Influence of naphthaleneacetic acid on the yield and bunch composition of the interspecific O × G hybrid of oil palm

Influencia del ácido naftalenacético en el rendimiento y la composición del racimo del híbrido interespecífico O × G de palma de aceite

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ABSTRACT

The interspecific hybrid O × G of oil palm is a promising genotype whose cultivated area in Colombia has increased in recent years due to its high productivity attributed to the formation of parthenocarpic fruits and its outstanding diseases tolerance. This study aimed to evaluate the effect of two forms of naphthaleneacetic acid, applied at different concentrations, on bunch composition variables that explain the yield of oil palm hybrids. A split-plot experimental design was employed, where the main factor was the type of auxins and the subfactor was dosage. A total of 31 bunch composition variables were evaluated through correlation analysis, principal component analysis, and a predictive yield model. Oil production was primarily associated with fruit set, bunch weight, and the weight of parthenocarpic fruits. There was no significant correlation with normal fruit traits such as seed weight or the kernel and seed-to-fruit ratio. The proposed model successfully explains oil yield based on the evaluated variables, which were influenced by the type and dose of auxin. The optimal response was obtained with 450 mg L^{-1} of sodium salt naphthaleneacetic acid (NAAS) and 1200 mg L^{-1} of naphthaleneacetic acid (NAA). These treatments promoted an ideal fruit set, increased parthenocarpic fruit weight, bunch weight, and oil-to-bunch ratio, as reflected in yield. These findings confirm the potential of auxins to enhance productivity and offer valuable insights for genetic improvement and the sustainability of oil palm cultivation.

Keywords: auxins, *Elaeis oleifera* (Kunth) Cortés × *Elaeis guineensis* Jacq., oil palm hybrid, artificial pollination, parthenocarpic fruits, oil production.

RESUMEN

El híbrido interespecífico O × G de palma de aceite es un genotipo promisorio cuya área de siembra en Colombia ha aumentado en los últimos años debido a su elevada productividad atribuida a la formación de frutos partenocárpicos y a su sobresaliente tolerancia a enfermedades. Esta investigación tuvo como objetivo determinar el efecto de dos moléculas de ácido naftalenacético, aplicadas en diferentes concentraciones, sobre las variables de composición del racimo que explican el rendimiento del híbrido de palma de aceite. Se empleó un diseño experimental de parcelas divididas, donde el factor principal fue el tipo de auxinas y el subfactor fue la dosis. Se evaluaron un total de 31 variables de composición del racimo mediante análisis de correlación, análisis de componentes principales y un modelo predictivo de rendimiento. La producción de aceite se asoció principalmente con el cuajado, el peso del racimo y el peso de los frutos partenocárpicos. No hubo correlación significativa con los rasgos normales de los frutos, como el peso de las semillas o la relación entre el grano y la semilla y el fruto. El modelo propuesto explica con éxito el rendimiento de aceite basándose en las variables evaluadas, que se vieron influidas por el tipo y la dosis de auxina. La mejor respuesta se obtuvo con 450 mg L^{-1} de sal sódica de ácido naftalenacético (SANA) y con 1200 mg L^{-1} de ácido naftalenacético (ANA), tratamientos que promovieron el llenado de los frutos, incrementaron el peso de los frutos partenocárpicos y del racimo, así como el porcentaje de aceite en racimo, reflejándose en un mayor rendimiento. Estos resultados confirman el potencial de las auxinas para mejorar la productividad y aportan información clave para el mejoramiento genético y la sostenibilidad del cultivo.

Palabras clave: auxinas, *Elaeis oleifera* (Kunth) Cortés × *Elaeis guineensis* Jacq., híbrido de palma de aceite, polinización artificial, frutos partenocárpicos, producción de aceite.

