractor 33.5 kW + plow 02 disks 26″	68
	Harrowing	Tractor 33.5 kW + disk harrow 18 disks	59
	Puddling	Tractor 33.5 kW + rotovator	118
	Harvesting	Combine harvester	118
	Harvesting	Mini-Combine Harvester	101
	Threshing	Thresher	76
Central districts	Plow	Tractor 33.5 kW + plow 02 disks 26″	68
	Harrowing	Tractor 33.5 kW + disk harrow 18 disks	59
	Puddling	Tractor 33.5 kW + rotovator	152
	Harvesting	Combine harvester	203
	Harvesting	Mini-Combine Harvester	169
	Threshing	Thresher	76
	Harvesting	Reaper	59
	Puddling	Power tiller	72
District of Mountains	Puddling	Tractor 33.5 kW + rotovator	118
	Harvesting	Mini-Combine Harvester	101
	Threshing	Thresher	76
	Harvesting	Reaper	42
	Puddling	Power tiller	59

Source: ADERIZ records. Custom charges are standardized to align with national cost benchmarks, including fuel, labor, and depreciation, while being adjusted for regional operational variations, such as higher fuel costs in mountainous areas.

operational contexts. The dataset comprises firm-level machinery inventories, service area coverage, and annual performance metrics of the firms.

SMEs operations and service portfolio

These Small and Medium Enterprises (SMEs) typically manage five to seven machines, including two tractors, one combine harvester, and two threshers. They cover an area of 800–1200 hectares annually and provide services to 150–250 farmers, each with average plot sizes ranging from 1.5 to 3 hectares. The services offered encompass plowing, threshing, harvesting, and, in certain instances, transportation [32]. The challenges faced by these SMEs include machine maintenance, delayed payments, and constraints in regional price adjustments, despite the existence of centralized pricing (Table 1).

Data collection

Primary data collection encompassed structured interviews, demonstrations of machine operations, and financial audits conducted under ADERIZ supervision. Secondary data were sourced from reports by ADERIZ and PRORIL, which included information on machinery specifications, regional fuel and labor costs, and maintenance schedules. Triangulation was used to validate the economic indicators. Comprehensive details of all cost components and operational parameters are provided in the supplementary material Cost_Calculations.xlsx. Worksheets 1–9 delineate the characteristics of the power tiller, paddy reaper, thresher-winnower, disk plow, rotovator, disk harrow, combine harvester, row seed drill, and mini combine harvester, respectively.

Economic assessment

This study employs a break-even analysis, a standard financial tool for determining business viability. This methodology integrates both a cost approach, by quantifying the fixed and variable costs associated with machinery operation (Sections 2.4.2, 2.4.3), and an income approach, by evaluating the revenue generated from custom charges (Section 2.4.5) [33,34]. This dual approach is standard practice in agricultural mechanization economics, facilitating the identification of minimum operational scales for profitability [11, 12]. All cost and revenue variables were calculated using real operational data from SMEs service providers, and empirical validation was performed by triangulating primary survey responses with ADERIZ administrative records and published data from similar mechanization studies in West Africa [5]. The core break-even formulas used align with those proposed by Kadhim et al.(2018) and adapted for context by Houssou et al. [12,34]. The economic evaluation of integrating agricultural machinery into smallholder and paddy farming systems necessitates an approach that considers both costs and benefits over time. This evaluation is crucial for assessing the impact of the mechanization strategy currently implemented in Cote d'Ivoire. This study utilized breakeven analysis techniques, encompassing total costs (fixed and variable), income or custom charges, and profit [33,34] of mechanization services offered by agricultural SMEs across the Northern, Central, and Mountains districts. The break-even analysis assesses the districts' profitability and sustainability regarding machinery adoption and demonstrates whether investments in agricultural machinery, such as tractors, seed drills, and harvesters, would yield positive returns.

Machinery capacity and covered area

The machinery capacity is the maximum output the machine can produce under optimal conditions, and it is calculated based on the duration of life or maximum operating hours. Covered area (CA) is the cultivated area per year under real-world conditions, such as Effective Field Capacity (EFC) directly measured on the field, the net work hours, and the available working days (Supplementary material *Cost_Calculations.xlsx*, Worksheet_10, Table_SM10, Worksheet_11, Table_SM11). The formula for CA is expressed as Eq. (1):

$$CA = \frac{EFC \times Dn \times AWD}{N} \tag{1}$$

where CA is the covered area (ha), EFC is the Effective Field Capacity (ha hr^{-1}), Dn is the net work hours per day (h d^{-1}), AWD is the available Work Days (d), and N is the number of operation times.

Fixed costs

Fixed costs are expenses that do not vary with the level of machine usage. These costs are incurred regardless of whether the machine is operated or not. The annual fixed costs (AnFC) are calculated as the sum of depreciation, taxes, garage costs, insurance fees, interest, and repair costs. These costs represent the baseline financial burden that the agricultural SMEs must support even if the machine is not in active operation (Supplementary material *Cost_Calculations.xlsx*, Worksheet_11, Table_SM12). The formula for AnFC is expressed as Eq. (2):

$$AnFC = AD + AT + AG + AP + AI + AM \tag{2}$$

where AnFC represents the annual fixed costs (\$ yr^{-1}), AD is the annual depreciation (\$ yr^{-1}), AT represents the annual taxes (\$ yr^{-1}), AG is the annual garage cost (\$ yr^{-1}), AP is the annual insurance fee (\$ yr^{-1}), AI is the annual interest (\$ yr^{-1}), and AR is the annual maintenance cost (\$ yr^{-1}).

