frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 24 August 2023
DOI 10.3389/fsufs.2023.1217653

OPEN ACCESS

EDITED BY
Matteo Balderacchi,
Independent Researcher, Piacenza, Italy

REVIEWED BY
Luca Lombardo,
Council for Agricultural Research and Economics, Italy
Mat Yunus Abdul Masani,
Malaysian Palm Oil Board, Malaysia
Claude Bakoume,
Chinese Academy of Sciences (CAS), China

*CORRESPONDENCE
Mauricio Mosquera-Montoya
✉ mmosquera@cenipalma.org

RECEIVED 05 May 2023
ACCEPTED 07 August 2023
PUBLISHED 24 August 2023

CITATION
Mosquera-Montoya M, Camperos JE, Ruiz E, Hernández D, García A, Vargas LE, Mesa E, Munévar D and Sinisterra K (2023) Evidence of sustainable intensification in the production of palm oil from crops planted with *Elaeis oleifera* x *Elaeis guineensis* in Colombia.
Front. Sustain. Food Syst. 7:1217653.
doi: 10.3389/fsufs.2023.1217653

Evidence of sustainable intensification in the production of palm oil from crops planted with *Elaeis oleifera* x *Elaeis guineensis* in Colombia

Mauricio Mosquera-Montoya*, Jhonatan Eduardo Camperos, Elizabeth Ruiz, Diego Hernández, Alejandra García, Liseth Estefanía Vargas, Eloina Mesa, Daniel Munévar and Kelly Sinisterra

Research Results Validation Unit, Colombian Oil Palm Research Center (Corporación Centro de Investigación en Palma de Aceite – Cenipalma), Bogotá, Colombia

Cultivars from crossings between *Elaeis oleífera* x *Elaeis guineensis* (OxG hybrids) have proven to have partial resistance to Bud Rot (BR), the most challenging disease for the Colombian palm oil agroindustry. Therefore, OxG hybrids were planted in areas that have experienced BR outbreaks since 2007. Soon, it was discovered that OxG hybrid female inflorescences required to be pollinated with pollen from *E. guineensis* to improve bunch formation. Researchers from Cenipalma noted that OxG hybrid bunches have a greater proportion of partenocarpic fruits. The latter generated a line of research that yielded artificial pollination in 2018. Artificial pollination consists of applying naphtaleneacetic acid (NAA) to female inflorescences in order to promote the formation of partenocarpic fruits. If artificial pollination was to be scaled up, many questions needed an answer such as, what was labor productivity, the stage at which bunches should be harvested and even, if it was profitable. This paper synthesizes the results of studies carried out by Cenipalma together with managers from oil palm plantations. These research studies were undertaken by means of time and motion studies, optimal harvesting time studies and cost–benefit analysis. Results come from plantations located at all the zones that have planted OxG cultivars that have planted the most common OxG hybrids. Our results indicate that an artificial pollination worker may be asked between 188 and 249 inflorescences per workday depending upon inflorescences density (inflorescences per hectare). We also found that by implementing criteria on optimal harvest time one may increase the oil extraction rate from 6 to 29.7%. Finally, it was found that artificial pollination is more costly than using only *E. guineensis* pollen, but the increase in yields at the field and the increase in the amount of oil extracted offset this extra cost and provide greater profitability to oil palm growers. This is a sample of how, by using the same natural resources, implementing artificial pollination, and harvesting at the proper stage; one can have greater yields and have a more resilient business. In other words, this is an example of sustainable intensification.

KEYWORDS

artificial pollination, oil extraction rate, economic assessment, labor productivity, yield increase

1. Introduction

Bud rot (BR) is considered the most limiting disease in oil palm production in Colombia (Martínez et al., 2018). As some interspecific OxG hybrid (*Elaeis oleifera* and *Elaeis guineensis*) cultivars (hereafter referred to as OxG hybrid cultivars) show partial resistance to BR, their cultivation has gradually increased since 2007 (Avila-Diazgranados et al., 2016). In 2022, approximately 90,000 hectares (ha) of land planted with these cultivars in Colombia was reported (Cooman, 2023).

When OxG hybrid cultivars were first introduced, their crop management had not been conducted on a commercial scale; therefore, the management criteria for *E. guineensis* were implemented. The management of OxG cultivars has been challenging because these cultivars show poor natural pollination caused by their low pollen viability (Hormaza et al., 2010; Prada and Romero, 2012; Socha et al., 2019; Caicedo et al., 2020). In addition, the female inflorescences are protected by fibers that prevent pollen from contacting the flowers at anthesis (Sánchez et al., 2011; Forero et al., 2012).

For those reasons, oil palm farmers had to resort to assisted pollination to improve bunch formation in OxG hybrid cultivars by removing the bracts and applying pollen from *E. guineensis* to the female inflorescences at anthesis. This practice improved the potential productivity of OxG crops, with gains in size, weight, bunch formation, and oil quality (Sánchez et al., 2011). However, the need to apply the pollen of *E. guineensis* at anthesis greatly reduces the time window for bunch formation. In addition, the flowers of OxG hybrid cultivars also tend to be asynchronous, so not all flower buds are receptive at the same time (Guataquira et al., 2019).

Aiming at optimizing palm oil yield, researchers at Cenipalma focused on the fact that 65% of the palm oil content in bunch components of OxG hybrids (Coari x La Mé) correspond to normal fruits and 35% to parthenocarpic fruits (Rincón et al., 2013), as opposed to that in *E. guineensis* cultivars in which the number of parthenocarpic fruits and the resulting palm oil content are so low that they are not even considered for bunch analysis (Prada and Romero, 2012). This led to a line of research to explore how seedless (parthenocarpic) fruits can be produced using growth regulators, such as auxins and gibberellins, in non-pollinated flowers (Lietzow et al., 2016; Taiz et al., 2017; Qian et al., 2018). The result of that research was artificial pollination, which consists of applying naphthalene-acetic acid (NAA) three times to each female inflorescence. The first application is performed when the inflorescence is at anthesis and either pollen or NAA can be used. The subsequent two applications are conducted at 7 and 14 days after anthesis with NAA (Daza et al., 2020; Romero et al., 2021).

Artificial pollination increases fruit set up to 95% and, enlarges the time window for application so one gets a proper bunch formation (Daza et al., 2020; Romero et al., 2021). The number of harvested bunch components also increases by up to 15% (Daza et al., 2020). Finally, artificial pollination has had an impact on oil production per ton of bunches, with extraction rates ranging from 25 to 28% (Romero et al., 2021). The above reasons contributed to the prompt implementation of artificial pollination by companies. In other words, artificial pollination is a clear example of sustainable intensification of palm oil cultivation with OxG cultivars. Sustainable intensification is understood as the increase in productivity of systems through the efficient use of supplies, reduction of environmental impacts, creation of natural capital, and flow of ecosystem services (Lerner et al., 2017; Sekaran et al., 2021).

In accordance with a toxicology study on the use of NAA over human health the US Environmental Protection Agency (EPA), the exposition to crops using NAA or food produced by means of using NAA are not harmful. Besides, the EPA concluded that if NAA is used within the allowed limits, it may not represent risk of contracting cancer to humans. Finally, the EPA study states that NAA is considered as a pesticide that may cause irritation on eyes, skin, or mucous membranes if they are directly exposed to contact with NAA. Additionally, direct exposition to NAA may cause coughing or running nose. In consequence, it is highly advised that workers performing artificial pollination should wear at all times personal protection items (PPI) (Enviromental Protection Agency, 2012).