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Introduction

Oil palm is one of the world's most significant oil crops due to its high productivity, its applications in industry, as human food, animal feed, nutraceutical products, and biofuel production. Global demand for palm oil is projected to reach 156 million t by 2050 (Murphy *et al*., 2021; Pirker *et al*., 2016). Increased oil production can be achieved without requiring more land or additional water, energy and fertilizers for crop cultivation, considering environmental protection and climate change (Chew *et al*., 2021). Colombia stands as the largest oil palm producer in Latin America and the fourth worldwide, playing a key role in meeting the growing global demand through sustainable intensification practices (Corley & Tiker, 2015; Fedepalma, 2015; Fedepalma, 2021). The primary source of commercial palm oil production comes from the species *Elaeis guineensis* Jacq., the African oil palm (Corley & Tiker, 2015). However, in recent years in Colombia, the O × G hybrid has emerged as a productive alternative to achieve higher yields without expanding the area of cultivated oil palm through the induction of parthenocarpic fruits (PF) (Daza *et al*., 2020; Nieto Mogollon *et al*., 2024; Romero *et al*., 2021).

O x G interspecific hybrids are derived from a cross between the two most notable species, the American oil palm, *Elaeis oleifera* (Kunth) Cortés, and the African oil palm *Elaeis guineensis* Jacq. (Arias *et al*., 2015). These show intermediate characteristics between their parental stock in certain agronomically interesting aspects, such as their high-quality oil rich in oleic acid and exhibiting high productivity potential (Avila *et al*., 2016; Montoya *et al*., 2023). These hybrids are partially resistant to bud rot disease, the most significant epidemiological threat to oil palm worldwide, particularly in Colombia, where it severely affects plantations of the African oil palm. This impact led to a marked decline in productivity and triggered a severe social and economic crisis, necessitating the implementation of an emergency plan to replace African oil palm plantations with the hybrid, particularly in municipalities such as Tumaco (Avila *et al*., 2016).

Nevertheless, under natural pollination conditions, hybrids exhibit low fruit set, poor bunch formation, and a reduced oil extraction rate. These limitations in bunch development may be linked to factors such as limited production of male inflorescences, low pollen viability, and germination capacity, as well as the presence of indehiscent peduncular bracts in female inflorescences, which complicate pollen entry, making the oil potential lower than that of the African oil palm. Assisted pollination emerged as a technique that, while improving oil potential through enhancements in bunch size, weight, and fruit set, is a labor-intensive and a costly activity with a very short application window, reducing its effectiveness (Daza *et al*., 2020; Hormaza *et al*., 2012; Mosquera-Montoya *et al*., 2023; Rincón *et al*., 2013).

Parthenocarpy is the mechanism of seedless fruit generation, which can occur with or without pollination or flower fertilization. During the ovary's development, this process can be artificially stimulated for agricultural purposes by applying natural or synthetic phytohormones, such as gibberellins, cytokinins, and auxins (Azzeme *et al*., 2020). The increase in hormonal levels and their interactions induce ovary growth, resulting in the formation of seedless fruits, which translates into more outstanding flesh content as the seeds and seed cavities are replaced by an expanded mesocarp (Azzeme *et al*., 2020; Liu *et al*., 2018; Mandal *et al*., 2022; Zhang *et al*., 2021). Developing parthenocarpic fruits is a desirable strategy for improving palm oil production. In the O x G hybrid, the accumulation of oil relies on the development of both normal, fertile fruits and parthenocarpic fruits, achieved by removing the kernel and expanding the mesocarp, leading to more significant oil accumulation within the fruits (Montoya *et al*., 2023; Rincón *et al*., 2013).

Recent studies have shown that inducing parthenocarpy is effective in increasing yield without affecting oil quality, fruit development, or bunch components using the auxin naphthaleneacetic acid (NAA) (Cayón Salinas *et al*., 2022; Daza *et al*., 2020; Romero *et al*., 2021). However, there are no studies explaining the effect of NAA on the behavior of bunch composition variables that increase yield in the hybrid, which would help to explain yield through the most representative variables, considering that these phenotypic traits related to bunch composition are of great interest in oil palm breeding programs (Rios *et al*., 2018; Van Hintum *et al*., 2000).