Variable costs

Variable costs are directly related to the operational hours available for the agricultural calendar in each district [36] (Supplementary material *Cost_Calculations.xlsx*, Worksheet_11, Table_SM13). The annual variable costs (AnVC) are calculated using Eq. (3):

$$AnVC = (VFh + VRh + VLh + VWh + VOh) \times Dn \times AWD \tag{3}$$

where AnVC is the annual variable cost ($), VFh is the fuel cost per hour ($\$.hr^{-1}$), VRh is the repairing cost per hour ($\$.hr^{-1}$), VLh is the lubricant cost per hour ($\$.hr^{-1}$), VWh is the labor cost per hour ($\$.hr^{-1}$), VOh is the overhead cost per hour, Dn is the net working hour per day (h), and AWD is the available working day per year (d).

The types of breakdowns encountered requiring repair vary depending on the machinery, equipment, farming practices, soil conditions, and operator expertise. Tractors and power tillers frequently experience engine-related issues, such as diesel leaks in fuel lines or injector pipes, oil leaks in the crankcase or gearbox, gearbox or hydraulic lift failures, seized connecting rods, diesel pump malfunctions, and power loss due to worn piston rings. Threshers and combine harvesters commonly face transmission and engine problems. Reapers often deal with broken cutting bars and transmission failures. Attachments or implements (e.g., plows, harrows) frequently suffer from broken hitching devices, damaged plow discs, and worn or failed bearings. Harsh working conditions, such as stumps, stones, and uneven terrain, lead to frequent tractor tire punctures. For power tillers, common issues include broken or lost tiller blades, leaks in the rotor's transmission chain, and broken anchoring legs on cage wheels. These constatations highlight how breakdown patterns differ across machinery types, influenced by operational demands and environmental factors [35].

Total costs

The total annual cost (AnTC) represents the cost of managing the machinery, including fixed and variable costs. This metric is relevant for agricultural SMEs because the annual operation area must be sufficient to cover the total annual costs and ensure profitability (Supplementary material Cost_Calculations.xlsx, Worksheet_12, Table_SM14). The equation for ATC is expressed in Eq. (4):

$$AnTC = AnFC + AnVC \tag{4}$$

where AnTC is the annual total cost ($\$\ yr^{-1}$), AnFC is the annual fixed cost ($\$\ yr^{-1}$), and AnVC is the annual variable cost ($\$\ yr^{-1}$).

Custom charge

The annual custom charge (ACC) is derived from the custom charge rate per hectare multiplied by the covered area. This metric provides the total revenue generated from mechanization services over a year (Supplementary material *Cost_Calculations.xlsx*, Worksheet_12, Table_SM14). The equation for ACC is Eq. (5):

$$ACC = CC \times CA \tag{5}$$

where CC is the custom charge per ha ($\$\ ha^{-1}$), ACC is the annual custom charge ($), and CA is the covered area per year (ha).

Table 2
Different costs and revenues per year per machine in each district.

DISTRICT	MACHINE	Covered Area (ha)	Annual fixed cost ($)	Annual Variable cost	Annual Total Costs	Annual Custom Charge
Mountains District	Power tiller	30.8	2690	3211.84	5902	3642
	Tractor 33.5 kW + Rotovator	77	5041	7057.05	12,098	9086
	Mini-Combine Harvester	62.4	5442	4543.55	9986	6302
	Reaper	41.6	2306	1761.30	4067	1757
	Thresher	62.4	2306	3747,37	6053	4743
Central districts	Power tiller	41.6	2690	4338.07	7028	5973
	Reaper	62.4	2306	2641.95	4948	3689
	Thresher	104	2306	6245.61	8552	7906
	Tractor 33.5 kW +plow 02 disks 26″	52	5176	2382.90	7559	3514
	Tractor 33.5 kW+ Rotovator	104	5041	9531.60	14,573	15,808
	Tractor 33.5 kW +disk harrow 18 disks	104	9175	2442,20	11,618	6149
	Combine harvester	234	21,031	18,807.64	39,839	47,433
	Mini-Combine Harvester	62.4	5442	4543.55	9986	10,546
Northern districts	Thresher	104	2306	6245.61	8552	7906
	Tractor 33.5 kW +plow 02 disks 26″	52	5176	2382.90	7559	3514
	Tractor 33.5 kW + Rotovator	52	5041	4765.80	9807	6136
	Tractor 33.5 kW +disk harrow 18 disks	104	9175	2442,20	11,618	6149
	Combine harvester	234	21,031	18,807.64	39,839	27,669
	Mini-Combine Harvester	62,4	5442	4543.55	9986	6302

Break-even point

The break-even point is the point at which the cost equals the customer charge. This point is the turning point of loss and gain. The custom charge must be at least higher than the variable cost per hectare; otherwise, the loss will increase. Additionally, in case the break-even point area is higher than the covered area or the limit of capacity of the machine, the activity is not viable (Supplementary

