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RESEARCH ARTICLE OPEN ACCESS

Adoption of mechanization alternatives in oil palm crops in the Colombian Orinoquía natural region☆

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Abstract – The Orinoquía Natural Region in Colombia, particularly the Cumaral and Bajo Upía subzone, serves as the country's primary palm oil production area. However, it faces with labor shortages and a lack of current mechanization data. This study aims to assess mechanization status to enhance productivity and competitiveness in the oil palm industry. The goal was to determine the mechanization landscape, characterize available technologies, and evaluate their impact on productivity and costs for different types of oil palm producers. Utilizing a semi-structured questionnaire, data was collected from plantation administrators and technical assistants. Analysis focused on identifying mechanization options and assessing machinery adoption, productivity, and costs. Tractors are predominantly used for power, with limited adoption of advanced machinery like grabbers, variable-rate fertilizers, and electrostatic sprayers. Additionally, there's a notable gap in harvest equipment availability, suggesting a need for further technological development and machinery rental strategies. This study highlights the importance of updated mechanization data and provides insights for decision-makers seeking to improve oil palm productivity and competitiveness in Colombia. By understanding the mechanization landscape, stakeholders can address labor shortages and drive sustainable growth in the oil palm sector.

Keywords: adoption / agricultural machinery / costs / labor productivity

Résumé – Adoption d'alternatives de mécanisation dans les cultures de palmiers à huile dans la région naturelle de l'Orinoquía en Colombie. En Colombie, la région naturelle d'Orinoquía, en particulier autour de Cumaral et de Bajo Upía, constitue la zone de production principale d'huile de palme du pays. Elle doit toutefois faire face à des pénuries de main-d'œuvre et à un manque de données sur la mécanisation. Dans le but d'améliorer la productivité et la compétitivité du secteur, la présente étude dresse un état des lieux du niveau de mécanisation. L'objectif est de brosser un portrait de la mécanisation, d'identifier les technologies disponibles, et d'évaluer leur impact sur la productivité et les coûts pour les différents types de producteurs. En suivant un questionnaire semi-structuré, les données ont été recueillies auprès de gestionnaires de plantations et d'assistants techniques. L'analyse s'est concentrée sur l'identification des options de mécanisation et sur l'évaluation de leur adoption, de la productivité et du coût des machines. Les tracteurs sont principalement utilisés pour leur puissance, tandis que l'adoption de matériels plus sophistiqués (grappins, distributeurs à dosage réglable et pulvérisateurs électrostatiques) reste limitée. En outre, on note des écarts notables dans la disponibilité en matériel de récolte, qui suggèrent un besoin de poursuivre leur développement technologique et de mettre l'accent sur la location de machines. La présente étude souligne l'importance de disposer de données actualisées sur la mécanisation ; elle fournit des informations aux décideurs qui cherchent à améliorer la productivité et la compétitivité du palmier à huile en Colombie. En comprenant mieux le paysage entourant la mécanisation, les parties prenantes seront équipées

☆ Contribution to the Topical Issue: "Palm and palm oil / Palmier et huile de palme".
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pour faire face aux pénuries de main-d'œuvre et pour contribuer au développement durable du secteur de l'huile de palme.

Mots clés : adoption / machines agricoles / coûts / productivité du travail

1 Introduction

Labor productivity has been associated with institutional factors, such as political infrastructure, credit markets, regional infrastructure, geographical and climatic conditions, and technological supply, among others (Hamann *et al.*, 2019). In turn, the high demand for manual labor, especially in rural areas, requires that human resources be used with the highest possible efficiency (FAO, 2016).

Evidence indicates that labor productivity in food production systems is low in developing countries (Cock *et al.*, 2022; FAO, 2022). In oil palm-producing countries, estimates show that a worker produces between USD 10 and 30 per hour of work. Conversely, in developed countries, a worker produces more than USD 70 per hour (Our World in Data, 2019). The low availability of manual labor and the low agricultural productivity of developing countries increase the costs of agricultural wages and limit the efficiency of agricultural businesses. Therefore, alternatives such as mechanization and automation stand out as strategies for mitigating these problems (FAO, 2022).

Agricultural mechanization refers to the introduction of different tools (manual, animal traction, motorized mechanization, digital technologies, and robotics) for agricultural production (FAO, 2022; Mdoda *et al.*, 2022). These tools streamline work, increase its efficiency and wages and free up manual labor for activities that generate more economic growth. (FAO, 2022; Mdoda *et al.*, 2022). In fact, under mechanized agriculture, two to five hours of farm labor produce the food consumed by a person in a year, whereas non-mechanized systems require approximately 200 times more labor (Cock *et al.*, 2022).

Agricultural mechanization has positively affected labor productivity by contributing to intensifying production (Peng *et al.*, 2022) by increasing crop productivity, reducing production costs, increasing farmer profitability, and strengthening the market for rural economic growth (Mdoda *et al.*, 2022; Rasooli Sharabiani and Ranjbar, 2008). However, the available data on the use of technologies in food production systems globally remain scarce. In fact, the information is limited to the use of agricultural tractors and has been updated only until 2009 (FAO, 2022).

1.1 Mechanization in oil palm plantations

In oil palm growing, the most labor-intensive activities are fresh fruit bunch (FFB) cutting and internal transportation and weed control (Alfonso *et al.*, 2009b, 2009a; Norhajijah et al., 2021). In terms of the demand for manual labor, estimates suggest that one worker is required for every 12 hectares to grow *Elaeis guineensis Jacq* in Malaysia (Ismail *et al.*, 2015); however, in Colombia, one worker is required for every 11.3 ha for *E. guineensis Jacq* cultivars and for every 7.1 ha for OxG hybrid cultivars (Ruíz *et al.*, 2022). The oil palm industry requires a large amount of labor in all the countries where it operates (Malasia, Indonesia, Colombia), but this resource is often scarce and difficult to obtain. This poses a challenge for the sustainability of oil palm production, as labor shortages can affect the productivity and profitability of the sector.

The introduction of agricultural mechanization has been reported as a crucial factor for productivity growth in Malaysia since the 1980s. In this country, mechanization has increased labor productivity from one worker per 10 ha to one worker per 15 ha (Norhajijah *et al.*, 2021). Similarly, the introduction of agricultural mechanization was positively correlated with the increase in crop yield (Norhajijah *et al.*, 2021). Moreover, the mechanization of oil palm plantations has helped improve working conditions, in addition to attracting the manual labor sector of young people previously uninterested in working in oil palm plantations (Shuib *et al.*, 2011; Syarifudin & Zareen, 2021).