Taking into account the above, in recent years, the hybrid has emerged as an alternative for oil palm production, replacing much of African oil palm cultivation, especially in Latin America (Avila *et al*., 2016; Rincón *et al*., 2013), due to its tolerance to pests and diseases, as well as its high yield per hectare per year with the use of NAA, and a reduction of production costs without increasing the planting area, thanks to the rise in oil extraction rate (Romero *et al*., 2021; Ruiz *et al*., 2021). This study aimed to determine the effect of two NAA molecules on the bunch composition variables that explain the yield of the O × G oil palm hybrid. The results precisely characterize the key variables determining the performance of the O × G hybrid, offering strategic insights that strengthen selection and agronomic improvement programs. The application of auxins, particularly naphthaleneacetic acid in its sodium salt form, positively affects bunch composition, enhancing oil accumulation and significantly contributing to the productivity and competitiveness of the oil palm agroindustry.

Materials and methods

Location and plant material

This experiment was conducted from October 2023 to May 2024 in the Palmeiras commercial plantation in Tumaco, Nariño, Colombia (1°26'50.75" N, 78°42'12.83" W). Climatic conditions during the experiment corresponded to the typical rainy season of the region, characterized by a bimodal rainfall pattern, with a cumulative rainfall of 840.5 mm during this period, an average relative air humidity of 82.7%, mean temperature of 27.0°C, and a mean daily light integral of 32.6 mol m^{-2} d^{-1}. A nine-year-old hybrid interspecific *Elaeis oleifera* (Coari-Brazil) x *Elaeis guineensis* (La Mé-Ivory Coast) was used. The palms were planted at a density of 115 trees per ha in an experimental field with clay soil characterized by pH 4.6, EC 0.14 dS m^{-1}, and 2.67% organic matter.

Experiment design and treatments

The experiment followed a split-plot structure with a 2 × 3 factorial arrangement. The main factor consisted of two types of auxin molecules: (1) 1-Naphthaleneacetic acid (NAA) and (2) 1-Naphthaleneacetic acid, sodium salt (NAAS). The secondary factor corresponds to the auxin dose, with three treatments: (1) application at 450 mg L^{-1}, (2) application at 1200 mg L^{-1}, and (3) a control treatment consisting of pollen (15 g talc + 1 g pollen per inflorescence). Female inflorescences were treated through liquid application, using 200 ml of the corresponding solution per inflorescence. NAA (product number N0640, Sigma) and NAAS (product number S572896, Sigma) were used as the auxin sources. For each treatment (subplot), three replicates were established, each consisting of 10 palms (each one considered as an experimental unit), from which three bunches per palm were analyzed.

Isolation of inflorescences and treatment application

Female inflorescences were isolated beforehand at phenological stage PS601, or pre-anthesis 1, as described by Rosero *et al.* (2017); they were isolated with polyester bags to prevent the entry of external pollen, ensuring that fruit development resulted exclusively from the applied treatments, while allowing gas exchange and supporting inflorescence development under similar natural conditions. The pollen used in this experiment was collected from selected pisifera palms (*Elaeis guineensis* (La Mé)). The treatments were applied when the inflorescences reached phenological stage PS607 of anthesis, when the flowers had receptive stigmas (Hormaza *et al.*, 2012). The application was made through a sprinkler, uniformly spraying each inflorescence with the corresponding dose. Subsequently, the inflorescence was sealed again. Three applications were made every eight days with the above-mentioned solution, and the isolation bags were removed 10 d after the last application.

TABLE 1. Analyzed variables from the bunch components of the (O x G) hybrid.

Abbreviation	Description	Abbreviation	Description
BW	Bunch weight	E/F	Endocarp-to-fruit ratio
SW	Stalk weight	K/F	Kernel-to-fruit ratio
S/B	Stalk-to-bunch ratio	ASW	Average seed weight
RN	Rachillae number	O/Fnf	Oil-to-fruit ratio in normal fruits
NAF	Number of aborted fruits	O/DMpf	Oil-to-dry-mesocarp ratio in parthenocarpic fruits
NNF	Number of normal fruits	M/Mnpf	Moisture-to-mesocarp ratio in parthenocarpic fruits
NFW	Normal fruit weight	NFS	Normal fruit set
NPF	Number of parthenocarpic fruits	PFS	Parthenocarpic fruit set
WPF	Weight of parthenocarpic fruits	FS	Fruit set (PFS + NFS)
WPNF	Weight of parthenocarpic and normal fruits	NFBO	Oil contribution of normal fruits to the bunch
AWpf	Average weight of parthenocarpic fruit	PFBO	Oil contribution of parthenocarpic fruits to the bunch
WFS	Weight of seeds per fruit	O/B	Oil-to-bunch ratio (NFBO + PFBO) or bunch oil percentage
WE	Weight of endocarp	LF	Loose fruits
O/DMnf	Oil-to-dry-mesocarp ratio in normal fruits	OC	Oil content or yield (kg oil/bunch)
M/Mnf	Moisture-to-mesocarp ratio in normal fruits	DTM	Days to maturity
M/nf	Mesocarp-to-normal fruit ratio		