For NAA applications, Cenipalma proposed to dilute NAA in water (NAA in a liquid suspension). However, companies in this industry proposed maintaining the concentration and mixing NAA with talc, with the argument that handling water in the field is complex and interferes with the logistics of the work (NAA in solid mixture). The results of NAA applications using NAA in a solid mixture have been equally positive (García et al., 2020). Nevertheless, it is important to consider that using powder products (pneumatic application systems) becomes more complex as the oil palm tree increases in height, so it is necessary to return to the method using NAA in liquid suspension (hydraulic application systems).

In OxG hybrid cultivars, the labor cost accounts for 49% of the production costs of one ton of fresh fruit bunches (FFB), thus constituting the factor with the highest contribution. Pollination is a labor-intensive task because 70–83% of the pollination cost corresponds to payment for labor (Mosquera-Montoya et al., 2019). Therefore, pollination concentrates 15% of the human resources used in OxG oil palm cultivation. Methodological tools should thus be developed to ensure that human resources are used as efficiently as possible. Time and motion studies are among the available tools, with the objective of determining labor performance to establish fair working hours (Hernández Rendón et al., 2022).

Another challenge when using OxG cultivars is that bunch maturity varies among cultivars, and bunch color is not a good criterion to determine when bunches are ripe (Caicedo et al., 2020). This led to another line of research at Cenipalma investigating the optimal harvesting time. This research has shown increases in the oil extraction rate (OER) (Hernández et al., 2020; Sinisterra et al., 2020). These results should be used by businessmen in this industry to redesign their harvest and properly train their workers.

Finally, the economic impact of implementing NAA is also an important issue, as it provides information that supports decision-making not only for oil palm farmers but also for businessmen who are considering investing. Therefore, a cost–benefit analysis of the implementation of NAA is presented in this article.

This article summarizes the results of industrial-scale analysis of the labor productivity of artificial pollination, the effect on the productivity of OxG crops, the optimal harvesting time, and the economic feasibility of implementing NAA. These studies were carried

---

Abbreviations: OxG, *Elaeis oleífera* x *Elaeis guineensis*; NAA, Naphthalene-acetic acid; FBB, Fresh fruit bunches; OER, Oil extraction rate; OHT, Optimal harvesting time; Inf, Inflorescences; CPO, Crude palm oil.

out by the Research Result Validation Unit of Cenipalma in the various landscapes where these cultivars are planted in Colombia and focused on the most widely planted OxG crops in Colombia.

2. Methodology

2.1. Labor productivity of artificial pollination

2.1.1. General information

Studies aimed at determining the labor productivity of artificial pollination were carried out in three of the four oil palm production zones in Colombia, using crops planted with two OxG hybrid cultivars Coarí x La Mé and Brasil x Djongo. The latter are the most widely planted OxG cultivars in Colombia. The crop age ranged from 6 to 14 years. As previously mentioned, the artificial pollination proposed by Cenipalma consisted of three applications of NAA in liquid suspension (Table 1). However, the farms have modified it to include physical mixtures of NAA with talc. In addition, a first application with pollen at anthesis has been proposed (for nut and kernel formation), followed by applications of NAA at 7 and 14 days after the first application. The density of inflorescences to be treated per hectare was variable when the studies were carried out, thus providing insights into production seasonality and its effect on the cost and efficiency of pollination (Table 1). Finally, the amount of NAA mixture (solid or liquid) applied per inflorescence varied among plantations, with NAA ranging from 6 and 8% in the solid mixture and having a concentration of 1,200 ppm in the liquid suspension (Table 1).

2.1.2. Time and motion studies

2.1.2.1. Motion studies

2.1.2.1.1. Process flow diagram

The activities carried out by artificial pollination operators in each plantation were documented over a period of 3 weeks. The observations were made in plantation lots to establish the operational dynamics. The result of this stage of the study is a process flow diagram that summarizes the activities of the artificial pollination tasks. The process flow diagram shows the work cycle, which is defined as the set of activities carried out most frequently during a working day. In the case of artificial pollination, a work cycle corresponds to the activities carried out to complete this task in each palm. Note that the work cycle does not consider activities that are necessary and require a good part of the working day, such as receiving tools and supplies and delivering them to the operator, traveling to and from the assigned lot, and preparing tools and supplies.

2.1.2.2. Time studies

The result of time studies is a summary of the time required for each activity performed by the operator during a working day. A time analyst monitored the artificial pollination operator during full working days (several days, several operators) to measure the time required for each activity. Data collection was performed using a digital form designed with the Cybertracker software (version 3.496). This form included the activities of the process flow diagram and was uploaded onto a smartphone. As each activity was carried out, the time analyst clicked on the activity icon. The software records the exact time of each activity (hour, minutes, and seconds), so their duration is determined from the time difference between different activities. In addition to the process flow diagram, these forms included the name of the pollination operator and the lot where the operator carried out the artificial pollination.

The concept of supplement is defined as time compensation granted for two reasons. The first is the fatigue caused by the conditions in which the work is carried out (heat, humidity, and equipment load). The second corresponds to the time taken for personal activities, such as eating, drinking, and resting. Data of complete working days were collected in these studies, consequently, it was not necessary to estimate the first type of supplements and, only supplements of the second type were taken into account.

Finally, strange items correspond to time lost throughout the working day in activities not related to artificial pollination. This category includes minor repairs to equipment or tools, conversations, calls, and waiting times.

2.1.2.2.1. Statistical design

The time and motion study implies a sampling design, in which the sampling unit corresponds to an oil palm tree. The response variable is the length of time that takes to artificially pollinate an oil palm tree (i.e., all the processes that are part of a work cycle). The sample size was determined by means of Equation (1) which

TABLE 1 General information on the plantations where labor productivity was estimated.

NAA presentation	Zone	Plantation	Cultivar	Crop age	Applications	Inflorescences per ha	Dose per inflorescence
NAA in solid mixture	Central	C1	Coarí x La Mé	13	NAA-NAA-NAA	94	3 g
		C2	Brasil x Djongo	8	NAA-NAA-NAA	122	3 g
		C3	Coarí x La Mé	14	Pollen-NAA-NAA	64	3 g
		C4	Coarí x La Mé	6	Pollen-NAA-NAA	62	4.4 g
	East	O1	Brasil x Djongo	8	NAA-NAA-NAA	123	3 g
	Southwest	S1	Coarí x La Mé	10	NAA-NAA-NAA	60	4.1 g
NAA in liquid suspension	Central	C5	Coarí x La Mé	8	NAA-NAA-NAA	112	120 ppm
		C6	Brasil x Djongo	8	NAA-NAA-NAA	122	150 ppm
	East	O2	Coarí x La Mé	8	NAA-NAA-NAA	123	150 ppm

correspond to a simple random sampling (Hernández Rendón et al., 2022). Data was collected along complete workdays for different workers with average skills (confirmed by the payroll). Workers were randomly selected to being subject of this study.

2.1.2.2.2. Work cycle sample size

The tasks carried out by the operators performing artificial pollination were sampled to define the required number of time measurements. Subsequently, the sample variance and the relative error (5%) were considered using Equation 1 (Camperos et al., 2021).

$$n_0 = \frac{Z^2 * S^2}{E^2} \tag{1}$$

n sub-zero is the calculated sample size, Z = value according to the normal distribution table with a confidence level of 95%, S^2 = sample variance, and E = absolute error. It should be noted that the minimum number of oil palms sampled (work cycle) for each case was approximately 5,000 for the time and motion studies performed in this study.

2.1.3. Estimation of labor productivity

2.1.3.1. Effective working time

The effective working time that an operator spends on artificial pollination tasks during a working day is calculated by the sum of the times required for artificial pollination in an oil palm (work cycles) (Camperos et al., 2021; Mosquera-Montoya et al., 2021).