Notwithstanding the above, the mechanization of oil palm plantations comes with challenges, including unsuitability of the terrain, and uneven FFB ripening and canopy height (Norhajijah *et al.*, 2021). In this scenario, the present study aimed identify, characterizer and analyze the mechanization technology available in different production processes involved in oil palm cultivation in the region that produces 44.4% of the Colombian palm oil (Fedepalma, 2022). The objective of this study is to present the current situation of mechanization in oil palm cultivation in Colombia, and to explore the new technologies that are being adopted by the producers to increase their labor efficiency. The study also aims to characterize these technologies in terms of their impact on labor productivity, their cost of implementation, and their level of adoption among different production scales (medium and large). This information is relevant because there is a lack of updated data on the mechanization options for oil palm growers, since the last report by FAO dates to 2006. Therefore, this study intends to provide useful information for decision-makers who are interested in improving the productivity and competitiveness of the oil palm sector in Colombia. Furthermore, this study provides some practical suggestions derived from data analysis to help leverage this information for developing effective strategies to increase the technology adoption.

2 Materials and methods

2.1 Study area

This research was conducted in oil palm plantations, located in the Colombian Orinoquía Natural Region, more specifically in the municipalities of Paratebueno, Barranca de Upía, Cumaral, Cabuyaro and Villanueva (*Fig. 1*). These municipalities are located in the Piedemonte region of the Colombian Eastern Ranges (*Cordillera Oriental*). Piedemonte is characterized by its flatlands, with a slope of <7% and with abundant grass cover. Its rainfall regime shows a unimodal

Fig. 1. Geographical location of the study area. Source: Google Earth.

pattern with rainfall between April and November and drought between December and March (IDEAM, 2005; Ramirez-Contreras *et al.*, 2021; Urrea *et al.*, 2019).

2.2 Study population and sampling

The study population consisted of 63 plantations from five palm oil groups, accounting for 35,583 ha of a total of 278,512 ha cultivated with oil palm in the Colombian Eastern Area (*Zona Oriental*), that is, for 13% of the cultivated area in this oil palm-growing area. A palm oil group can be defined as a palm growing company that normally has a palm oil extraction plant, purchases fruit from a group of local farmers and, in some cases, provides the supplier network with facilities for its operations and maintenance (Ruiz *et al.*, 2017). The study sample consisted of medium- (from 50 to 500 ha) and large-scale (>500 ha) plantations. In the sample plantations, the crops were mostly in the maturity stage (>7 years after planting) (Fig. 2). As for the cultivars, 59% were *Elaeis guineensis* Jacq, and 41% were *Elaeis guineensis* Jacq x *Elaeis Oleífera* (OxG) hybrid cultivars.

In this population, stratified sampling was performed, using the palm oil group as the stratification criterion. The sample size was estimated with a 5% confidence level and a 15% sampling error; 26 plantations were selected, accounting for 89% of the study area cultivated with oil palm.

2.3 Data collection and analysis

A semi-structured questionnaire was administered to plantation administrators and technical assistants. The multiple-choice and open-ended questions aimed at identifying agricultural equipment and machines available by production process. (harvest, fertilization, pesticide spraying, weed control, infrastructure maintenance, and tillage).

The questionnaire assessed the level of adoption of machines (percentage of plantations that adopted agricultural machinery), equipment model (percentage of plantations with equipment purchased between 2010 and 2022 and those with equipment purchased before 2010), tenancy (owned or rented machinery), equipment frequency by process (amount of equipment adopted with respect to the total amount of equipment available according to production process), annual use (percentage of working time the equipment is used in a year), productivity rate (amount of work an equipment can perform in one hour, expressed as tons or hectares per hour), and costs.

The initial capital investment (CAPEX) included depreciation (straight line) and equipment costs (Srivastava *et al.*, 2006).

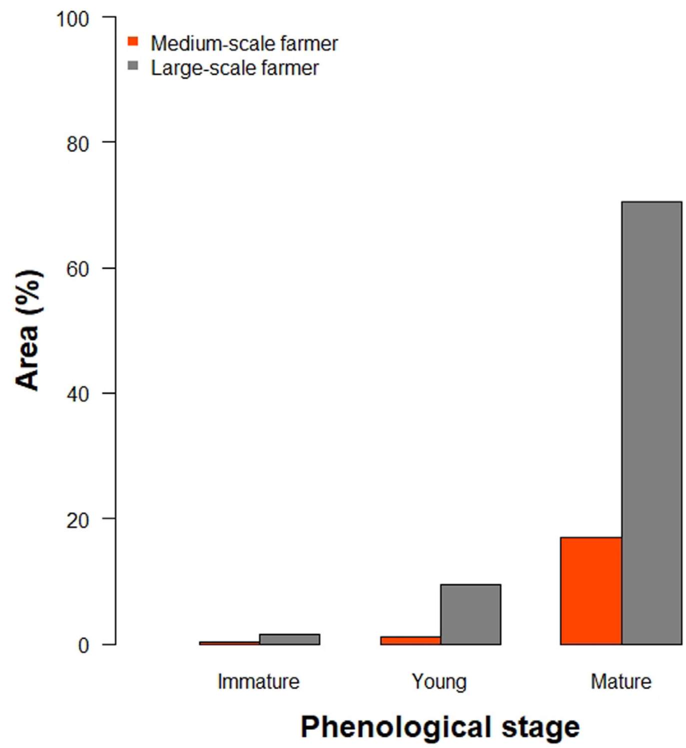

Fig. 2. Percentage of crop area according to phenological stage and type of farmer.

Table 1. Coefficients used to estimate initial capital investment and operating costs.

Agricultural machinery/ process	Useful life (hours)*	Salvage value (%)**	Maintenance and repair (% price)***	Specific fuel consumption (gallons/hour)
50 hp tractor	16000	50	45	2.1
75 hp tractor	16000	37	45	2.1
90 hp tractor	16000	35	45	4.4
120 hp tractor	16000	41	45	6.5
Tillage	2000–3000	17–44	58–74	4.3–5.8
Weed eaters	2000	31–35	44	1.4–3.6
Fertilizers	2000–3000	38–48	63	1.4–3.6
Sprayers	1200–2000	33–65	61	0.3–1.7
FFB cutters	1800	0	15	0.03
FFB harvesters	10000–14000	0	5	0.5–0.6
Trenchers	1500–2000	20–39	58	1.6–4.5
Backhoe	10.0000	28	45	1.6

* Retrieved from Hunt (2008)
** Retrieved from Estimating Farm Machinery Costs (Iwoa State University, 2015)
*** Retrieved from the American Society of Agricultural and Biological Engineers (ASABE) (Srivastava et al., 2006)

The reference prices for the study area were deemed constant for 2022. The economic life of the machines was analyzed according to reports by Hunt (2008) (Tab. 1). The salvage value or sale value of machines once their economic life ended was estimated from coefficients reported by the Iowa State University and expressed as a percentage of the purchase price, considering the annual hours of economic life of the machines, as outlined in Table 1 (Iowa State University, 2015).