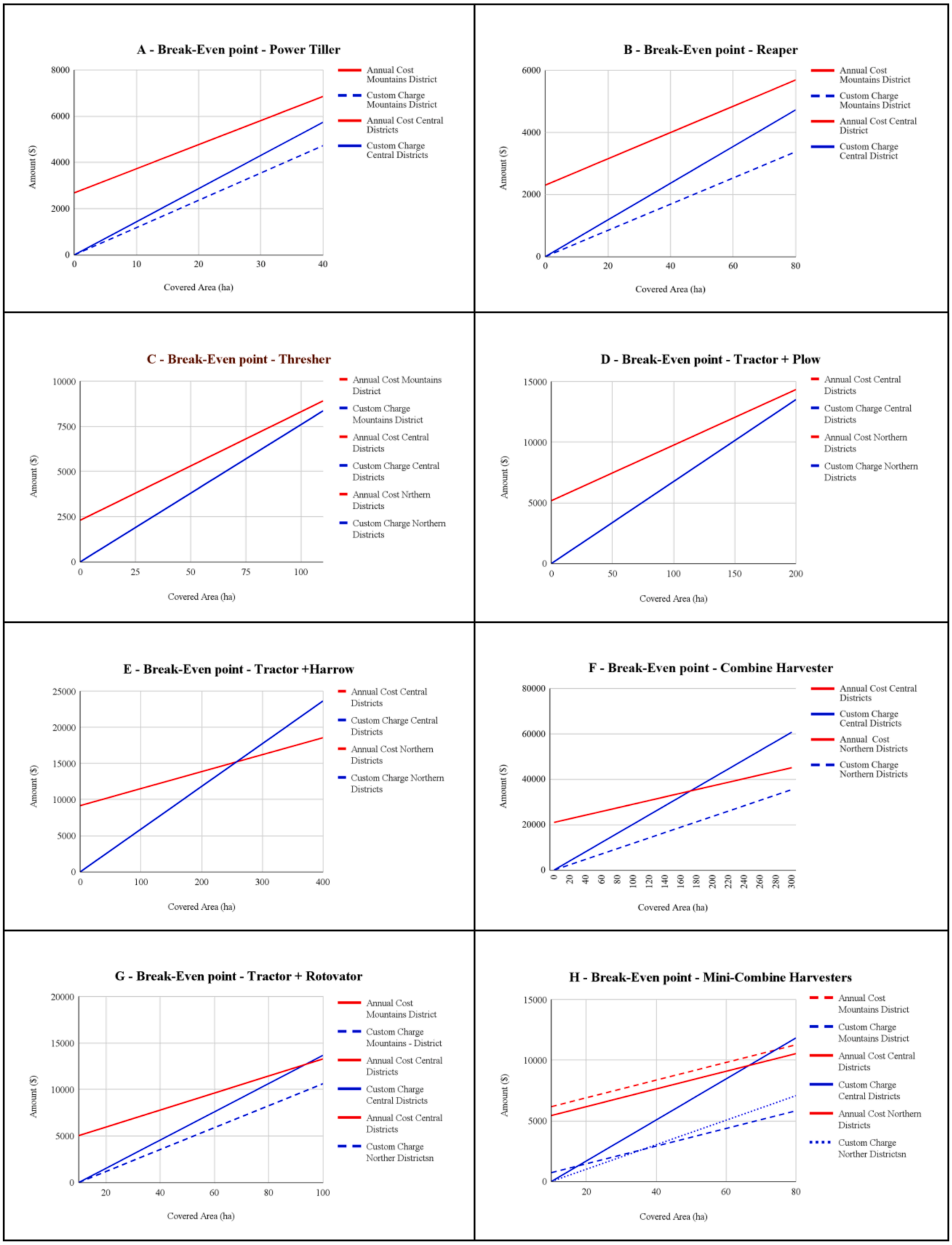

Fig. 2. Comparison of break-even point areas across the Mountain, Central, and Northern districts.

material *Cost_Calculations.xlsx*, Worksheet_12, Table_SM15). The break-even points are calculated using Eqs. (6) and (7):

$$Abp = \frac{AnFC}{(CC - VCa)} \quad (6)$$

$$Sbp = \frac{AnFC \times CC}{(CC - VCa)} = Abp \times \ CC \quad (7)$$

where Abp is the break-even point area (ha yr^{-1}), AnFC is the annual fixed cost (\$ yr^{-1}), CC is the custom charge per ha (\$ ha^{-1}), VCa is the variable cost per ha (\$ ha^{-1}), and Sbp is the break-even point of sales (\$).