2.1.3.2. Duration of work cycles

The time required for artificial pollination on an oil palm was categorized according to the number of inflorescences to be treated per oil palm (0, 1, 2, and 3 inflorescences to be treated on an oil palm). The objective was to establish a data recording system that would consider the time variability arising from the number of inflorescences to be treated per palm, which in turn has an impact on the time.

After the necessary time data were collected, they were analyzed by descriptive statistics to determine the standard time. The median is the measure of central tendency most frequently used in time and motion studies to estimate labor productivity, as the histograms of data distribution tend to present a bias to the right. Then, the sum of medians of each activity of the work cycle is used to estimate the duration of the work cycle in seconds according to the number of inflorescences to be treated.

2.1.3.3. Proportion of the different categories

This indicator reflects crop yield. A greater number of female inflorescences is associated with a greater number of bunches in the future. This indicator should be considered when estimating labor productivity because it is often affected by production seasonality. Intuitively, the operator spends more time moving around and inspecting oil palms to find inflorescences to treat than on the application of NAA or pollen to oil palms if there are fewer inflorescences to treat. Two contrasting scenarios were considered: the first scenario corresponds to a high density of inflorescences to be treated per hectare (123 inflorescences/ha) and the second to a low density of inflorescences to be treated per hectare (60 inflorescences/ha).

2.1.3.4. Time per hectare

It is the time spent by an operator to carry out artificial pollination tasks in one hectare. It is calculated according to Equation 2.

$$\text{Time per ha}\left(\frac{h}{\text{ha}}\right) = \frac{\left(\sum_{i=0}^{3} t_i * p_i\right)}{3{,}600} \tag{2}$$

where i is the category according to the number of inflorescences (0, 1, 2, 3); t_i is the duration in seconds of the work cycle according to category; and p is the number of oil palms of each category in one hectare. As time is measured in seconds, 3,600 corresponds to the number of seconds in 1 h (h).

2.1.3.5. Labor productivity per man-day

It is expressed as hectares per man-day (workday) and calculated by the ratio between the effective working time in hours per man-day (workday) and the time per hectare in hours per hectare.

2.1.4. Cost estimation

The labor cost per inflorescence was calculated by dividing the cost per working day by labor productivity in terms of inflorescences per man-day, this term is calculated by multiplying labor productivity (hectares per man-day) by the density of inflorescences per hectare. The cost per working day corresponds to daily minimum wage in Colombia (16 USD), which includes social payments such as contributions to their retirement fund, access to health services, and housing subsidies.

2.2. Optimal harvesting time

2.2.1. General information

The study on the optimal harvesting time (OHT) was carried out in two oil palm production zones in Colombia: Southwest and East. As for the cultivars, in addition to the most frequently cultivated cultivars (Coarí x La Mé and Brasil x Djongo), a cultivar massively planted by small-scale farmers in Tumaco (Cereté x Deli) was also analyzed (Table 2). Adult oil palms aged 10 and 11 years were analyzed. The impact of the implementation of the optimal harvesting time on a commercial scale was investigated in two stages in each plantation:

2.2.2. Stage 1: baseline

Systematic sampling was carried out to assess one bunch per five harvested bunches to ultimately assess at least 200 bunches. It was also sought to have sufficient FFB to process one bunch of the mill and to measure the OER. During this stage, bunches harvested according to

TABLE 2 Characteristics of the plantations where OHT studies were carried out.

Plantation	Oil palm production zone	Cultivar	Age
S2	Southwest	Cereté x Deli	10
S3	Southwest	Brasil x Djongo	11
O3	East	Coarí x La Mé	10

the harvesting criteria traditionally used in the plantation, which is typically a given number of naturally loose fruit, were assessed. The number of loose fruits depends on the OxG cultivar to be harvested. A maturity stage was assigned to each bunch according to the OHT criteria established by Cenipalma, i.e., the number of detached fruits, percentage of fruit cracking, and opacity of fruits (Table 3) (Caicedo et al., 2020). In addition, bunch formation was assessed according to the proposal presented by García et al. (2017), in which a class I bunch has 90.1–100% of fruits, a class II bunch has 70.1–90%, a class III bunch has 50–70%, and a class IV bunch has less than 50% (Figure 1).

2.2.3. Stage 2: implementation of the optimal harvesting time

During this stage, the FFB harvesting criteria previously used by the plantation were modified, and the OHT criteria were implemented for each cultivar for FFB harvesting. The harvesting workers in the plantation were instructed on the OHT criteria. As in Stage 1, systematic sampling was carried out to select the bunches to be assessed (one out of every five bunches) according to bunch formation and maturity, following the same criteria as in Stage 1. As before, it was also sought to have sufficient bunches to process to determine the OER.

2.2.4. Data analysis

OHT assessment did not result from an experimental design. OHT was previously studied by means of experiments carried out by the plant physiology lab from Cenipalma (Caicedo et al., 2020; Romero et al., 2021). Since OHT results were promising the Research Results Validation Unit from Cenipalma scaled up OHT to be tested at plantation level. This is why, our results correspond to three different assessments carried out in fields planted with three different cultivars, each of them managed properly in terms of nutrition and artificial pollination. We compared the OER obtained at two different moments, before implementing OHT and after implementing OHT. One must note that these palm oil extraction rates (OER) result from processing FFB batches up to 40 metric tons. As opposed to estimating oil contents at the lab.

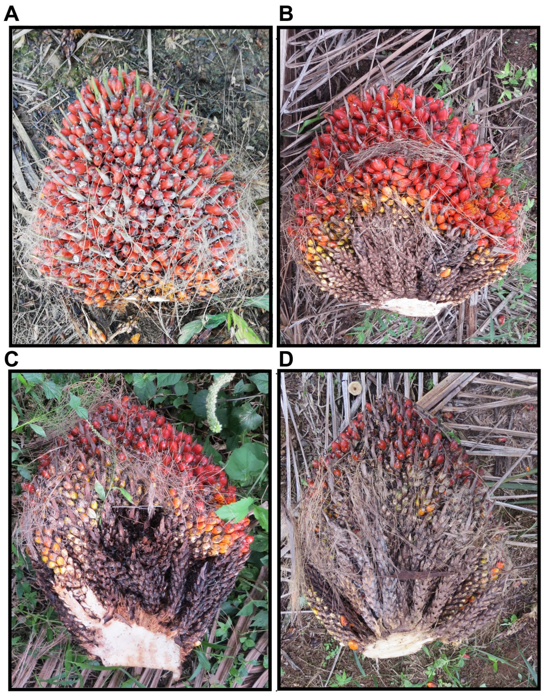

FIGURE 1
OxG hybrid bunch conformation classification scale. Expressed in terms of percentage of fruits properly formed. **(A)** Class I – 90.1–100%. **(B)** Class II – 70.1–90%. **(C)** Class III – 50.1–70%. **(D)** Class IV – Less than 50%. Images: Elizabeth Ruiz and Arley Caicedo.

2.3. Benefit-cost analysis of implementing NAA

Using the methodology proposed by Ruiz-Alvarez et al. (2021), two scenarios were compared: (1) Cultivation of OxG hybrid with assisted pollination using pollen (Pollen) and (2) Cultivation of hybrid with artificial pollination using pollen at anthesis and NAA 7 and 14 days after anthesis (Pollen-NAA-NAA). Historical data from plantations located in Urabá Antioqueño were used for the analysis, given the great range of technologies implemented in these crops. The values were estimated in pesos for the year 2021 and then converted to dollars using the mean exchange rate for 2021 [Colombian pesos (COP) 3,743/USD 1]. The following indicators were estimated.