In terms of financing costs, it was considered that all machines were financed using the interest rate of the Special Line of Credit (*Línea Especial de Crédito* – LEC) *A Toda Máquina* [At top speed] program of the Financing Fund for the Agriculture Sector (*Fondo de Financiamiento del Sector Agropecuario* – Finagro) (Fedepalma, 2012). In 2022, this interest rate was 16% of the effective annual rate (EAR) (Finagro, 2022). The operation costs (OPEX) were associated with maintenance, fuel consumption, and manual labor necessary for operating the machines. Maintenance and repair costs were estimated from the American Society of Agricultural and Biological Engineers (ASABE) coefficients

Fig. 3. Percentage distribution of all agricultural equipment used in the production process.

(Srivastava *et al.*, 2006) for each machine, piece of equipment, and implement, and expressed as percentage hours accumulated at the end of the useful life of the equipment (Tab. 1).

The cost of fuel was estimated from technical specifications of the equipment and the engine power required to perform the tasks according to the method proposed by the American Society of Agricultural Engineers (ASAE) (2003), considering the specific fuel consumption of tractors determined by the Nebraska Tractor Test Data. Based on these data, fuel consumption was calculated using the average price of a gallon of diesel fuel in Colombia, in 2022 (TRM COP$ 4.255), and expressed as gallons per hour.

The cost of manual labor was estimated from the value of the daily salary of an average tractor driver in the plantations surveyed in this study. This salary was divided by the number of hours of the workday (8 hours/ day or 40 hours/week). Costs were expressed as USD per hour.

The data were analyzed using descriptive statistics, presented in frequency tables, plots, and boxplots using the statistical software RWizard (Guisande *et al.*, 2014).

3 Results and discussion

3.1 Adoption of agricultural equipment by production process

Figure 3 shows the percentage distribution of all agricultural equipment used in the production process in oil palm growing in Piedemonte, in the Colombian Orinoquía Natural Region. The highest equipment availability was found in processes such as harvest, maintenance, and fertilization. These results corroborate the findings of studies on mechanization levels in oil palm plantations previously conducted in Colombia and Malaysia, which reported that a low amount of equipment and machinery is used in different production processes (Alfonso *et al.*, 2009b; Norhajijah *et al.*, 2021).

Harvesting one hectare of oil palm requires visiting the same lot every 10 to 15 days (between 20 and 30 visits per year). Therefore, as expected, the harvest operation requires most mechanized equipment, followed by crop maintenance (weed control and maintenance of drainage and irrigation channels and roads). These results are in line with the prevalence of grass cover in the study area in which extensive livestock farming was mainly developed in the past. In third place, fertilization is predominantly performed manually because, in the study area, this process entails applying two or three fractions of the nutritional doses, which encourages the use of manual labor (Norhajijah *et al.*, 2021; Ruíz *et al.*, 2022). Some pieces of equipment are used in lower numbers for foliar spraying, tillage, and plant health management activities associated with palm eradication because these tasks are less frequent.

3.2 Tractors used in oil palm plantations and their characteristics

Tractors are the most powerful machines used in oil palm cultivation, accounting for 75% of the engine power generated with mechanized equipment. This value matches data reported by the Food and Agriculture Organization (FAO), indicating that tractors remain the primary source of energy for numerous agricultural activities worldwide and that their adoption is also facilitated on flat terrain, such as that of the study area (FAO, 2022).

Figure 4a shows the type of tenancy of the tractors by type of farmer. Medium-scale farmers own these machines, whereas large-scale farmers commonly rent them. The increasingly growing availability of alternatives other than purchasing agricultural machinery, such as renting or leasing these assets, is becoming attractive to large-scale farmers, especially for fiscal advantages, access to modern machinery, and cost

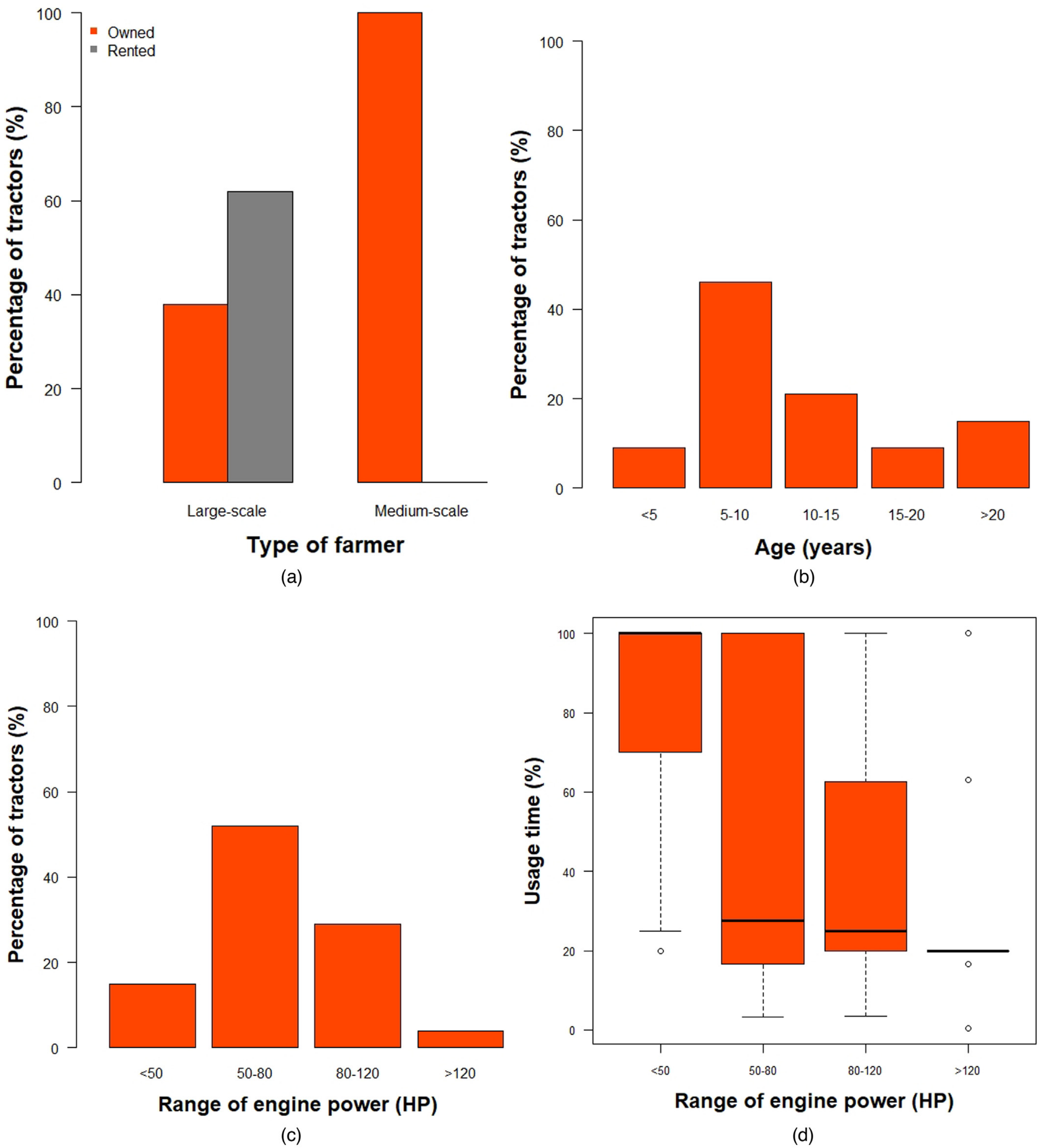

Fig. 4. Characteristics of the tractors used in oil palm plantations. (a) Tenancy by type of farmer, (b) age, (c) engine power distribution, (d) usage time as a function of engine power.

control. These services have helped to accelerate rural mechanization (Liu *et al.*, 2022). Renting mechanization services is also perceived as a suitable option, whereby a third party bears the maintenance costs of the machinery (Chaya *et al.*, 2019).