Response variables

The harvest and analysis of bunches were carried out following Prada and Romero (2012), who established parameters for accurately quantifying all variables involved in bunch analysis of the (O × G) hybrid, including those related to bunch composition, structure, and oil productivity (Tab. 1). The harvest was performed when the optimum harvest point was reached, approximately 175 d after anthesis, between phenological stages PS807 and PS809 (Romero *et al*., 2025).

Data analysis

To determine the correlation between variables, we performed a Pearson correlation analysis (P<0.05) (Pearson, 1900), presented as a colored heatmap using the 'PROC CORR' procedure and the 'PROC TEMPLATE' function. We performed a principal component analysis (PCA) using 'PROC PRINCOMP' to reduce the dimensionality of the variables and explore the relationships and grouping patterns among them (Jolliffe, 2002), helping to explain yield. We performed a cluster analysis using the 'CLUSTER' procedure, applying the average linkage method based on squared Euclidean distances: the analysis aimed to group related variables (Jain, 1988). We generated a dendrogram to visualize relationships, providing insights into potential patterns within the dataset.

We proposed a model to explain the total oil yield through the PROC REG procedure with the Oil Content (OC) as a function of the bunch composition variables using a multiple linear regression equation as follows:

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i X_i + \varepsilon \qquad \text{(Eq. 1)}$$

where:

Y represents the yield through the oil content (OC) in the bunch; β_0 is the model intercept; β_i are the regression coefficients associated with each predictor variable; and X_i corresponds to the explanatory variables included in the model, each representing an analyzed bunch composition characteristic. The term ε accounted for the random error, capturing the variability not explained by the predictor variables. The variables ultimately retained in the model were selected based on statistical significance and their explanatory contribution to model fit.

Finally, we analyzed the most essential variables in the study using analysis of variance (ANOVA) with the 'PROC MIXED' procedure. We applied the residual maximum likelihood (REML) estimation method. We used the following linear mixed model, considering hormone and dose as fixed effects, and the replicate number as random effects:

$$Y_{ijk} = \mu + \alpha_i + \beta_j + (\alpha\beta)_{ij} + u_k + \varepsilon_{ijk} \qquad \text{(Eq. 2)}$$

where $Yijk$ is the response variable observed for the k - th experimental unit receiving the $l - th$ hormone and the $j - th$ dose, μ is the overall mean, α_i represents the fixed effect of the $l - th$ hormone, and βj represents the fixed effect of the $j - th$ dose. The term $(\alpha\beta)_{ij}$ corresponds to the fixed effect of the hormone × dose interaction. The random effect u_k represents the $k - th$ subject, which is assumed to follow a normal distribution with mean zero and variance σ_u^2. Finally, ε_{ijk} is the random error term, supposed to follow a normal distribution with zero mean and variance σ_ε^2. All analyses were performed using SAS® statistical software version 9.4 (SAS, Inc., 2013).

Results

We harvested the bunches when they ripened, identified by an intense orange color, the presence of stretch marks arranged in a circular pattern around the apical part of the fruit, and the presence of fruit detachment. In most bunches, fruit set (FS) exceeded 80%. Subsequently, each of the 31 variables included in the bunch analysis was quantified immediately after harvest.

To identify associations, we performed a Pearson correlation analysis among the 31 variables evaluated in this study, represented through a heatmap (Fig. 1). Variables that showed a statistically significant positive correlation (P<0.05) included bunch weight (BW) and stalk weight (SW) (r = 0.82). We also observed associations among variables related to normal fruits, such as normal fruit set (NFS) and the oil contribution of normal fruits to bunch (NFBO) (r = 0.82), as well as between the number of normal fruits (NNF) and their weight (NFW) (r = 0.89). Similarly, we found a positive correlation between moisture and the oil-to-fruit ratio in normal fruits (M/nf and O/Fnf) (r = 0.82).