2.3.1. Costs estimation

2.3.1.1. Cost of pollination

The cost of pollination ($/ha) was estimated based on labor productivity, supply requirements, equipment and tools, and labor supervision.

2.3.1.2. Costs per metric ton of FFB

This was estimated according to the methodology proposed by Mosquera-Montoya et al. (2022), which considers a 30-year crop flow and estimates costs for each production stage (establishment, non-productive stage, development stage, and mature stage). The costs are estimated based on an analysis that considers the performed tasks, task frequency, supplies (doses and prices), and labor (rates and labor productivity). The costs associated with the use of capital goods, opportunity land cost, and those associated with technical assistance and crop supervision are also considered.

The unit cost results from the ratio between the sum of the total expenses for one cultivated hectare during the 30-year life cycle of the crop and the sum of the tons of FFB produced in the same unit area and in the same period. Crop yields differed for each scenario, mainly owing to the mean bunch weight and the percentage of spoiled bunches.

2.3.1.3. Crop net income

This estimates the amount of money generated by one hectare of adult crop in 1 year after deducting the production costs from the gross income (sales). Revenues were estimated based on the production per hectare in each scenario, considering the mean reference price paid for one ton of fruit.

TABLE 3 Characteristics of the bunches according to maturity stage and cultivar.

Cultivar	Stage	Status	Characteristics of the bunch		
			Detachment	Cracking (%)	Opacity
Coarí x La Mé	805	Immature	Not present	Not present	Bright
	806		Not present	Low	Bright
	807	Mature	1–5	More than 40	Opaque
	809		More than 15	Very high	Opaque
Brasil x Djongo	805	Immature	Not present	Not present	Bright
	806		Not present	Not present	Bright
	807	Mature	4–10	Low	Opaque
	809		More than 10	More than 60	Opaque
Ceretè x Deli	805	Immature	Not present	Not present	Bright
	806		1–7	Not present	Opaque
	807	Mature	10–54	Less than 20	Opaque
	809		More than 50	20 to 40	Opaque

Adapted from Caicedo et al. (2020).

2.3.1.4. Costs per metric ton of crude palm oil

Colombian mills are designed to process fruit from *E. guineensis* cultivars. Processing the OxG cultivars leads to a decrease in pressing capacity of at least 15% (Ruiz-Alvarez et al., 2021). This increases the extraction costs because the husk is added to replace the nut, thus increasing energy and labor costs.

This study considered both fixed (plant depreciation) and variable (energy consumption, water consumption, labor, and maintenance) costs for Scenarios 1 and 2 for a mill in Urabá. The production costs reported by Mosquera-Montoya et al. (2022) were used, which considers a 30-year crop flow, and the price paid for the raw material (FFB) would be the crop production cost. In addition, the OER and the kernel extraction rate were analyzed. The latter corresponds to the percentage of clean and dry kernel recovered from one ton of FFB and sold as a by-product of the process, generating revenue (Sue, 1992). The parameters used to estimate the cost of CPO are shown in Table 4.

2.3.1.5. Oil net income

The income generated by one hectare was calculated based on the amount of oil extracted from FFB for each scenario. The production (raw material) and extraction costs are deducted from the gross income resulting from the sale of oil per hectare, resulting in the production cost of one ton of oil. The price parameters used for this analysis are shown in Table 5.

2.4. Statistical analysis

We studied the descriptive statistics of the data gathered (mean, standard deviation, maximum and minimum). For the work cycles time length, depending upon the number of inflorescences to be treated per palm, we performed a normality test and homoscedasticity test to decide whether using parametric data analysis (ANOVA) or non-parametric data analysis (Kruskal-Wallis). The null hypothesis was that the average time length for all categories was equal (significance level 0.05).

TABLE 4 Parameters used to estimate oil production cost.

Parameter	Pollen	Pollen + ANA
Nominal processing capacity (t FFB/h)	12	12
Reduction in processing capacity (%)		−15%
Amount of husk added to process FFB (%/t processed FFB)	10%	10%
Oil extraction rate (OER) (%)	20.6	23.5
Amount of fruit to produce one ton of oil (t)	4.85	4.26
Kernel extraction rate (%)	2.5%	0%

TABLE 5 Parameters to estimate the oil net income per hectare.

Parameter	Price
Price per ton of oil ($/t CPO)	USD 1022
Price per ton of FFB ($/t FFB)	USD 173
Price per ton of kernel ($/t kernel)	USD 321
Husk ($/t husk)	USD 53.4

3. Results and discussions

3.1. Labor productivity of artificial pollination

3.1.1. Process flow diagram

Table 6 presents the process flow diagram that summarizes the activities carried out in all companies where studies on artificial pollination were completed. The activities in dark cells correspond to the artificial pollination work cycle.

3.1.2. Time per activity of the working day

Time studies showed that the working day of an artificial pollination operator lasted on average 7.09 h in the companies where the studies were carried out (Table 7). The effective time, i.e., the time

TABLE 6 Process flow diagram for artificial pollination.

No.	Activity	Description
10	Receiving equipment and supplies	The operator is assigned to the lot and receives equipment, tools, and supplies (mixture) to carry out artificial pollination
15	Moving to the lot	Travel from the point of delivery of equipment and supplies to the assigned lot
20	Preparation	The operator puts on personal protective equipment and prepares the equipment, tools, and supplies (NAA/Pollen)
25	Moving outside the lot	Movements outside the lot that do not correspond to work cycles
30	Moving inside the lot	Movement of the operator from one oil palm to the next
35	Inspection	Search for inflorescences at anthesis to apply NAA/Pollen or for inflorescences that require a second and third application of NAA
40	Decision-making	Any inflorescences still requiring an application? Yes: continue to 45 No: continue to 70
45	Decision-making	Is the inflorescence in its first application? Yes: continue to 50 No: continue to 55
50	Bract opening	Removal of the peduncular bracts of the inflorescence to be pollinated
55	Leaf marking	Marking of the base of the leaf holding the inflorescence
60	Decision-making	Is the pump empty? Yes: continue to 65 No: continue to 70
65	Pump filling	Filling of the application equipment with liquid and solid NAA
70	NAA/Pollen application	NAA/Pollen application on the inflorescence as applicable
75	Data collection	Record data in digital, paper, or manual form Continue to 35
80	Decision-making	End of labor? Yes: continue to 85 No: continue to 30
85	Moving to the warehouse	Operator moves from the lot to the warehouse (company)
90	Delivery of equipment	Operator delivers equipment, tools, and surplus supplies (if any)

spent by the operator pollinating oil palms was 3.47 h, i.e., 48.9% of the working day was dedicated to work cycles. The time spent on supplements and strange items accounted for 1.24 h and 0.62 h (37.2 min), respectively. Regarding the latter, it is possible to improve the process because most of the time on strange items corresponded to minor repairs to pollination equipment (such as nozzle clogging and pump pressure adjustments) and unnecessary waiting time. Therefore, more robust equipment and better logistics for NAA delivery in the field are two issues that can be improved to increase labor productivity. Another factor affecting artificial pollination was reported by Camperos et al. (2020), who measured a transportation waiting time up to 1,5 h at a plantation from Colombia. In that case, a recommendation to the managerial staff was to improving personnel transportation processes, so workers could dedicate more time to the task assigned (i.e., artificial pollination).

3.1.3. Labor productivity

Labor productivity was estimated for the two limits of the range of inflorescence density per hectare density found at the time the studies were carried out (i.e., 60 and 123 inflorescences per hectare). As previously noted, this indicator represents FFB production seasonality and is closely related to crop yield (Table 8). Inflorescence density reported in this work are consistent with those found in other pollination studies, that reported inflorescences densities ranging from 50 to 130 inflorescences per hectare (García et al., 2020; Camperos et al., 2021; Hernández Rendón et al., 2022).