Another variable of interest is the total time during which the tractors are available throughout the year. Medium-scale farmers use them 74% of the time, whereas large-scale farmers use them 55% of the time. This difference is related to the type of use of the tractors in each group; 69% of the tractors are used

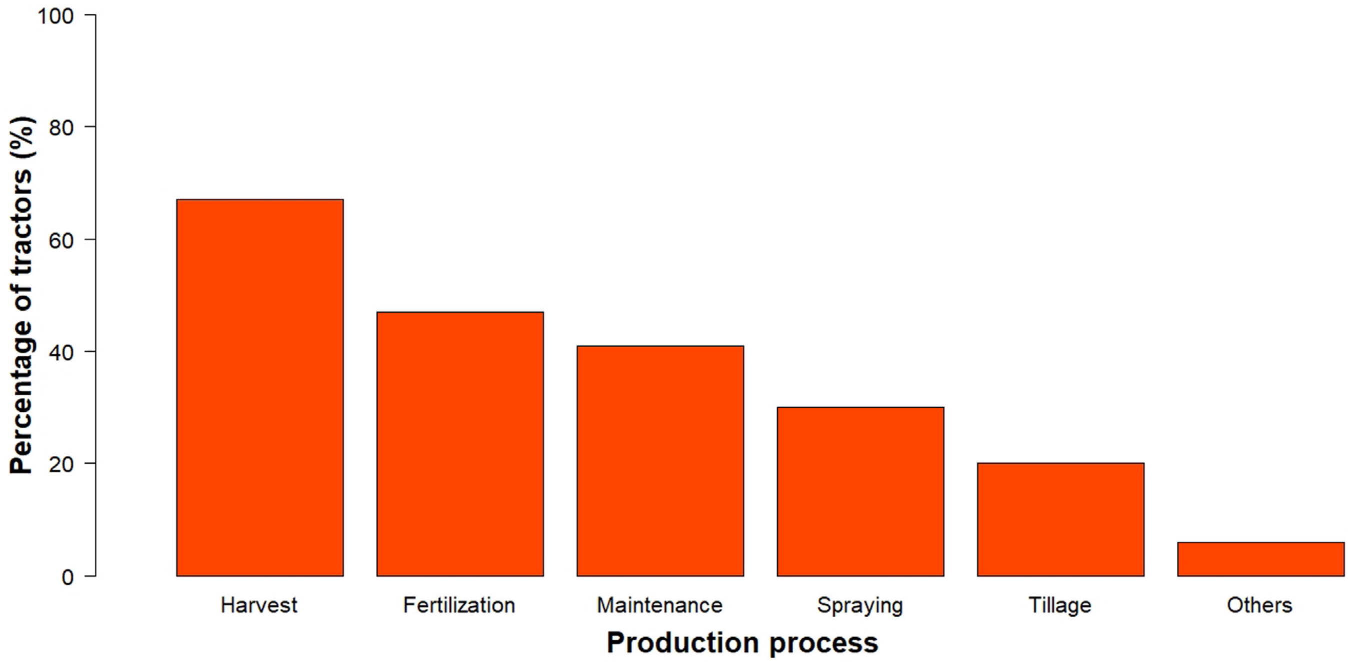

Fig. 5. Percentage of tractors according to the production process.

by medium-scale farmers to perform various crop-related tasks, whereas only 40% of the tractors are used by large-scale farmers in various tasks.

Regarding the age of the tractors (Fig. 4b) at the time of the survey, 76% of tractors fell below the 15-year threshold, which is commonly accepted as the economic life span for tractors (American Society of Agricultural Engineers (ASAE), 2003; FAO, 2022; Iowa State University, 2015; Kienzle *et al.*, 2013). Conversely, 24% of tractors may exceed this age, leading to repair and maintenance costs that are not typically justified. The engine power of the most used tractors ranged from 50–80 to 80–120 hp (Fig. 4c). These versatile equipment can be implemented for various crop-related tasks, such as harvest, weed management, foliar spraying, and fertilizer transport (Fig. 6 and Tab. 3). These tractors are more affordable than tractors with an engine power above 120 hp, which are generally used for tillage tasks.

Figure 4d shows the relationship between the range of engine power and time of use of the tractors. Tractors with a lower engine power (<50 hp) tend to record a longer use time. Conversely, tractors with a 50–80 hp engine power range show a greater variation in use time. In particular, tractors with an engine power >120 hp are only used approximately 20% of the time because, as mentioned above, they are mostly used for tillage, which is not a task undertaken frequently. In addition, due to the climate of the area, this activity is only performed during the transitions between the dry and wet seasons.

3.2.1 Use of tractors in production processes of oil palm cultivation

Tractors are used in different palm production processes. The FFB harvest involves the most tractors, followed by fertilization and maintenance. The tasks that use the fewest tractors are spraying, tillage, and plant health management (Fig. 5). In Malaysian oil palm crops, machinery is largely used for harvesting, weed control, and fertilization (Norhajijah *et al.*, 2021), as recorded in this study as well. As expected, harvesting is the production process involving the most tractors. For example, in Malaysian oil palm plantations, this activity and fruit transportation account for 60% of the mechanized activities for this crop (Shuib *et al.*, 2020).

Figure 6a shows that the engine power of the tractors used in maintenance, in pesticide spraying and other plant health management activities and in fertilization is highly similar, averaging 70–80 hp. Nevertheless, in harvests, tractors with less powerful engines are frequently adopted. Conversely, in tillage, tractors with more powerful engines are used given the engine power required by the implements.

In relation to the time of annual use of the tractors in each production process of the crop (Fig. 6b), the harvest shows the highest percentage of tractor use. Tillage, spraying, and plant health management are the farming activities with the lowest percentages of tractor use.

3.2.2 Adoption of agricultural implements in production processes

The adoption of agricultural equipment or implements (other than tractors) for production process in oil palm cultivation in the study area is presented in Table 2. This table outlines the levels of adoption of alternatives available for production process, which are discussed below. These alternatives can also be characterized based on variables such as equipment age, tenancy (owned or rental), and annual use.