Results

Costs and revenues calculation results

Based on the determination of the covered area for each machine used in the different Cote d'Ivoire districts' conditions, fixed and variable costs necessary for the break-even analysis were calculated (Supplementary material *Cost_Calculations.xlsx*, Worksheet_12, Table_SM14) and summarized in Table 2. The examination of the annual costs and revenues for various types of machinery across the Mountains, Central, and Northern districts of Cote d'Ivoire revealed significant disparities in economic performance influenced by both geographical location and equipment type. In the Mountains District, all machinery types operated below their economic break-even point, with annual revenues insufficient to cover the total costs. For instance, power tillers generated an annual custom charge of \$3642 but incurred total costs of \$5902, resulting in an operational loss exceeding \$2260 per year. Similarly, mini combine harvesters and threshers recorded deficits of \$3684 and \$1310 per year, respectively, with reapers exhibiting the largest negative margin relative to their size, with an annual loss of \$2310. The persistently negative margins in this region are attributed to the limited covered area, high per-unit fixed costs, and elevated logistical and fuel expenses. In the Central Districts, performance varied more, with some machines achieving profitability while others remained unviable. Combine harvesters emerged as the most profitable investment, with an annual revenue of \$47,433 against total costs of \$39,839, yielding a substantial profit of \$7595 and a margin of approximately 19 %. Tractors with rotovators also achieved a positive outcome, with a modest yet significant profit of \$1235, reflecting a profit margin of approximately 8 %. Conversely, power tillers, reapers, and thresher units typically operated near or below the break-even point, and tractors with plows and disk harrows continued to struggle because of high fixed costs relative to the covered area. Notably, the mini-combine harvester in this region narrowly surpassed the break-even point, achieving a modest profit of \$560 annually. In the Northern Districts, nearly all types of machinery failed to achieve profitability, with total costs consistently surpassing revenues. For instance, combine harvesters incurred an annual loss exceeding \$12,169, primarily due to high fixed and variable costs coupled with lower demand density. Tractors equipped with rotovators and mini-combine harvesters reported losses ranging from \$3671 to \$3684 per year. Only the threshers approached a break-even point; however, they still operated at an annual deficit of \$646. The limited operational days and sparse field distribution in this region are the principal factors undermining economic viability. Across all regions, the findings underscore that profitability is highly sensitive to both the machinery type and regional context. High-capacity machines, such as combine harvesters, can be profitable when deployed in favorable agroecological zones with consolidated demand, as observed in the central districts. In contrast, smaller-scale machines and those in marginal areas consistently underperformed, highlighting the importance of context-specific investments and pricing strategies.

Break-even analysis

The results of break-even point analysis show that reapers (Fig. 2B) in the Mountains District leads the agricultural SMEs to deepen their loss without any possibility to make profit by increasing their covered area. The custom charge is less than the variable cost per hectare, signaling unmanageable variable costs under current pricing models. High fuel and repair costs render the machines economically unfeasible.

However, for power tillers across all districts (Fig. 2A), reapers in the central districts (Fig. 2B), threshers across all districts (Fig. 2C), tractors with plows across all districts (Fig. 2D), tractors with harrows across all districts (Fig. 2E), combine harvesters in Northern districts (Fig. 2F), tractors with rotovators in the Mountains districts and Northern districts (Fig. 2G), and mini-combine harvesters in Mountains districts and Northern districts (Fig. 2H), the respective break-even point areas are higher than the covered area. It shows that these machines face viability challenges due to narrow seasonal demand and high annual fixed costs due to elevated logistics costs (including fuel and maintenance) coupled with a sparse demand density due to fragmented demand and less consolidated agricultural plots, which calls for the implementation of land consolidation policies.

In Central districts, tractors with rotovators (Fig. 2G), combine harvesters (Fig. 2F), and mini-combine harvesters (Fig. 2H), the break-even point area is achievable within the covered area. These machines thrive in Central districts' consolidated plots. They demonstrate high profitability, boasting respective margins of 8 %, 19 %, and 6 %, and the success can be attributed to favorable conditions such as bimodal rainfall patterns, well-maintained road infrastructure, the presence of irrigated fields, the existence of large, consolidated plots (greater than 5 hectares), and concentrated demand within the districts, all of which facilitate the optimal use of machinery.

The analysis reveals significant disparities in break-even points across various districts, primarily influenced by agro-ecological constraints, differences in farm structures, and variations in infrastructure.

Several factors influence the operational effectiveness and financial viability of machinery in different districts: Mechanical breakdowns and fuel shortages significantly raise variable costs and delay the achievement of break-even points. In addition, payment delays strain the cash flows of agricultural SMEs, restricting their ability to manage fixed costs effectively. The rugged terrain in mountainous areas diminishes the efficiency of heavy machinery. Moreover, the dry seasons in the Northern districts limit the number of available working days for rice cultivation. A lack of repair hubs in the Northern and Mountains districts prolongs machinery downtime, while poor rural roads in the Northern districts reduce field accessibility, further complicating operational effectiveness [31].

Profitability analysis by machine type and district

The analysis of profitability across various districts and machinery types revealed significant disparities in economic outcomes, primarily influenced by variations in custom charge rates, machine utilization, and cost structures (Fig. 3). Profitability is not uniform; rather, it is contingent upon both the district and machine type, with only a limited number of combinations yielding sustainable returns. The central districts exhibited the highest potential for profitable mechanization services. Notably, combine harvesters in this region achieved superior performance, generating an annual profit of $7594, which corresponds to a profit margin of 19 %. This favorable outcome was facilitated by a high custom charge ($203/ha), near-optimal utilization (78 % of capacity), and sufficient demand to offset substantial fixed costs ($21,031/year). Similarly, tractors equipped with rotovators realized a profit of $1235 (8 % margin), although this was accomplished by exceeding the machine's recommended annual capacity (104/100 ha), indicating a potential risk of future maintenance issues due to overuse of the machine. In contrast, the profitability landscape in the Northern and Mountains districts was considerably less favorable. Machines in these regions, including mini-combine harvesters, threshers, and tractors, consistently fail to cover their annual costs, resulting in persistent operational losses. For instance, the combine harvester in the Northern district incurred a significant annual loss of over $12,000, despite high fixed costs like the Central district, primarily due to lower custom charges and under-utilization. The reaper in the Mountains District was particularly unviable, with a low custom charge ($42/ha) and negative profit margins.