We also detected significant associations between seed-related variables, such as the weight of seeds per fruit (WFS) and the weight of endocarp (WE) (r = 0.90), as well as with the endocarp-to-fruit ratio (E/F) (r = 0.82). Additionally, we identified positive correlations among parthenocarpic variables, such as weight of parthenocarpic fruits (WPF) and the contribution of these fruits to the bunch oil percentage (PFBO) (r = 0.90). The latter was also highly correlated with the oil-to-bunch ratio (O/B) (r = 0.80).

Most of the variables showing negative correlations correspond to relationships between characteristics of normal and parthenocarpic fruits. For instance, the number of normal fruits (NNF) was negatively correlated with the weight of parthenocarpic fruits (WPF) (r = -0.82), which, in turn, was negatively correlated with the weight of normal fruits (NFW) (r = -0.91). The latter also negatively correlated with the oil contribution of parthenocarpic fruits to the bunch (PFBO) (r = -0.81).

Similarly, a negative correlation was observed between fruit set (FS) and the number of aborted fruits (NAF) (r = -0.94). Finally, the mesocarp-to-normal fruit ratio (M/nf) was negatively correlated with seed-related variables, such as average seed weight (ASW) (r = -0.80) and the endocarp-to-fruit ratio (E/F) (r = -0.86). The above suggests that oil production in the O × G hybrid is favored by a higher fruit set, which is reflected in increased bunch weight. In this context, parthenocarpic fruits, lacking the structural components typical of normal fruits, may allocate more resources to oil content, thereby increasing the bunch oil percentage (O/B).

The PCA revealed two principal components that together explained 47.24% of the total variability in the dataset (Fig. 2). The first principal component (PC1) accounted