3.2.3 Plant health management (spraying)

This process is managed using sprayers, electrostatic sprayers, thermal foggers, and crop dusters. The most adopted equipment is the cannon sprayer (70% of the plantations),

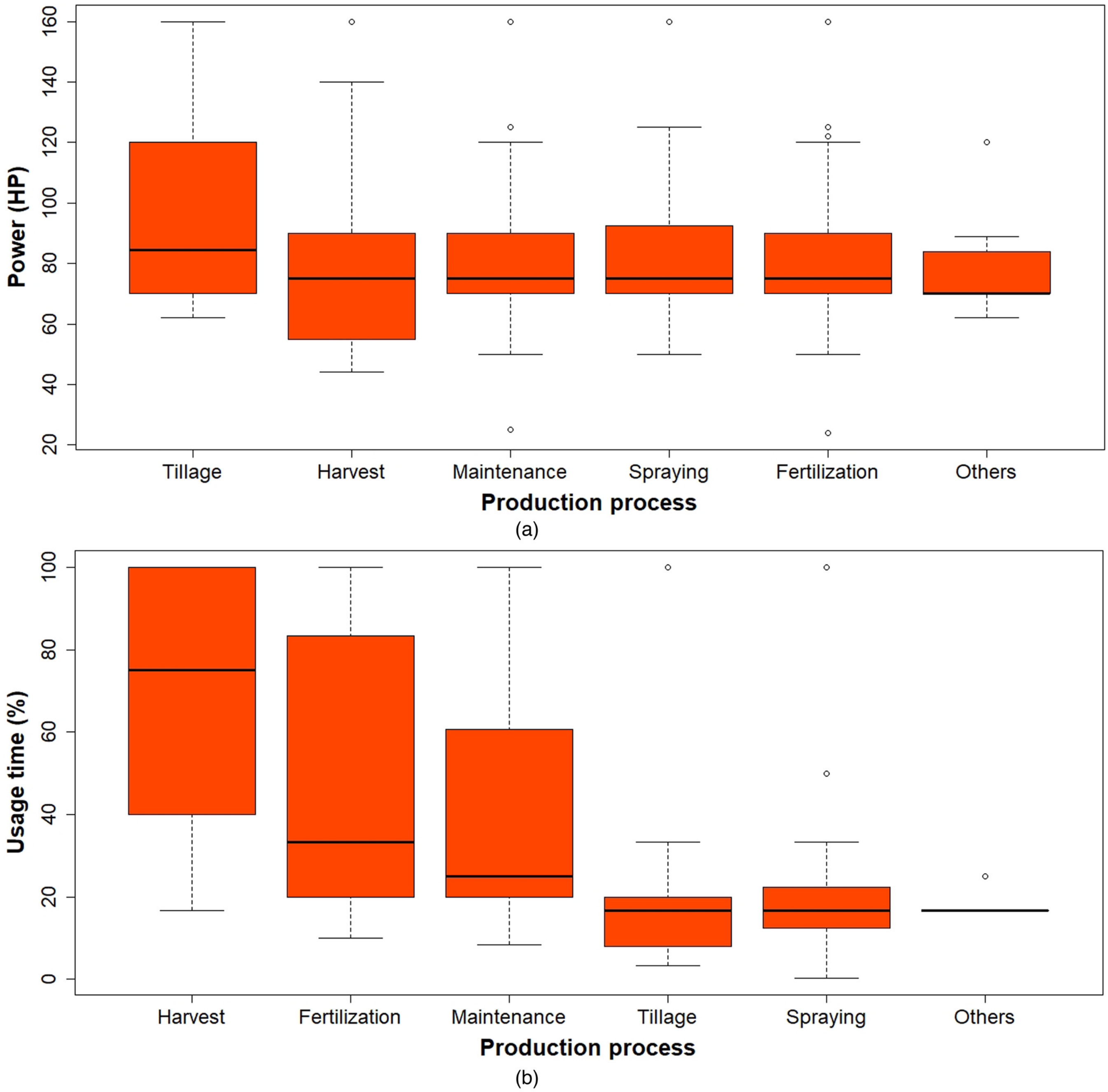

Fig. 6. Characteristics of tractor use according to the process. (a) Ranges of engine power used and (b) percentage of tractor use time.

accounting for 40% of all spraying equipment of the study area. The adoption of this equipment is not a recent phenomenon. Studies have reported the use of thermal foggers and electrostatic sprayers for more than a decade in Colombian oil palm cultivation (Alfonso *et al.*, 2009b).

Most equipment used for foliar spraying were manufactured between 2010 and 2020 and are owned by the plantation owners, in contrast to crop dusters and thermal foggers, which are rented 100 and 50% of the times, respectively. On average, spraying equipment is used 27% of the time annually. However, annually, power and electrostatic sprayers are the most used equipment, with a usage of 54 and 47%, respectively.

3.2.4 Fertilization

The adoption of broadcast spreaders (39% of the plantations) stands out, accounting for 53% of all fertilization equipment. Other pieces of equipment are less commonly adopted, such as compost spreaders, compost turners, big bags for storing, transporting and loading the fertilizers into the spreaders, and variable-rate fertilizer spreaders (4–16% of the plantations). In terms of annual use, most of the fertilization equipment is used at a low percentage (16%).

Equipment such as variable-rate fertilizer spreaders (*Tab. 2*), which are associated with precision agriculture for enabling

Table 2. Characterization of equipment and implements available according to the production process.

Process	Equipment and implements	Adoption (%)	Age frequency (%)		Tenancy (%)		Frequency of the equipment by process (%)	Annual use (%)
			<2010	2010–2022	Owned	Rented		
Plant health management (spraying)	Cannon sprayer	7	45	54	82	18	40	17
	Motorized backpack sprayer	26	100	0%	100	0%	15	16
	Thermal fogger	9	0%	100	100	0%	5	39
	Power sprayer	17	0%	100	100	0%	10	54
	Crop duster	22	ND	ND	0%	100	13	1
	Electrostatic sprayer	13	0%	100	100	0%	8	47
	Airblast sprayer	9	ND	ND	50	50	5	5
	Articulated cannon sprayer	9	0%	100	100	0%	5	37
Fertilization	Broadcast spreader	39	20	80	73	27	53	6
	Drop spreader	17	66	33	80	20	24	6
	Variable-rate fertilizer spreader	4	0%	100	100	0%	6	50
	Compost spreader	4	0%	100	100	0%	6	20
	Compost turner	4	ND	ND	100	0%	6	0%
	Big bag	4	ND	ND	100	0%	6	ND
Harvest	Tractor + Trailer	96	40	60	74	26	79	91
	Motorized cutter	17	0%	100	83	17	14	75
	Tractor + Grabber	9	0%	100	100	0%	7	100
Tillage	Disc plow	52	83	17	86	14	39	18
	Chisel plow	26	50	50	86	14	19	17
	Disc harrow	22	100	0%	100	0%	16	7
	Grader blade	9	ND	ND	100	0%	6	6
	Subsoil plow	4	0%	100	100	0%	3	25
	Field cultivator	4	100	0%	100	0%	3	5
	Ripper	4	0%	100	0%	100	3	7
	Mulch finisher	4	ND	ND	100	0%	3	1
	Tine harrow	4	100	0%	100	0%	3	0%
	Mole plow	4	ND	ND	100	0%	3	0%
Weed management	Brush hog	78	33	67	83	17	35	39
	Brush cutter	70	33	67	63	37	31	48
	Land roller	48	43	57	92	8	22	34
	Finish mower	17	0%	100	100	0%	8	22
	Handheld spinning disc sprayer	4	ND	ND	100	0%	2	ND
Maintenance	Backhoe	57	77	23	45	55	43	52
	Trencher	52	0%	100	75	25	40	11
	Land shaper	13	0%	100	100	0%	10	3
	Ditcher	9	ND	ND	0%	100	7	0%
	Rotary ditcher	0%	ND	ND	ND	ND	0%	ND