A hectare with a low density of inflorescences concentrated the number of oil palms per category in the categories of 0 and 1 inflorescence to treat per oil palm, with both accounting for 93% of the work cycles. On the contrary, in the scenario with the highest density of inflorescences per hectare, 81% of the oil palms had at least one inflorescence to treat (Table 8).

Results from ANOVA and means comparison (Tukey) yielded significant statistical differences for artificial pollination time length among palms with no inflorescences to treat, with one inflorescence to treat and two/three inflorescences to treat (p-value ≤ 0.001). Palms with two or three inflorescences to treat did not yield significant statistical differences in terms of artificial pollination time length (Table 9). The shortest work cycle was found for oil palms without inflorescences to treat, so the operator's work cycle only consisted of searching for inflorescences in the crown, which took 14.82 ± 3.84 s on average. Once the operator determined that there were no inflorescences to treat, he moved to the next oil palm tree. In the case of oil palms with three inflorescences to treat, the work cycle consisted of carrying out the work cycle operations three times (inspection, marking, application, and registration), which required 93.68 ± 15.26 s on average. Once finished, the operator moved to the next oil palm tree (Table 9). The time length of work cycles per palm found in our study were consistent to those reported by other studies according to which, the time to treat a palm with 0 inflorescences ranged between 12.7 and 17.7 s; while treating a palm with three inflorescences took between 74 and 110.4 s (Camperos et al., 2020; Hernández Rendón et al., 2022).

As described in the Methodology section, the time spent on each work cycle for each category multiplied by the number of work cycles for each category provided the time spent by the operator on pollination tasks on one hectare. Thus, 0.9 h was required for a density of 60 inflorescences per hectare, whereas 1.5 h was required for a density of 123 inflorescences per hectare. Based on this value, the artificial pollination operator covered 3.5 ha (210 inflorescences) in a low inflorescence density (60 inflorescences per ha) scenario during the effective working time and, covered 2.2 ha in a high inflorescence density scenario (Table 8). Our observed labor productivity is lower than that reported by Ruiz et al. (2015) and Fontanilla Díaz et al. (2016), who estimated between 7 and 12 ha/day for assisted pollination,

TABLE 7 Time per activity and contribution of each activity to the working day.

No.	Activity	Time elapsed average (h) ± standard deviation	Average contribution (%)	Minimum	Maximum
10	Receiving equipment and supplies	0.22 ± 0.13	3.2%	0.07	0.32
15	Moving to the lot	0.25 ± 0.07	3.5%	0.2	0.33
20	Preparation	0.41 ± 0.12	5.8%	0.26	0.55
25	Moving outside the lot	0.27 ± 0.14	3.8%	0.11	0.38
30	Moving inside the lot	0.73 ± 0.51	10.3%	0.41	1.64
35	Inspection	0.96 ± 0.46	13.5%	0.41	1.64
50	Bract opening	0.56 ± 0.35	7.9%	0.26	1.05
55	Leaf marking	0.26 ± 0.08	3.7%	0.18	0.35
65	Pump filling	0.24 ± 0.09	3.4%	0.08	0.31
70	NAA/Pollen application	0.61 ± 0.2	8.6%	0.38	0.83
75	Data collection	0.35 ± 0.24	4.9%	0.04	0.68
85	Moving to the point of delivery of equipment and supplies	0.34 ± 0.05	4.8%	0.3	0.39
90	Delivery of equipment	0.03 ± 0.04	0.4%	0.003	0.07
95	Supplements	1.24 ± 0.87	17.5%	0.46	2.5
100	Foreign items	0.62 ± 0.39	8.7%	0.18	0.92
Duration of the working day		7.09	100%		
Effective working time (blue activities)		3.47	48.90%		

TABLE 8 Simulation of labor productivity and cost per inflorescence for two contrasting scenarios of inflorescences densities.

Density of inflorescences (inf/ha)	60				123			
Categories	0 inf	1 inf	2 inf	3 inf	0 inf	1 inf	2 inf	3 inf
Number of oil palms per category per ha	65	41	8	1	23	64	25	3
Category contribution	57%	36%	7%	1%	20%	56%	22%	3%
Average duration of work cycle (s)	14.82	49.04	83.56	93.68	14.82	49.04	83.56	93.68
Time per category (h/category)	0.27	0.56	0.19	0.03	0.09	0.87	0.58	0.08
Total time per hectare (h/ha)	1.05				1.62			
Labor productivity (ha/man-day)	3.12				2.02			
Labor productivity (inf/man-day)	188				249			
Labor cost per NAA application (USD/inf)	0.09				0.06			
Cost of supplies per NAA application (USD/inf)	0.018							
Total cost per application (USD/inf)	0.108				0.078			

which consisted in applying only *E.guineensis* pollen on inflorescences in the stage of anthesis (just once). The lower labor productivity when implementing artificial pollination is explained by the need of treating each inflorescence three times. The difference on number of bunches formed and fruit set (bunch conformation) have boosted the adoption of artificial pollination over assisted pollination (Romero et al., 2021).

3.2. Optimal harvest time

3.2.1. Evaluations at the field and at the palm oil extracting mill

Bunch conformation results from the pollination tasks. A good pollination ensures that bunches are in Class I and II, meaning that more than 70% of the bunch fruits have formed. In the case of the work carried out in Cereté x Deli in Stage 1, 88% of the bunches were well formed, whereas this percentage was 81% in Stage 2. For the work carried out in Brasil x Djongo, 94 and 99% of the bunches were well-formed in Stages 1 and 2, respectively. The study undertaken on Coarí x La Mé had a percentage of well-formed bunches of 82 and 88.5% in Stages 1 and 2, respectively. The fact that bunches were well-formed at all studies indicates that those figures were comparable because the pollination tasks were carried out correctly. Properly carried out NAA applications on inflorescences at an industrial level, confirms what was observed by Romero et al. (2021) at their experiments. In fact, a properly treated inflorescence, yield a fresh fruit bunch well conformed, with conformation values higher than 80% (Romero et al., 2021).

TABLE 9 Average elapsed time of work cycles by category (inflorescences per palm).

Categories	Average elapsed time of work cycle (s)	Standard deviation (s)	Minimum (s)	Maximum (s)	Normality test (*p*-value)*	Group (Test Tukey)**
0 inf	14.82	3.83	11	20	0.3844	a
1 inf	49.04	12.53	35.7	69	0.604	b
2 inf	83.56	20.59	65	110.4	0.2357	c
3 inf	93.68	15.26	79.5	116	0.4423	c

*Data normality. p-value ≤ 0,05, reject null hypothesis (H_0 = data normal distribution).
**Categories with the same letter do not present statistical significant differences (p-value ≤ 0.05).

Regarding bunch maturity, bunches are considered immature if harvested at stages 805 and 806, which has a negative impact on the oil content of the fruits. Conversely, bunches are considered mature if harvested at stages 807 and 809. Implementing the OHT increased the percentage of mature bunches in all three cases. Specifically, the percentage of harvested mature bunches for Cereté x Deli increased from 70.7% in Stage 1 to 100% in Stage 2. As for Brazil x Djongo, the percentage of mature bunches increased from 47% in Stage 1 to 82.1% in Stage 2. Finally, the percentage of mature bunches for Coarí x La Mé increased from 29% in Stage 1 to 97.9% in Stage 2 (Table 10).