The primary factors influencing these outcomes were evident: elevated profit margins were closely linked to premium custom charge rates and high utilization levels, particularly in regions characterized by consolidated farm plots and a concentrated demand for mechanization. Conversely, negative margins were predominantly observed in contexts where custom charges were suppressed, machine utilization was low, or fixed costs were disproportionately high relative to the area covered. Machines such as mini-combine harvesters and tractors equipped with disk harrows, especially in less favorable regions, necessitate either enhanced marketing, relocation to zones with higher demand, or an increase in the custom charge to achieve break-even status. Although some machines (e.g., the mini-combine harvester in the Central district) narrowly surpassed their break-even thresholds, most machinery types outside the optimal districts remain economically unsustainable. For instance, tractors with disk harrows in both the Central and Northern districts, despite incurring relatively low variable costs ($23.48/ha), experienced profitability erosion due to high fixed costs ($9175/year) and low utilization rates (as low as 26 %).

The findings of this study yield several key recommendations for future research. First, it is advisable to prioritize investment in combine harvesters and tractors equipped with rotovators in the central districts, where conditions are most favorable for profitability. Second, consideration should be given to increasing custom charges for machinery that consistently operates at a loss, such as reapers in the Mountains District. Third, resource optimization should be encouraged by enhancing the utilization rates of underutilized machines or reallocating them to regions with higher demand. Fourth, efforts should be made to negotiate or reduce fixed costs for high-burden machinery, potentially by adopting lower-cost brands or models with similar capacities. A one-way ANOVA was conducted to statistically evaluate the observed differences. The results indicate a marginally significant effect of district on profitability (*F*

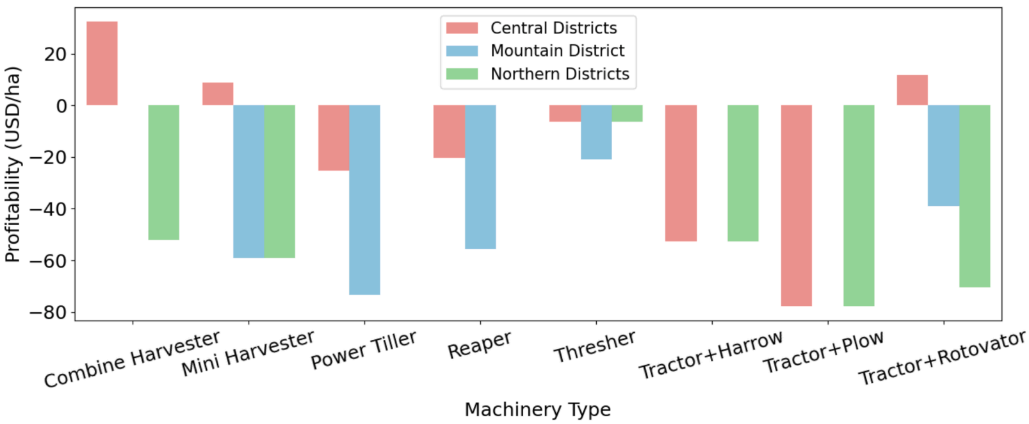

Fig. 3. Profitability by machinery type across the Mountains, Central, and Northern districts. Combine harvesters, mini harvesters, and tractors with rotovators show efficient performance in the Central districts. The rest of the machinery shows persistent losses across districts.

= 3.36, $p = 0.06$), suggesting that regional context may influence financial outcomes, although the difference does not meet conventional significance thresholds. Post-hoc analysis using Tukey's Honest Significant Difference (HSD) test revealed that the Central and Northern districts exhibited the largest mean difference in profitability (–$36.94/ha, $p = 0.08$), supporting the trend that the Central districts are more profitable (Fig. 4). The differences between the Central and Mountains districts ($p = 0.14$) and between the Mountains and Northern districts ($p = 0.98$) were not statistically significant, indicating a broad overlap in less favorable regions.

Factors influencing profitability across districts

Although ANOVA did not identify statistically significant differences in profitability across districts, the considerable variability among service providers suggests the impact of underlying operational and contextual factors. To further investigate these determinants, multivariate linear regression was performed to evaluate the combined effects of machinery type, hectares serviced, and number of operational days on SMEs profitability. The regression model accounted for approximately 58 % of the variation in profitability outcomes ($R^2 = 0.577$), indicating that these factors collectively exerted a substantial, albeit not entirely predictive, influence. Nevertheless, the model as a whole was not statistically significant ($F = 1.366$, $p = 0.325$), primarily due to the limited sample size and the high heterogeneity in the operational contexts. Analysis of the regression coefficients and partial effect plots (Fig. 5) revealed several notable trends in the data. SMEs utilizing mini-combine harvesters and tractors with rotovators tended to achieve profitability at or above the baseline (established by combine harvesters), although these differences were not statistically significant. In contrast, power tillers, tractors with harrows, and tractors with plows were associated with consistently lower or negative profitability, corroborating earlier findings regarding their limited economic viability under current market and operational conditions.

The analysis further underscores the significance of the operational scale. Both the hectares serviced and the number of active operational days exhibited positive correlations with profitability, with extended periods of machine utilization demonstrating particularly pronounced upward trends. This indicates that optimizing asset utilization, either by prolonging the service season or consolidating demand, can substantially enhance the financial outcomes of SMEs. However, the impact of servicing additional hectares was less consistent, suggesting that merely expanding area coverage without adequate demand density or logistical support may not necessarily lead to increased profits. Although no single predictor was a statistically significant determinant, the collective evidence highlights the importance of both machine selection and operational efficiency. Specifically, investments in threshers, mini-harvesters, and tractors equipped with rotovators, coupled with strategies to maximize active service days, hold the greatest potential for enhancing profitability. These findings emphasize the necessity of tailored machinery promotion and business support services, rather than a uniform approach, to bolster the viability of SMEs mechanization service providers across Cote d'Ivoire's diverse agro-ecological zones.