ND: No Data

adjustments to fertilizer doses applied at each specific site (Alfonso *et al.*, 2009b) and a longer period of annual use due to its efficiency (50% annual use), show a low level of adoption (only 4% of the plantations use a variable-rate fertilizer spreader).

In the plantations considered in this study, compost turners were not adopted. Among the reasons for not using this equipment, compost management and the economic viability of the technology were mentioned. The implementation of fertilization equipment aimed at reducing fertilizer losses due to leaching and runoff (Alfonso *et al.*, 2011b, 2011a) was not observed either.

3.2.5 Harvest

The percentage of adoption of mechanical equipment for FFB cutting, such as motorized cutters, is low (17%). This trend is also found in other latitudes. In Malaysia, a wide range of alternatives for motorized FFB cutting are available to oil palm growers (Cantas™ and Ckat™ Cutters), with advantages in efficiency (Jelani *et al.*, 2018; Ruiz *et al.*, 2020), but studies report low percentages of adoption (2.36%) (Norhajijah *et al.*, 2021).

For FFB lifting, most (96%) plantations adopt a tractor-pulled hydraulic trailer system, whereas 9% plantations employ grabber systems. In Malaysia, similar results have been reported for this equipment, with 19.5% adoption of tractors + trailer and 5% adoption of tractors + grabber (Norhajijah *et al.*, 2021), albeit without data on the adoption of mechanized equipment for loose fruit collection.

This study shows the availability of mechanized technologies that have shown their efficiency in cutting, lifting, and collecting oil palm bunches, such as motorcycle trailers, grabbers, and minitractors with trailer, grabber and cableway systems (Alfonso *et al.*, 2009b, 2009a; Mahadi et al., 2018; Shuib et al., 2011, 2020). However, the results also show low adoption of the most efficient technologies; the difficulty in mechanizing FFB harvesting processes is evident in studies conducted in Malaysia (Nawi *et al.*, 2015; Norhajijah *et al.*, 2021). This difficulty has been related to soil characteristics, funding availability, area of operation of these technologies, and crop yield, among other factors (Mosquera-Montoya *et al.*, 2023).

Due to its inherent nature, the harvest stage demands sophisticated equipment, leaving few alternatives available for

Table 3. Labor productivity using machines and equipment.

Type of production process	Equipment	Required engine power (hp)	Labor productivity	Unit
Plant health management (Spraying)	Cannon sprayer	45	2.0	ha/hour
	Motorized backpack sprayer	N/A	1.0	ha/hour
	Crop duster	N/A	39.6	ha/hour
	Thermal fogger	40	3.8	ha/hour
	Airblast sprayer	40	4.4	ha/hour
	Articulated cannon sprayer	70	2.1	ha/hour
	Electrostatic sprayer	75	5.0	ha/hour
	Power sprayer	40	1.25	ha/hour
Fertilization	Variable-rate fertilizer	60	7.5	ha/hour
	Broadcast spreader	75	1.9	ha/hour
	Compost spreader	80	1	ha/hour
	Drop spreader	60	2.24	ha/hour
Harvest	Motorized cutter	1.3	0.65	t FFB/hour
	Lift with tractor + Grabber	44	2.5–3.8*	t FFB/hour
	Lift with tractor + Trailer	44	1.8–3.1*	t FFB/hour
Tillage	Chisel plow	120	0.6**	ha/hour
	Disc harrow	100	1.0**	ha/hour
	Ripper	100	0.6**	ha/hour
	Disc plow	100	1.05**	ha/hour
Weed management	Brush cutter	N/A	0.28	ha/hour
	Land roller	120	1	ha/hour
	Brush hog	60	1.5	ha/hour
	Finish mower	60	1.3	ha/hour
Maintenance	Backhoe	N/A	0.06***	ha/hour
	Trencher	90	1.8	ha/hour
	Land shaper	120	1.6	ha/hour

N/A: not applicable because it is self-propelled
*Depends on the amount of fruit available on the field
**Depends on the physical characteristics of the soils
***Construction of drainage channels

machinery and adopted systems. Enhancing the human-machine interface is crucial during product design, and manufacturers must actively disseminate information and provide training to workers (Nawi et al., 2015). As suggested by Ramli *et al.* (2021) and Syarifudin and Zareen (2021), a Manufacturing Powerhouse with expertise in developing and marketing high-capital equipment is also needed to bridge the gap between research, development, and technology adoption in plantations.

3.2.6 Tillage

The disc plow method stood out, with up to 52% implementation in plantations. Equipment such as subsoil plow, field cultivator, ripper, mulch finisher, tine harrow, and mole plow showed low levels of adoption and were found in only 4% of the plantations. Given the low annual utilization of these equipment, and in an effort to optimize resource usage, it could be proposed that plantation centers consider renting schemes, as suggested by Chaya *et al.* (2019) and FAO (2022).

3.2.7 Weed management

Equipment such as the brush cutter and brush hog stood out for their adoption in 70–78% of the plantations. In addition, 37% of the brush cutters were rented because some plantations prefer outsourcing such equipment to avoid processes associated with repair, maintenance, and fuel (Chaya *et al.*, 2019). In plantations where chemical methods are used for weed management, this labor is manual and relies on backpack sprayers. As alternatives to the manual method, mechanized technologies, such as boom sprayers or mini-tractors with anti-drift panels, which confine the drops of the product applied to oil palms, not only increase labor productivity rates but also minimize off-target spray drift, thereby protecting oil palms (Alfonso *et al.*, 2009a)

3.2.8 Maintenance labor

This includes building, maintaining, and cleaning irrigation and drainage canals and roads. The pieces of equipment most commonly used in plantations are backhoes and trenchers. The backhoes stand out because 46% of them were manufactured before 2005, and they are used 52% of the time.