Most studies on bunch maturity determine oil yield by conducting oil extractions in the laboratory. Our results came from OER measured in the mill, which is a relevant contribution. Note that OER increased by 6.01 points from Stage 1 to Stage 2 for Cereté x Deli, which represented a 29.7% increase in the amount of oil extracted per ton of FFB. In the case of Brazil x Djongo, the OER increased by 1.41 points, representing a 6% increase in the amount of oil extracted per ton of FFB. Finally, Coarí x La Mé evidenced an increase of 5 points in the OER, equivalent to a 27% increase in the amount of oil extracted per ton of FFB (Table 10). Our results confirmed that changing the harvesting criteria led to increasing the FFB oil content, providing a practice strongly directed toward sustainable intensification of oil palm cultivation. These results are in line with previous reports from OxG crops from three different high yielding Colombian plantations where; by implementing OHT they obtained an average yield increase from 40 to 43.1 t FFB/ha per year and, an average OER increase from 25.1 to 27.3%. These figures allowed companies to get about 11 t CPO/ha per year (Romero and Ayala-Díaz, 2021).

TABLE 10 Effect of the optimal harvest time on the proportion of bunches cut according to their developmental stage.

Plantation	Cultivar	Stages	Bunch maturity		OER (%)
			Stage	(%)	
S2	Cereté x Deli	Stage 1. Baseline	805	0.5	20.23
			806	28.8	
			807	59.8	
			809	10.9	
		Stage 2. OHT criteria	805	0	26.24
			806	0	
			807	28	
			809	72	
S3	Brasil x Djongo	Stage 1. Baseline	805	6	23.62
			806	47	
			807	43	
			809	4	
		Stage 2. OHT criteria	805	2.6	25.03
			806	15.3	
			807	77.3	
			809	4.8	
O3	Coarí x La Mé	Stage 1. Baseline	805	20	18.38
			806	51	
			807	11	
			809	18	
		Stage 2. OHT criteria	805	0	23.39
			806	2.1	
			807	21.3	
			809	76.6	

3.2.2. Cost-benefit of artificial pollination

3.2.2.1. Pollination costs

Figure 2 depicts the pollination costs according to each scenario. A cost of USD 326/ha per year was estimated when only pollen was used, which increased by 39% when the two NAA applications were implemented to a total of USD 452/ha per year. The labor cost increased by 14% as a result of changes in labor productivity. Note that Scenario 2 requires three applications on inflorescences instead of one that characterizes Scenario 1. Regarding supplies, the increase in cost was 210% because the two booster NAA applications represent an additional investment.

3.2.2.2. Costs per hectare

An increase of 13% in cropping costs was observed in Scenario 2 (from USD 2,580 to USD 2,918) because, in addition to the extra pollination cost, a greater amount of fertilizer was required for nutrient replacement, with also greater costs for harvesting and transporting FFB to the mill (Table 11).

3.2.2.3. Costs per metric ton of FFB

NAA application results in a higher number of bunches, which were previously lost for not reaching anthesis, and a lower number of malformed bunches. However, less nut was produced, which decreased the mean bunch weight. The net effect was a 6% increase in

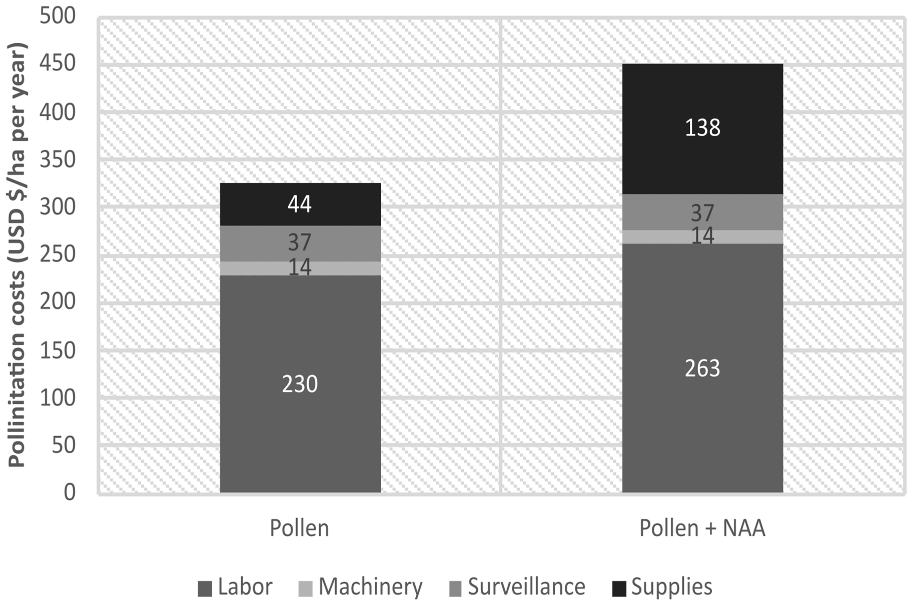

FIGURE 2
Pollination costs for each method.

TABLE 11 Unit crop production cost.

Item	Pollen	Pollen + NAA
Number of bunches/ha per year	2,042	2,414
Mean bunch weight (kg/bunch)	17.8	15.9
Productivity (t FFB/ha/year)	36.4	38.4
Annual cost (USD/ha)	2,580	2,918
Unit cost (USD/t FFB)	77.5	78.1
Gross income (USD/ha per year)	6,317	6,671
Net income (USD/ha per year)	3,500	3,673

crop yield (Table 11). The result was an increase of 0.8% in the cost per ton of FFB from USD 77.5 to USD 78.1 (Table 11).

3.2.2.4. Crop net income

The net crop income increased by 5% in Scenario 2 as a result of the increase in crop yield (Table 11). Therefore, the greater FFB yield compensated for the increase in unit cost. This result contradicts the notion that implementing NAA only benefits those in the palm oil extraction business.

3.2.2.5. Costs per ton CPO

The cost of a ton of oil decreased by 3% when moving from Scenario 1 to Scenario 2. Such variation is related to the oil content of FFB, which materializes in the OER. In the case studied, an OER of 20.6% was reported for Scenario 1, whereas Scenario 2 had an OER of 23.5%. This is due to Scenario 2 requiring fewer bunches to produce one ton of oil (Figure 3).

3.2.2.6. Oil net income per hectare

The net income generated per hectare per year increased by 22% when Scenario 2 was implemented instead of Scenario 1. This is a considerable change in business profitability and results from an increase from 7.6 tons (Scenario 1) to 9.1 tons (Scenario 2), which corresponds to an increase of 19% in oil production per hectare (Table 12).

These results are in line with those reported by Mosquera-Montoya et al. (2022), who state that Adopting NAA implies greater financial resources to be invested in the cropping stage of the palm oil value chain in terms of USD per hectare. Additionally, one must consider the loss in efficiency at the oil extraction process which also implies an extra cost in terms of USD per metric ton of FFB processed at the oil palm mill (Mosquera-Montoya et al., 2022). However, the greater amount of FFB obtained at the field and the increase in the oil content of FFB, offset the greater spendings yielding on a more profitable business (Mosquera-Montoya et al., 2022). Additionally, it was evident at the Colombian oil palm agroindustry that almost all planters having OxG crops adopted rapidly artificial pollination (Arias et al., 2023).

4. Conclusion

This article summarizes the results of studies aimed at determining the labor productivity of artificial pollination operators on an industrial scale and the impact of using OHT criteria on OER. Studies were carried out in OxG Coarí x La Mé and Brasil x Djongo hybrid cultivars in all oil palm production zones. Artificial pollination was analyzed using NAA in liquid suspension and NAA in a solid mixture. Although the latter does not correspond to the technology developed by Cenipalma (NAA in liquid suspension), it maintains the biological principles for the induction of oily parthenocarpic fruits. In fact, NAA in a solid mixture was developed by Colombian oil palm agroindustry companies that found logistic advantages in not transporting water to perform the work.