Discussions

Interpretation of key findings

The findings of this study reveal important trends in the operational and financial performance of agricultural SMEs providing mechanization services in Cote d'Ivoire. Among the three agroecological zones analyzed, the Central districts demonstrated the highest profitability, with SMEs achieving more operational days and more efficient use of machinery, particularly combine harvesters. This superior performance is attributable to Central districts' bimodal rainfall pattern, better road infrastructure, and greater access to irrigated fields, consistent with observations from Takeshima and Birner et al. [29,37]. In contrast, the Northern districts exhibited the lowest profitability, primarily due to harsher dry season constraints, limited irrigation infrastructure, and higher logistical costs, confirming trends reported by Houssou and Chapoto [38].

Machinery-specific performance also followed clear patterns. Combine harvesters achieved the highest profit margins across all

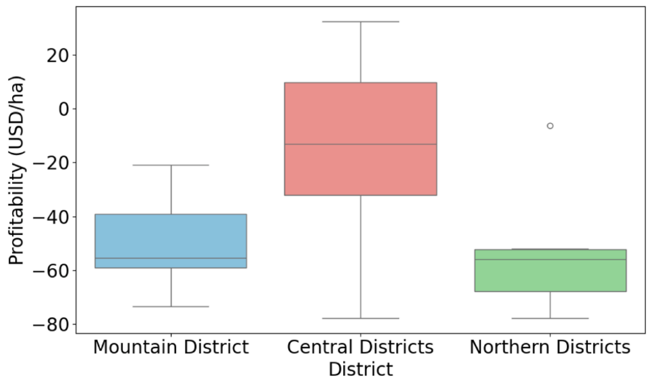

Fig. 4. Distribution of profitability (USD/ha) across Mountain, Central, and Northern districts. Although not statistically significant, the Central districts show the highest variability and median profitability, indicating potential regional performance advantages.