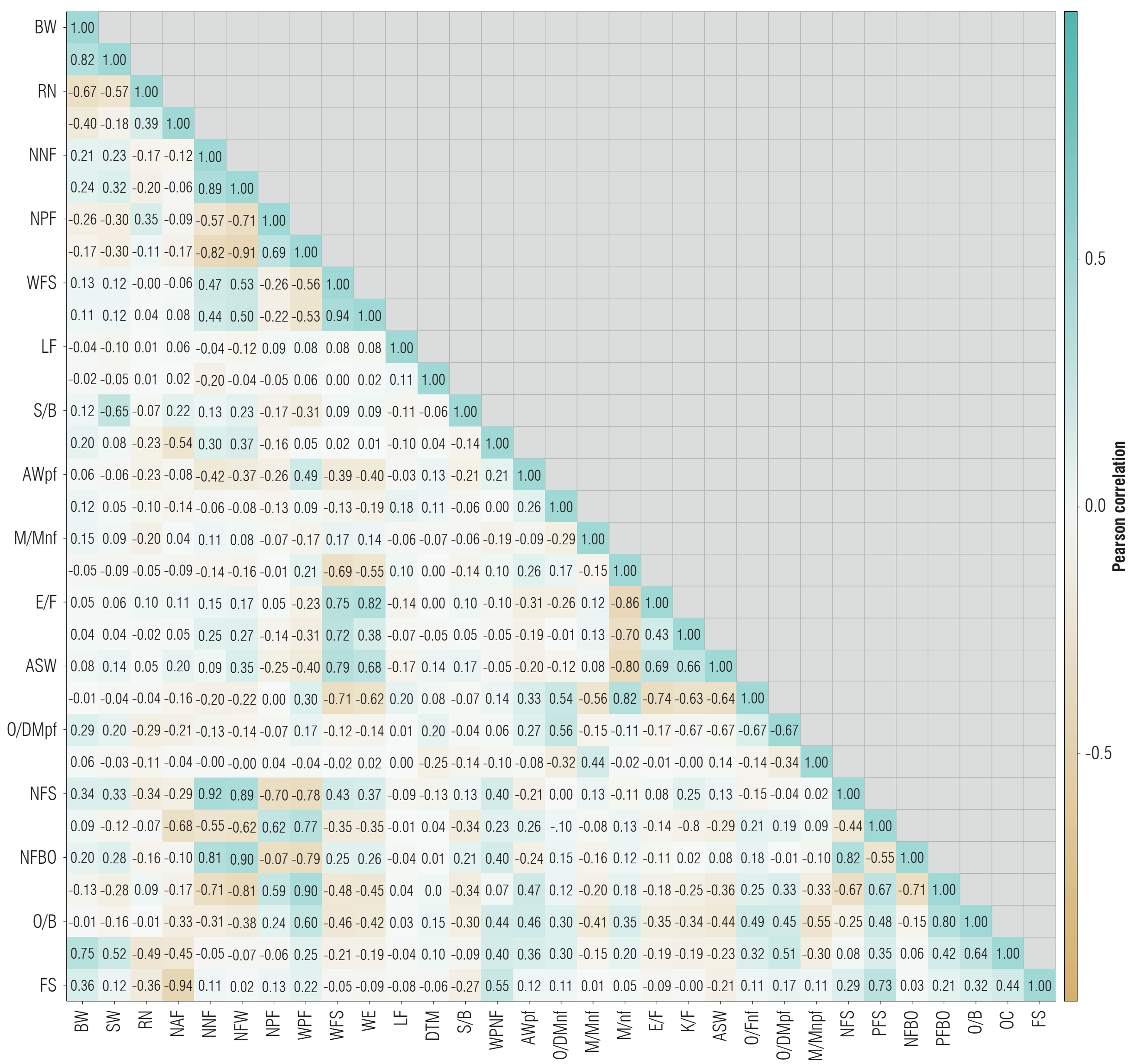

FIGURE 1. Heatmap of Pearson correlations among the composition variables of oil palm bunches in the (O x G) hybrid. The description of the variables is provided in Table 1.

for 29.55%, and the second principal component (PC2) contributed 16.73% to the total variance (Fig. 2A). The results, represented in the biplot, show a clear separation and differential clustering of the evaluated variables. In the upper left quadrant, variables related to fruit set (FS), mesocarp weight, and oil content—both in normal fruits (O/Fnf, M/nf, O/DMnf) and parthenocarpic fruits (AWpf, O/DMpf)—are grouped. These variables exhibit strong associations with one another and contribute positively to the bunch oil percentage (O/B). This indicates that mesocarp development and accumulation efficiency in both fruit types are key to overall bunch oil yield.

In contrast, the lower right quadrant contains variables with an opposite correlation pattern, notably the number of aborted fruits (NAF), moisture content in the mesocarp of normal and parthenocarpic fruits (M/Mnf, M/Mnpf), and seed-related traits in normal fruits: weight of seeds per fruit (WFS), average seed weight (ASW), weight of endocarp (WE), endocarp-to-fruit ratio (E/F), and kernel-to-fruit ratio (K/F). These variables negatively correlate with oil percentage, suggesting that increased development of reproductive structures (such as seeds and endocarp) or higher mesocarp moisture content may be associated with reduced oil yield per bunch.

The hierarchical clustering analysis (Fig. 2B) enabled the classification of variables into four main groups with distinct characteristics, facilitating a clearer understanding of the factors influencing bunch formation in the O × G hybrid. Group I includes variables related to structural growth and reproductive biology, such as fruit set, parthenocarpic fruit set, number of aborted fruits, and loose fruits, which directly reflect reproductive performance. Group II comprises variables associated with bunch architecture, such as bunch weight, peduncle weight, and the proportion of normal fruits, including the number of normal fruits, which directly reflect structural development and productive potential. Group III brings together key variables for oil production efficiency, such as the bunch oil percentage (O/B), oil content in the mesocarp of both normal and parthenocarpic fruits (O/DMnf and O/DMpf), and the average weight of parthenocarpic fruits (AWpf). This group is identified as the most relevant for yield optimization, given its strong contribution to final oil content.