The variable annual use and its relationship with adoption is particularly interesting, especially in processes such as pesticide and fertilizer spraying. Widely adopted pieces of equipment, nevertheless, show low annual use (less than 40%). For example, in pesticide spraying, cannon and backpack sprayers are the most adopted pieces of equipment, but they are used only 17% of the time annually. Conversely, pieces of equipment with lower levels of adoption, such as power and electrostatic sprayers, are used more than 50% of the time annually. In fertilization labor, the same relationship is observed; although broadcast and drop spreaders are the most commonly adopted pieces of equipment, they are used only 6% of the time annually, whereas variable-rate fertilizer spreaders show very low levels of adoption but are nonetheless used 50% of the time annually.

Similar results are found when analyzing the relationship between the variable equipment tenancy and annual use. Although a high percentage of the equipment adopted is owned by the farmer, its use during the year is low, particularly when it comes to tillage, maintenance, and fertilization, which are used less than 25%, 11%, and 50% of the time, respectively, annually.

In relation to the age of the implements, most of the machinery adopted in plantations of this region was purchased between 2010 and 2022, suggesting an adequate age according to their economic life (American Society of Agricultural Engineers (ASAE), 2003; FAO, 2022; Iowa State University, 2015; Kienzle *et al.*, 2013). However, among the adopted models, autonomous equipment using digital technology remain unavailable. These technologies can enhance farming precision and timeliness, in addition to addressing environmental problems derived from mechanization (FAO, 2022).

3.3 Adoption of agricultural implements by type of producer

Based on the survey results, it has been determined that both large and medium-sized producers use the same equipment for various crop tasks in most cases. Additionally, they exhibit similar conditions regarding equipment age, ownership, and usage time. However, differences are observed in the adoption of specific equipment for certain tasks: 1. Spraying: Medium-sized producers have not adopted equipment such as the electrostatic sprayer and the articulated cannon sprayer, despite these implements offering better performance. 2. Fertilization: In this aspect, there is a higher adoption of broadcast spreaders by large producers (60%) compared to medium-sized ones (23%). In addition, medium-sized producers have also not adopted technologies like variable-rate fertilizer applicators, which are known for their superior performance. 3. Maintenance: Large producers lead in the adoption of equipment such as the backhoe (90%) and trenchers (70%), while medium-sized producers show lower adoption rates in these areas (31% and 38%, respectively).

3.4 Productivity rates and costs

Labor productivity rates were estimated for each equipment according to the production process in which machines were used. Table 3 outlines labor productivity rates according to the production process and equipment adopted by production process and expressed as hectares (ha) or t FFB per hour. Table 4 presents the costs of using different alternatives.

3.4.1 Harvest

In the FFB lifting process (harvest), the tractor + trailer system shows the highest level of adoption, despite having lower productivity rates (22–38%) than the tractor + grabber system (Tab. 2). The productivity rates reported in this study are similar to those reported in the literature, ranging from 20.3 t FFB (31 ha/day) in low bunch density seasons to 30.5 t FFB (12.7 ha/day) in high bunch density seasons (Munévar *et al.*, 2020; Pebrian and Yahya, 2013; Sierra, M; Alfonso, 2010). As shown in Table 4, the grabber system reduces the unit cost in lifting by 44% compared to the tractor + trailer system. Global harvesting (including bunches cutter) costs decrease by 21–25% when coupling the grabber to the tractor + trailer system (Mosquera-Montoya *et al.*, 2023). In the same way, the grabber system eliminates the need for manual loading and unloading of the logs, which saves time and labor, the grabber system can also save 1 or 2 wages compared to the traditional method. This paragraph highlights a significant benefit of using the grabber system for harvesting crops that need to be collected every two weeks. This means that 8 fewer wages are needed per hectare per year compared to the manual system. This is a substantial saving for the farmers and a more efficient way of harvesting.

3.4.2 Plant health management (spraying)

The most widely adopted pieces of equipment include cannon and motorized backpack sprayers (Tab. 2), which have the lowest productivity rates (ranging from 1 to 2 ha/hour) (Tab. 3). Conversely, airblast sprayer and electrostatic sprayers are less adopted despite reaching productivity rates ranging from 4.4 to 5 ha/hour due to the higher cost per hour (Tab. 4). The unit cost (USD/ha) of different alternatives for pest and disease control can be compared by revising the data. The results show that Airblast sprayer has a 52% lower unit cost than the most adopted alternative, which is Cannon sprayer. Moreover, electrostatic sprayer reduces the need for human labor by 58% annually and allows for more timely and efficient applications. Oil palm cultivation faces many challenges from pests and diseases, especially in tropical countries. Some of the most serious threats are Lethal wilt, Bud rot and basal stem rot, which can reduce the productivity and sustainability of oil palm crops. Therefore, it is crucial to explore the possibility of enhancing the applications for pest and disease management in oil palm (Pinnamaneni and Potineni, 2022). This could help to protect the oil palm from these harmful agents and improve its resilience and performance.

3.4.3 Fertilization

Broadcast spreaders are predominantly adopted over variable-rate fertilizer spreaders (Tab. 2). In terms of labor productivity, broadcast spreaders can cover 1.9 ha/hour (Tab. 3), in line with the value of 2.8 ha/h reported by Alfonso *et al.* (2009a). Using variable-rate fertilizer spreaders increases labor productivity by 295%. The low adoption of these technologies may be associated with the higher initial investment required to purchase the equipment. A common mistake that producers make is to base their fertilization choices only on the capex, without considering the unit cost. Table 4 shows that using alternatives such as variable-rate fertilizer spreader can lower the cost of application by 45% compared to broadcast spreader. Moreover, the variable-rate fertilizer can save 56% of labor annually, which is significant given the scarcity of labor and the short time window for fertilizer application (depending on the

Table 4. Cost per hour of the use of machines and equipment.