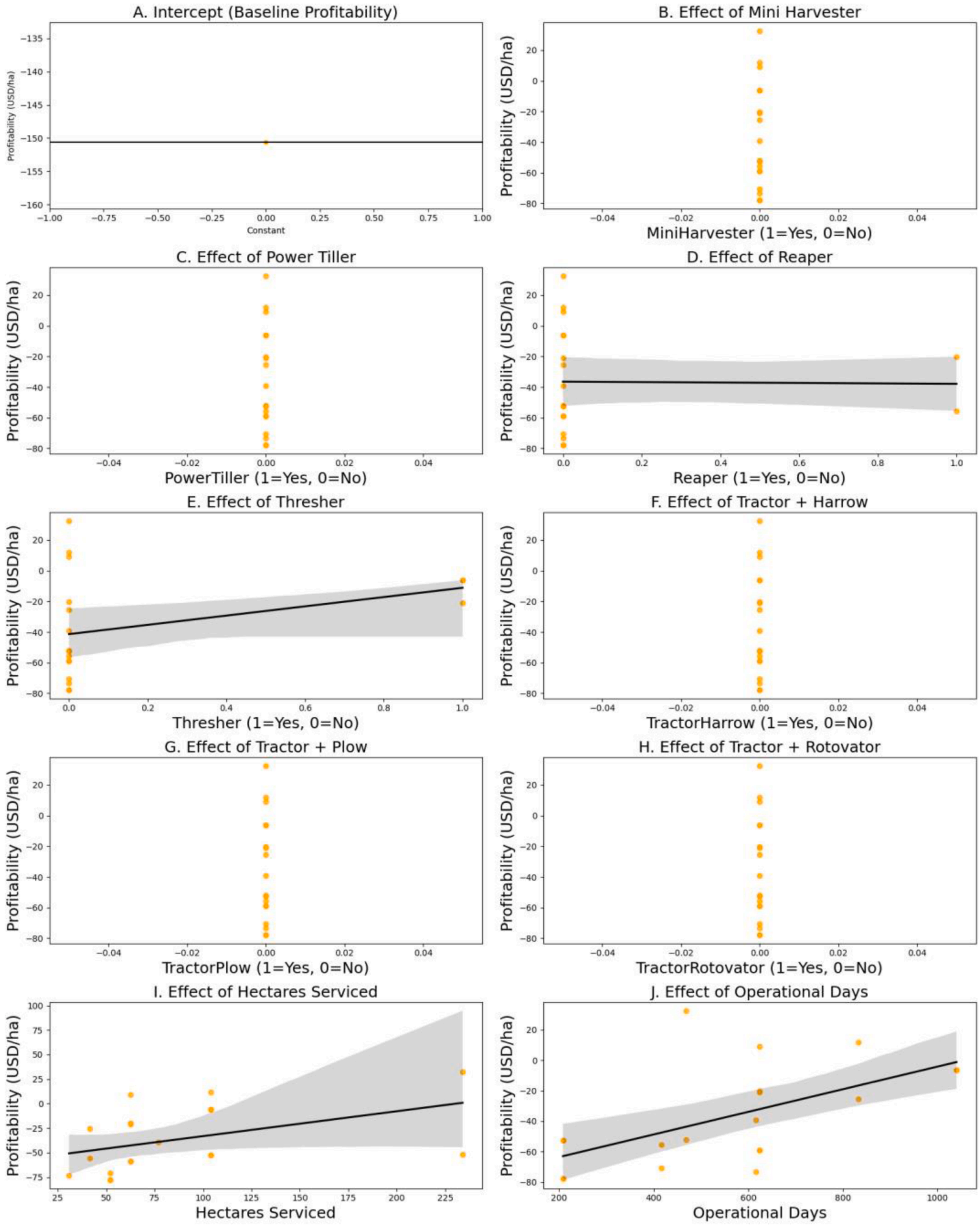

Fig. 5. Partial regression plots illustrating the individual effects of key predictors on SMEs profitability (USD/ha) in rice mechanization services across Cote d'Ivoire. Panel A represents the baseline profitability (intercept) for SMEs using the reference machine type (combine harvester). Panels B–H show the relative effects of using alternative machinery types, including Mini Harvester, Power Tiller, Reaper, Thresher, Tractor + Harrow, Tractor + Plow, and Tractor + Rotovator, respectively. Panels I and J depict the continuous effects of hectares serviced and operational days on profitability. Shaded regions indicate 95 % confidence intervals.

regions, supporting findings from Daum and Birner (2020) that highlight their strategic role in mechanization-driven yield increases [9]. Tractors and rotovators with high productivity, instead of power tillers with their impracticality for operators, were the second-most profitable, reflecting their vital land preparation role in irrigated conditions, where rice can have high potential yield [13, 26]. Conversely, power tillers and reapers displayed the least profitability due to narrow operational niches and competition from manual labor, a limitation similarly noted by Kienzle et al. [11].

A significant gap between theoretical and field-level outcomes was observed. SMEs faced a 10–15 % increase in the hectares needed to break even compared to ideal conditions. This discrepancy arises from a combination of climatic disruptions, mechanical downtimes, fuel shortages, and inconsistent farmer demand [30,39]. Moreover, factors such as terrain difficulty in the Mountains District and infrastructural underdevelopment in the Northern districts exacerbated inefficiencies [14,15].

The regression analysis further confirmed that larger service areas and the use of combine harvesters positively impacted profitability, in line with studies by Mrema et al. and Houssou et al. [10,12], which emphasized scale economies in mechanization. Regional advantages, especially in Central districts, underline the critical importance of agro-ecological suitability and infrastructure quality [13,27].

The results substantiate that while mechanization offers substantial potential for improving agricultural productivity and rural incomes, its success heavily depends on aligning machinery investments with local agro-ecological realities, scaling operations appropriately, and ensuring supporting services like maintenance and operator training are available [17,24].

Comparison with existing literature

The findings of this study align closely with several recent works on mechanization dynamics in Sub-Saharan Africa. Similar to Pingali et al. (2019), the results confirm that scale-appropriate mechanization models operated by SMEs can be economically viable, particularly when tailored to regional agro-ecological realities [13]. The higher profitability of combine harvesters in Central districts supports Adu-Baffour et al. (2019), who emphasized that mechanization services oriented toward bottleneck operations, such as harvesting, yield the most rapid returns [23]. Moreover, the observed profitability advantage in irrigated systems mirrors insights from Takeshima, Sims and Kienzle [22,30], who highlighted irrigation access as a critical enabler of mechanization success [22,30].

However, the study also reveals some nuanced departures from previous literature. While Daum and Birner (2017) advocated for the transformative potential of mechanization across diverse contexts, this study illustrates that without addressing infrastructural and logistical barriers, regions like Northern districts may continue to experience mechanization bottlenecks despite machinery access [17]. Similarly, whereas Mrema et al. [10] reported strong potential for tractors to drive scale efficiencies, our results show that, apart from tractors and rotovators for land preparation in irrigated systems with better profitability, tractor-based services showed only moderate profitability compared to combine harvesting or threshing due to higher maintenance and operating costs in field realities [10].

Contrary to Houssou et al. [12], who suggested relatively uniform mechanization outcomes across regions under standardized programs, this study underscores pronounced regional disparities requiring context-specific strategies. Furthermore, Onwude et al. (2018) stressed the centrality of post-harvest mechanization (threshing), a finding confirmed here with combine harvesters, with their double function of harvesting and threshing emerging as a consistently profitable machinery category [12,26].

Overall, while the general trajectory of findings confirms key patterns in the recent mechanization literature, the study uniquely contributes by quantifying the real-world gaps between theoretical and achieved operational performance, emphasizing the urgent need for regionally adapted business models and public policy support. This layered understanding complements recent calls by Pingali et al. and Otsuka et al. [13,27] for nuanced, ecosystem-based mechanization pathways that account for local infrastructural, climatic, and market realities [13,27].

Practical implications

For agricultural SMEs, investment decisions should prioritize combine harvesters and tractors with rotovators, which demonstrated the highest profitability across regions. These machines address critical bottlenecks in the rice value chain [23,40]. SMEs should also consider maintaining a balanced fleet that includes tractors for land preparation, as diversified service offerings increase resilience to seasonal demand fluctuations [9].