Finally, Group IV includes variables that do not directly contribute to oil yield, such as those related to seed structure (average seed weight, endocarp weight, kernel and endocarp-to-fruit ratio) and fruit moisture content. These variables negatively or marginally influence the hybrid's

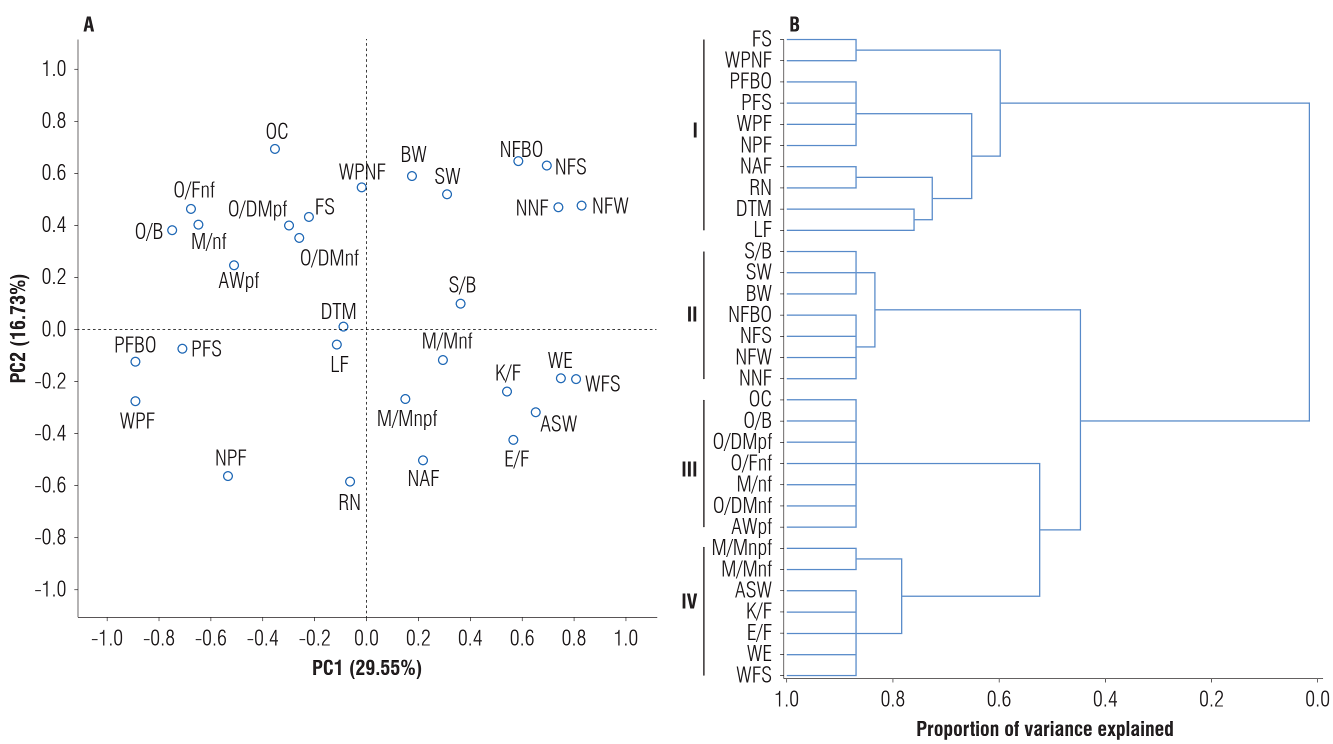

FIGURE 2. Principal component analysis of highly correlated bunch composition variables of the O × G hybrid (A) and dendrogram of their cluster grouping (B). The description of the variables is provided in Table 1.

productive efficiency. This analysis reveals that bunch formation in the O × G hybrid is primarily influenced by fruit set and mesocarp oil content in normal and parthenocarpic fruits.

A regression model was developed to determine which variables analyzed in this study significantly influenced the oil content in the O × G hybrid. The resulting regression model showed an excellent fit to the data, with a coefficient of determination (R^2) of 0.9635 and an adjusted R^2 of 0.9599, indicating that approximately 96% of the variability in oil content (OC) can be explained by the independent variables included in the model. The root mean square error (RMSE) was 328.29, reflecting high prediction accuracy. The mean oil content value was 5.29 kg of oil/bunch, and the coefficient of variation (CV) was 6.19%, indicating low relative dispersion of the data around the mean and suggesting consistency in the measurements. Furthermore, the model yielded an F-statistic of 266.93 with a $P < 0.0001$, confirming that the model is statistically significant and that at least one of the predictor variables had a statistically significant effect on oil content.