The results of the time and motion studies provide sufficient information on the activities required for artificial pollination and its productivity. This information is very helpful to those in charge of planning the pollination work (logistics and personnel allocation) because it shows that the area to be allocated per day depends on two

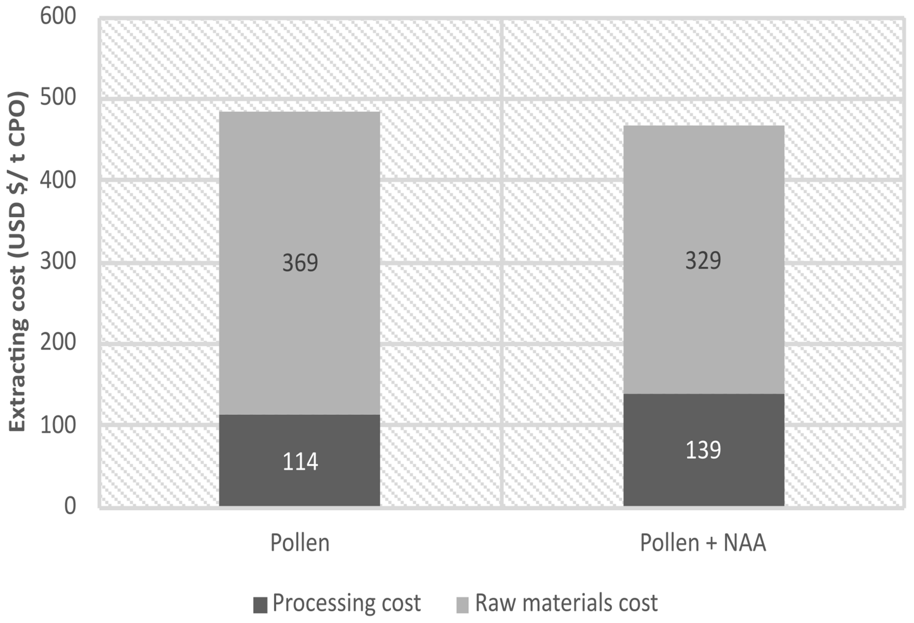

FIGURE 3
Oil extraction cost of one ton of crude oil palm.

TABLE 12 Oil net income per hectare.

Item	Pollen	Pollen + NAA
Oil production (t CPO/ha per year)	7.6	9.1
Gross income (USD/ha per year)	7,655	9,221
Costs (USD/ha per year)	3,690	4,382
Net income (USD/ha per year)	3,964	4,838

factors. The first is the density of inflorescences, which depends on crop yield and production seasonality. The second factor is the height at which inflorescences are located, as not only inflorescences at a greater height are more difficult to inspect, but it is also harder to apply a liquid suspension than a solid mixture to these inflorescences. The impact of this second factor should be evaluated in future studies when oil palms are taller.

Regarding commercial-scale work aimed at assessing the OHT for fruit harvesting, the objective of harvesting is to maximize the amount of oil to be delivered to the mill. The results of harvesting bunches in the OHT were obtained for Coarí x La Mé, Brasil x Djongo, and Ceretté x Deli cultivars. OER values were compared using the FFB harvesting criteria of the plantation (baseline) with respect to the implementation of the OHT criteria, with increases of 6 to 27% in the OER. This has a direct impact on the amount of oil produced per unit area, and, therefore, on the business profitability.

Finally, the benefit–cost analysis investigated the economic feasibility of changing the strategy using assisted pollination with pollen of *E. guineensis* at anthesis to a strategy that complements assisted pollination with two applications of NAA at 7 and 14 days after anthesis, and the results showed that the cost of one ton of FFB increased by 0.8%, but a greater amount of FFB was produced; thus, the net crop income increased by 5%. Moreover, a higher OER means fewer tons of FFB are required to produce CPO, and, therefore, the cost of one ton of oil decreases by 3%.

Data availability statement

Results of the data analysys are presented in the article, any further inquiries may be directed to the corresponding author.

Author contributions

MM-M contributed to conception, methodological approach, and raise funds for carrying out this research. JEC, DH, AG, and KS carried out the field studies at the different Colombian oil palm growing zones. ER, DM, and EM carried out the economic assessment of the data and estimated unit costs. EM and LV designed the data gathering strategies and carried out data Analysis. MM-M, JEC, and ER wrote the final draft. All authors contributed to the article and approved the submitted version.

Acknowledgments

Authors are grateful to The Fondo de Fomento Palmero (FFP) which provided the funds to perform this research. The authors are also grateful to the staff from the oil palm companies that participated in these studies. Finally, the authors would like to express our gratitude to the reviewers of our paper, who provided us with valuable corrections and insights that helped us improving our work.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Arias, N., Beltrán, J., Camperos, J. E., and García, J. (2023). "Tiempos de inversión, reducir la incertidumbre e incrementar la productividad" in *51° Congreso Nacional de Cultivadores de Palma de Aceite 2023.*

Avila-Diazgranados, R., Daza, E. S., Navia, E., and Romero, H. M. (2016). Response of various oil palm materials (Elaeis guineensis and *Elaeis oleifera* × *Elaeis guineensis* interspecific hybrids) to bud rot disease in the southwestern oil palm-growing area of Colombia. *Agron. Colomb.* 34, 74–81. doi: 10.15446/agron.colomb.v34n1.53760

Caicedo, A., Millan, E., Ruiz, R., and Romero, H. M. (2020) Criterios de cosecha en cultivares híbrido: características que evalúan el punto óptimo de cosecha en palma de aceite. *Cenipalma*. 1–52.

Camperos, J. E., Barrera, E., and Mosquera-Montoya, M. (2021). Estudo de tempos e movimentos para mensurar a produtividade da mão de obra nas plantações de palma de azeite de palma na Colômbia: O caso da polinização artificial. *Revista Eletrônica Competências Digitais para Agricultura Familiar* 7, 146–171. Available at: https://owl.tupa.unesp.br/recodaf/index.php/recodaf/article/view/137/317

Camperos, J. E., Pulido, N. F., Munévar, D. E., Torrecilla, E., Requena, J. A., Arias, H. A., et al. (2020). Estudio de tiempos y movimientos para la polinización artificial: estudio de caso en una plantación de la Zona Central. *Revista Palmas* 41, 11–23.

Cooman, A. (2023) in *Los híbridos interespecíficos OxG de palma de aceite*. ed. H. M. Romero.

Daza, E., Ayala-Díaz, I., Ruiz-Romero, R., and Romero, H. M. (2020). Effect of the application of plant hormones on the formation of parthenocarpic fruits and oil production in oil palm interspecific hybrids (*Elaeis oleifera* Cortes x *Elaeis guineensis* Jacq.). *Plant Prod. Sci.* 24, 354–362. doi: 10.1080/1343943X.2020.1862681

Enviromental Protection Agency (2012). 1-Naphthaleneacetic acid; pesticide tolerances. *Federal Register Daily J. United States of Government* 77, 26954–26959. Available at: https://www.govinfo.gov/content/pkg/FR-2012-05-08/pdf/2012-11117.pdf

Fontanilla Díaz, C., Romero, V. R., Fuquen, E. M., Mariño, D., González, E. B., and Montoya, M. M. (2016). Estimación del rendimiento de la mano de obra en labores de cultivo de palma de aceite: caso polinización asistida. *Revista Palmas* 37, 21–35.

Forero, D., Hormaza, P., Moreno, L., and Ruiz, R. (2012) Generalidades sobre la morfología y fenología de la palma de aceite. Colciencias - Cenipalma. 1–152.