Type of production process	Machinery	Capex (USD$/hour)	OPEX (USD $/hour) M & R	OPEX (USD $/hour) Fuel	OPEX (USD $/hour) Manual labor	Total cost (USD$/hour)	Unit cost (USD$/ha or t RFF *)
Tractors	50 hp tractor	1.63	0.66	4.72	3.67	10.68	N/A
	75 hp tractor	2.44	0.99	4.72	3.67	11.82	
	100 hp tractor	2.91	1.32	9.91	3.67	17.82	
	120 hp tractor	3.49	1.59	14.71	3.67	23.47	
Plant health management (spraying)	Cannon sprayer	2.96	1.31	2.41	6.54	13.22	6,61
	Motorized backpack sprayer	0.09	0.08	0.31	2.86	3.34	3,44
	Thermal fogger	3.46	1.77	0.92	6.54	12.69	3,34
	Airblast sprayer	5.53	2.60	2.14	3.67	13.93	3,17
	Articulated cannon sprayer	6.85	3.36	3.74	3.67	17.62	8,39
	Electrostatic sprayer	15.79	12.41	4.01	3.67	35.87	7,17
	Power sprayer	2.33	1.05	0.79	9.40	13.57	10,8
Fertilization	Variable-rate fertilizer	20.66	11.00	6.57	3.67	41.90	5,59
	Broadcast spreader	5.09	2.38	8.21	3.67	19.36	10,19
	Compost spreader	6.32	3.03	4.28	3.67	17.29	17,29
	Drop spreader	2.84	1.25	3.21	3.67	10.97	4,90
Harvest	Motorized cutter	0.18	0.69	0.07	2.86	3.80	5,85
	Lift with tractor + Grabber	3.82	0.72	1.12	3.67	9.33	2,96
	Lift with tractor + trailer	2.09	0.68	1.43	8.81	13.02	5,31
Tillage	Chisel plow	6.97	3.47	12.89	3.67	27.01	45,0
	Disc harrow	9.23	4.28	10.74	3.67	27.93	27,9
	Subsoil plow	6.79	3.59	13.14	3.67	27.20	ND
	Field cultivator	7.25	3.34	14.71	3.67	28.98	ND
	Ripper	4.27	2.08	10.74	3.67	20.76	34,6
	Mulch finisher	7.23	3.08	9.67	3.67	23.65	ND
	Spring-tooth harrow	9.18	4.05	10.74	3.67	27.65	ND
	Tine harrow	6.80	3.08	10.74	3.67	24.29	ND
Weed management	Brush cutter	0.18	0.03	0.28	2.86	3.35	11,9
	Land roller	7.59	3.20	6.41	3.67	20.87	20,8
	Brush hog	5.37	1.92	3.21	3.67	14.18	9,45
	Finish mower	5.46	1.92	3.21	3.67	14.26	10,9
Maintenance	Backhoe	21.82	3.54	3.80	3.67	32.83	ND
	Trencher	6.73	3.03	9.67	3.67	23.10	12,8
	Land shaper	7.67	3.88	3.80	3.67	19.02	11,8
	Rotary ditcher	12.30	4.95	10.21	3.67	31.12	ND

M&R: maintenance and repair
*For the harvest technology the unit is t RFF for the rest is ha
ND: No Data
N/A: Not applicable because the estimation is done with the implement.

start or end of rains). Therefore, the fertilizer equipment should be able to cover more area in less time.

3.4.4 Weed control

The limited availability of alternatives for this process is evident. In fact, brush cutters, land rollers and brush hogs are widely adopted (Tab. 2). Broadly speaking, the productivity rates range from 0.28 to 1.5 ha/hour (Tab. 3). This work aimed to explore alternatives to lower the unit cost and labor demand of the latest process. One possible alternative is the use of Brush hog, which could reduce the time spent on clearing vegetation by 21% compared to brush cutter and save 75% of the annual wages for this task.

4 Conclusion and recommendations

This study synthesized data on the adoption of equipment used in each stage of oil palm cultivation, identifying technical aspects and operational costs. The highest availability of tractors was found in processes such as harvest, maintenance, and fertilization. Tractors account for 75% of the power generated by agricultural machinery available for different production processes. Tractor usage time is a key factor in the efficiency of agricultural operations. The low annual use time of the tractors and equipment adopted in some processes, such as fertilization, weed control, and pesticide spraying, may convert profit opportunities into losses considering the investment costs while the equipment remain stored for most of the year.

Regarding to the age of the machinery, it was found that 76% of tractors have an economic life shorter than 15 years, during which maintenance and repair costs remain justifiable. Additionally, most other agricultural implements are less than 10 years old, aligning with the commonly accepted economic life span. This information can be used to estimate future demand for agricultural machinery based on their expected economic life. In the context of large-scale agricultural production, using tractors exclusively for harvesting, for optimal results, it is advisable to employ tractors with power ratings below 80 HP. However, it's essential to note that higher-powered tractors incur greater operating expenses due to increased fuel consumption and maintenance requirements.

Although the harvest stage demands a high level of equipment, few alternatives are available for equipment and adopted systems. Technological adoption studies must examine the reasons why equipment available in the market for FFB cutting and lifting (cutters and grabbers) have not been widely adopted yet. The need for manual labor in the harvest is extensive due to the frequency with which tasks must be performed and is proportional to the crop area. Accordingly, such studies should aim at identifying approaches to improving the technology offer. Design is essential, enhancing the human-machine interface is crucial, manufacturers should actively disseminate information and provide training to workers. It is require, a Manufacturing Powerhouse specializing in high-capital equipment that can bridge the gap between research, development, and technology adoption in plantations.

The decision of adopting machines and equipment should consider not only investment costs but also returns on investment from their use, especially when considering manual labor problems resulting from the use of equipment involving labor-intensive tasks. Technology adoption can be influenced by the economic advantages of a technology, as they enable a logical evaluation of different alternatives and the choice of the optimal solution (Ploll *et al.*, 2022; Rizzo *et al.*, 2023). We examined various alternatives that could enhance the labor demand and decrease the production cost. The alternatives we found could lower the unitary cost of each production process by 44% to 52% in comparison to the manual activities. Likewise, they could save labor demand, as they boost labor productivity. This information should be disseminated to the technical assistance units, so that they can inform the farmers on the significance of calculating the unitary cost and the benefits of adopting technology, rather than making decisions based on the capex.

This paper suggests study the relation between public policies on mechanization adoption should be evaluated in terms of how they affect the demand for machinery. For further research it is important to determine key factors that influence the decision and capacity of the facilities to adopt technology, such as infrastructure, credit and subsidies, training and education, and collective renting schemes for machinery. The paper finds that the utilization rate of machinery is low throughout the year, which reduces the profitability of the mechanization investment. Therefore, the paper proposes that collective renting is a viable option to increase the use of mechanization technologies and improve labor productivity.

Renting machinery provides farmers with the flexibility to access equipment with different engine power levels and characteristics according to the needs of each stage of the crop cycle. In addition, by renting tractors, farmers can access more modern and up-to-date equipment, which can improve the efficiency and productivity of agricultural tasks.

Based on information from a Colombian region with a long-standing tradition of oil palm-growing, this study shows the lack of adoption of digital technologies incorporated into mechanization (autonomous equipment or robotics). These technologies have been developed for other production systems since the 1970s. Such a diagnosis is essential to explore alternatives for improving productivity in oil palm plantations in the Piedemonte region and serves a pilot project, which can be implemented in other subzones of the country interested in developing their mechanization strategies.

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Conflicts of Interest

The authors declare that there is no conflict of interest in relaiton ot this article.

Author contribution statement

Arley Zapata: Conceptualization, Formal Analysis, Investigation, Methodology, Writing – Review & Editing**. Elizabeth Ruiz:** Conceptualization, Formal Analysis, Investigation, Methodology, Writing – Review & Editing**. Nolver Arias:** Project Administration, Supervision, Writing – Review & Editing**. Mauricio Mosquera:** Supervision, Writing – Review & Editing. **Alexandre Cooman:** Conceptualization, Funding Acquisition, Supervision.

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