Maintenance practices and operator training are essential factors influencing machinery efficiency and economic sustainability. Regular preventive maintenance can significantly reduce machine downtime [12,13]. Operator proficiency, particularly for complex equipment like combine harvesters, directly impacts effective field capacity and service reliability, reinforcing the conclusions of Kienzle et al. and Onwude et al. [11,26].

For policymakers, the need for decentralized repair and maintenance hubs is critical, particularly in underserved regions like Northern and Mountains districts, where logistical delays inflate operational costs [14,15]. Establishing such hubs would align with strategies proposed by Takeshima (2017) and promote sustainable machinery utilization [37]. Expanding financial access through leasing models, concessional loans, and microcredit facilities is vital for enabling SMEs to scale operations sustainably. Experiences from Kenya and Ghana documented by Biggs et al. and Takeshima et al. demonstrated that tailored financial instruments can significantly accelerate mechanization adoption [18,39].

Finally, district-specific mechanization strategies should be developed, recognizing the diverse agro-ecological and infrastructural realities across Cote d'Ivoire. Central districts, with their high potential for two cropping cycles, could benefit from expanded combine harvester fleets, whereas Northern districts might prioritize rugged, low-maintenance machinery and repair support. This approach advocates for ecosystem-adapted mechanization interventions [27,30]. These practical implications underscore the necessity of coordinated action between SMEs, government agencies, financial institutions, and development partners to foster an inclusive, resilient, and economically viable mechanization sector.

Challenges and limitations

Despite the encouraging findings, several operational and methodological challenges constrain the broader scalability of mechanization service provision models in Cote d'Ivoire. Operationally, SMEs frequently faced fuel shortages, especially during peak agricultural seasons, leading to unplanned service interruptions [9,24]. In addition, delays in the availability of spare parts, particularly for imported combine harvesters and tractors, extended machinery downtime and increased operational costs [13,40]. Payment lags from farmers, often exceeding 60 days post-service, strained SMEs' cash flows, demonstrating challenges documented by Houssou et al. and Diao et al. [12,15].

Another critical challenge was the insufficient availability of certified mechanics and trained operators, particularly in more remote areas like the Northern and Mountains districts. This limitation reduced the reliability and longevity of mechanization services [18, 28]. Moreover, logistical inefficiencies, including poor rural road networks, further compounded costs and reduced service area accessibility [14,27].

Methodologically, this study is limited by its sample size, encompassing only 26 SMEs in the Central districts area, which may not capture the full spectrum of operational heterogeneity across Cote d'Ivoire. This constraint aligns with similar limitations acknowledged in localized mechanization studies [11,26]. Additionally, the study relied on a single-year data collection period (January–December 2023), which may not fully reflect interannual variability in climatic conditions, market dynamics, or policy impacts [10, 14].

Areas for future research

Future research should expand on this study by adopting multi-year, longitudinal panel designs to capture the dynamic and seasonal variability of mechanization service provision in diverse agro-ecological zones. Longer-term studies would allow the identification of patterns in operational sustainability, equipment degradation rates, and the long-term effects of policy interventions [9,24]. Research could investigate innovative financing mechanisms, such as pay-per-use models and digital microleasing platforms, which have shown promise in pilot programs across East Africa [13,18]. Examining the integration of ICT tools for service booking, fleet management, and predictive maintenance could offer insights into enhancing SMEs profitability and operational resilience [30].

Another promising area for future research is the comparative analysis of two-wheel versus four-wheel tractor services, particularly in upland and fragmented land systems where large machinery is less viable [12,27]. Finally, future studies should incorporate environmental sustainability metrics, evaluating the carbon footprint and soil health impacts of mechanized systems, aligning with global sustainable intensification agendas [10,13]. Addressing these areas can provide a more comprehensive evidence base to guide policy formulation and private sector investment aimed at sustainable agricultural mechanization in Cote d'Ivoire and beyond.

Conclusion

This study illustrates that the economic feasibility of mechanization services led by Small and Medium Enterprises (SMEs) in rice cultivation in Cote d'Ivoire is significantly influenced by the type of machinery employed and the regional context. Specifically, combine harvesters and tractors equipped with rotovators were found to be profitable solely in the central districts, where high demand and favorable infrastructure facilitated profit margins of up to 19 %. Conversely, in the Northern and Mountains districts, most machinery types operated below the break-even point because of limited demand, low custom charges, and elevated fixed costs. These findings highlight the necessity of regionally tailored investment and support policies that prioritize high-performing machinery and optimize asset utilization to ensure the sustainability of private-sector mechanization services.

CRediT authorship contribution statement

Mahe Franck Marcel Guei: Writing – review & editing, Writing – original draft, Data curation, Visualization, Validation, Methodology, Formal analysis, Conceptualization. **Wiyao Banakinaou:** Writing – original draft, Methodology, Formal analysis. **Moussa Bakayoko:** Resources, Investigation, Validation. **Hideo Hasegawa:** Supervision, Visualization, Writing – review & editing.

Declaration 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.

Acknowledgements

The authors would like to express their sincere gratitude to the Japanese International Cooperation Agency (JICA) for their support and also acknowledge the assistance provided by the Agency of Rice Development (ADERIZ) and the Ministry of Agriculture in Cote d'Ivoire during the data collection and fieldwork phases, which was instrumental in facilitating this research. The opinions expressed in this work are those of the authors alone; the funding organizations' opinions and beliefs are not reflected. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Data availability statement

All data used for this study are available in the supplementary Excel file *Cost_Calculations.xlsx*.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.sciaf.2025.e02848.

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