García, A., Ibagué, D. F., Munévar, D. E., Hernández, J. S., and Mosquera, M. (2020). Polinización artificial: ¿ANA en suspensión líquida o ANA en mezcla sólida? *Palmas* 41, 15–26. doi: 10.56866/issn.0121-2923

García, J., Cortés, I., Caballero, K., and Ramírez, N. (2017). "Challenges in processing fresh fruit bunches from interspecific hybrid cultivars (OxG). En conventional palm oils Mills in Colombia" in *International Palm Oil Congress and Exhibition (PIPOC).* Malaysian Palm Oil Board (MPOB). Kuala Lumpur.

Guataquira, S., Mesa-Fuquen, E., Ruíz-Romero, R., and Romero-Angulo, H. M. (2019). Evaluación de la viabilidad y germinabilidad del polen durante la labor de polinización asistida en campo. *Revista Palmas* 40, 13–20.

Hernández Rendón, D. A., Daza, E. S., Acosta Hernández, Y. A., and Mosquera-Montoya, M. (2022). Assessing the labor productivity of two methods of artificial pollination in oil palm crops from Colombia. *OCL Oilseeds Fats, Crops Lipids* 29, 12–10. doi: 10.1051/ocl/2022006

Hernández, D., Rodríguez, J., Daza, E., Lemus, L., and Mosquera, M. (2020). Implementación del punto óptimo de cosecha sobre racimos del híbrido interespecífico OxG (Coarí x La Mé) asperjados con reguladores de crecimiento en la plantación Oleaginosas San Marcos. *El Palmicultor* 580, 16–17.

Hormaza, P., Forero, D., Ruiz, R., and Romero, H. M. (2010). *Fenología de la palma de aceite africana (Elaeis guineensis Jacq.) y del híbrido interespecfico (Elaeis oleifera (Kunt) Cortes x Elaeis guineensis Jacq.).* Bogotá: Colciencias - Cenipalma, 1–110.

Lerner, A. M., Zuluaga, A. F., Chará, J., Etter, A., and Searchinger, T. (2017). Sustainable cattle ranching in practice: moving from theory to planning in Colombia's livestock sector. *Environ. Manag.* 60, 176–184. doi: 10.1007/s00267-017-0902-8

Lietzow, C. D., Zhu, H., Pandey, S., Havey, M. J., and Weng, Y. (2016). QTL mapping of parthenocarpic fruit set in north American processing cucumber. *Theor. Appl. Genet.* 129, 2387–2401. doi: 10.1007/s00122-016-2778-z

Martínez, G., Sanz, J., Torres, G., Sarria, G., Vélez, D., Zúñiga, F., et al. (2018). "The integrated management of bud rot disease and Phytophthora palmivora in oil palm" in *Achieving sustainable cultivation of oil palm*. ed. A. Rival. *2nd* ed (London: Burleigh Dodds Science Publishing)

Mosquera-Montoya, M., Ruiz, E., Munévar, D. E., Estupiñán, M. C., Díaz, L., Guerrero, A., et al. (2022) Costos de producción para empresas que adoptan mejores prácticas en el año 2020. Available at: www.cenipalma.org.

Mosquera-Montoya, M., Lopéz-Alfonso, D., Ruíz-Álvarez, E., Valderrama-Villanobona, M., and Castro-Zamudio, L. E. (2019). Mano de obra en cultivos de palma aceitera de Colombia: participación en el costo de producción y demanda. *Revista Palmas* 40, 46–54.

Mosquera-Montoya, M., Camperos, J. E., García, A., Sinisterra, K., Munévar, D., Ruiz, E., et al. (2021). Tecnologías validadas a escala comercial para el manejo del híbrido interespecífico OxG. Boletín Técnico No. 39. *Cenipalma*. 1–77.

Prada, F., and Romero, H. M. (2012) *Muestreo y análisis de racimos en el cultivo de la palma de aceite. Tecnologías para la agroindustria de la palma de aceite: guía para facilitadores. 1.* Bogotá: Cenipalma.

Qian, C., Ren, N., Wang, J., Xu, Q., Chen, X., and Qi, X. (2018). Effects of exogenous application of CPPU, NAA and GA on parthenocarpy and fruit quality in cucumber (*Cucumis sativus* L.). *Food Chem.* 243, 410–413. doi: 10.1016/j.foodchem.2017.09.150

Rincón, S., Hormaza, P. A., Moreno, L. P., Prada, F., Portillo, D. J., Nuñez, J. A. G., et al. (2013). Use of phenological stages of the fruits and physicochemical characteristics of the oil to determine the optimal harvest time of oil palm interspecific OxG hybrid fruits. *Indust. Crops Prod. J.* 49, 204–210. doi: 10.1016/j.indcrop.2013.04.035

Romero, H. M., and Ayala-Díaz, I. (2021). Cómo alcanzar 10 toneladas de aceite por hectárea: tecnologías de manejo de los híbridos interespecíficos OxG hacia una producción altamente eficiente. *Revista Palmas* 42, 55–64. Available at: https://publicaciones.fedepalma.org/index.php/palmas/article/view/13449/13190

Romero, H. M., Daza, E., Ayala-Díaz, I., and Ruiz-Romero, R. (2021). High-oleic palm oil (Hopo) production from parthenocarpic fruits in oil palm interspecific hybrids using naphthalene acetic acid. *Agronomy* 11, 1–18. doi: 10.3390/agronomy11020290

Ruiz, E., Fontanilla, C., Mesa, E., Mosquera, M., Molina, D., and Rincón, A. (2015). Prácticas de manejo y costos de producción de la palma de aceite híbrido OxG en plantaciones de la Zona Oriental y Suroccidental de Colombia*. *Palmas* 36, 11–29.

Ruiz-Alvarez, E., Daza, E. S., Caballero-Blanco, K., and Mosquera-Montoya, M. (2021). Complementing assisted pollination with artificial pollination in oil palm crops planted with interspecific hybrids O × G (*Elaeis guineensis* × *Elaeis oleifera*): is it profitable? *OCL Oilseeds Fats, Crops Lipids* 28:27. doi: 10.1051/ocl/2021014

Sánchez, Á., Daza, E., Ruíz, R., and Romero, H. M. (2011). *Polinización asistida en palma de aceite. Tecnologías para la agroindustria de la palma de aceite: guía para facilitadores. 1.* Bogotá: Cenipalma. 1–168.

Sekaran, U., Lai, L., Ussiri, D. A. N., Kumar, S., and Clay, S. (2021). Role of integrated crop-livestock systems in improving agriculture production and addressing food security – a review. *J. Agricult. Food Res.* 5, 100190–100110. doi: 10.1016/j.jafr.2021.100190

Sinisterra, K., Caicedo, A., Castilla, C., Ceballos, D., Cortés, I., Camperos, J. E., et al. (2020). Validación a escala comercial del punto óptimo de cosecha para el cultivar híbrido interespecífico OxG Cereté x Deli. *Revista Palmas.* 42, 15–23.

Socha, J., Cayón, D., Ligarreto, G., and Chaves, G. (2019). Effect of pollen doses on fruit formation and oil production in two hybrid palm genotypes (*Elaeis oleifera* H.B.K. Cortes x *Elaeis guineensis* Jacq.). *Agron. Colomb.* 37, 12–17. doi: 10.15446/agron.colomb.v37n1.75313

Sue, T. T. (1992). Calidad actual del palmiste y del aceite de palmiste. *Palmas* 13, 55–66.

Taiz, L., Murphy, A., Monshausen, G., and Peer, W. (2017). "Sinais e Transdução de Sinal" in *Fisiologia e desenvolvimento vegetal*. 6th ed, Artmed. 407–445.