All variables included in the model showed a significant effect ($P<0.05$) on oil content, with bunch weight (BW) identified as the most influential predictor (Tab. 2). The analysis revealed that increases in oil content in parthenocarpic fruits and the number of rachillae (RN) are positively associated with oil yield. Overall, the developed regression model proved to be a robust and accurate tool for explaining and predicting oil yield in the *Elaeis oleifera* × *E. guineensis* (O × G) hybrid, providing key information for decision-making in breeding and genetic selection programs.

TABLE 2. Regression analysis of variables affecting yield (OC): model estimates and fits statistics.

Variable	Parameter estimate	Standard error	*t*-value	*P*-value	VIF
Intercept	-10043.0	929.12	-10.81	<0.0001	-
AWpf	123.73	46.36	2.67	0.0090	1.67
O/Fnf	34.97	4.17	8.38	<0.0001	1.26
O/DMpf	54.75	9.0	6.09	<0.0001	1.44
M/Mnpf	-51.55	5.05	-10.22	<0.0001	1.24
BW	0.31	0.01	29.43	<0.0001	1.86
RN	31.95	9.05	3.53	0.0007	2.05
NNF	4.21	1.68	2.51	0.0137	5.69
NFW	1.68	0.26	6.45	<0.0001	11.17
WPF	3.23	0.23	14.0	<0.0001	7.63

VIF: Variance inflation factor.

We performed an ANOVA to evaluate the individual and combined effects of auxin (hormone) application and its different doses on key variables related to oil content. This analysis included the variables previously identified in the regression model and others relevant to oil palm productivity, as presented in Table 3. The ANOVA results revealed significant effects of hormone, doses, and interaction on several analyzed variables. Auxin application had a significant impact on increasing bunch oil percentage (O/B) and the average weight of parthenocarpic fruits (AWpf) (Figs. 3A and 3B).

On the other hand, the dose factor significantly affected most of the evaluated variables, except M/Mnpf and RN, indicating that the level of auxin application directly influenced bunch formation and composition. Moreover, the hormone × dose interaction (H × D) was significant for multiple key variables, including BW, S/B, O/B, OC, AWpf, and O/Fnf. This effect was evident in variables such as oil content (OC), oil-to-fruit ratio in normal fruits (O/Fnf), and the weight of parthenocarpic fruits (WPF). Notably, although the highest dose of NAA (1200 mg L^{-1}) showed a prominent effect, the intermediate dose of NAAS (450 mg L^{-1}) presented very similar values, since it increased both BW and O/B (Figs. 3A and 3C), clearly reflected in the oil content (OC) (Fig. 3D). Additionally, fruit set (Fig. 3E) was equally effective with auxin application (artificial pollination) and the control treatment (assisted pollination). These results indicated that the hormone effect on these variables depended on the applied dose, reflecting a differential response among the evaluated variables.

TABLE 3. ANOVA Type III F-values for the effects of hormone, dose, and their interaction.

Effects	df	BW	S/B	O/B	OC	AWpf	O/Fnf	O/DMpf	M/Mnpf	RN	NNF	NFW	WPF
Hormone	1	1.88	2.16	4.11*	0.04	5.87*	0.04	0.03	2.88	0.83	3.47	0.25	1.94
Dose	2	0.78*	2.56*	15.80*	5.35*	12.19*	3.48*	3.14*	2.65	0.17	15.54*	41.54*	34.10*
H x D	2	1.27*	1.60*	4.16*	4.25*	0.37*	3.49*	0.65	1.69	2.68	0.21	0.17	0.74

df (degrees of freedom), BW (bunch weight), S/B (stalk-to-bunch ratio), O/B (oil-to-bunch ratio), OC (oil content), AWpf (average weight of parthenocarpic fruit), O/Fnf (oil-to-fruit ratio in normal fruits), O/DMpf (oil-to-dry-mesocarp ratio in parthenocarpic fruits), M/Mnpf (moisture-to-mesocarp ratio in parthenocarpic fruits), RN (rachillae number), NNF (number of normal fruits), NFW (normal fruit weight), WPF (weight of parthenocarpic fruits). *$P<0.05$.

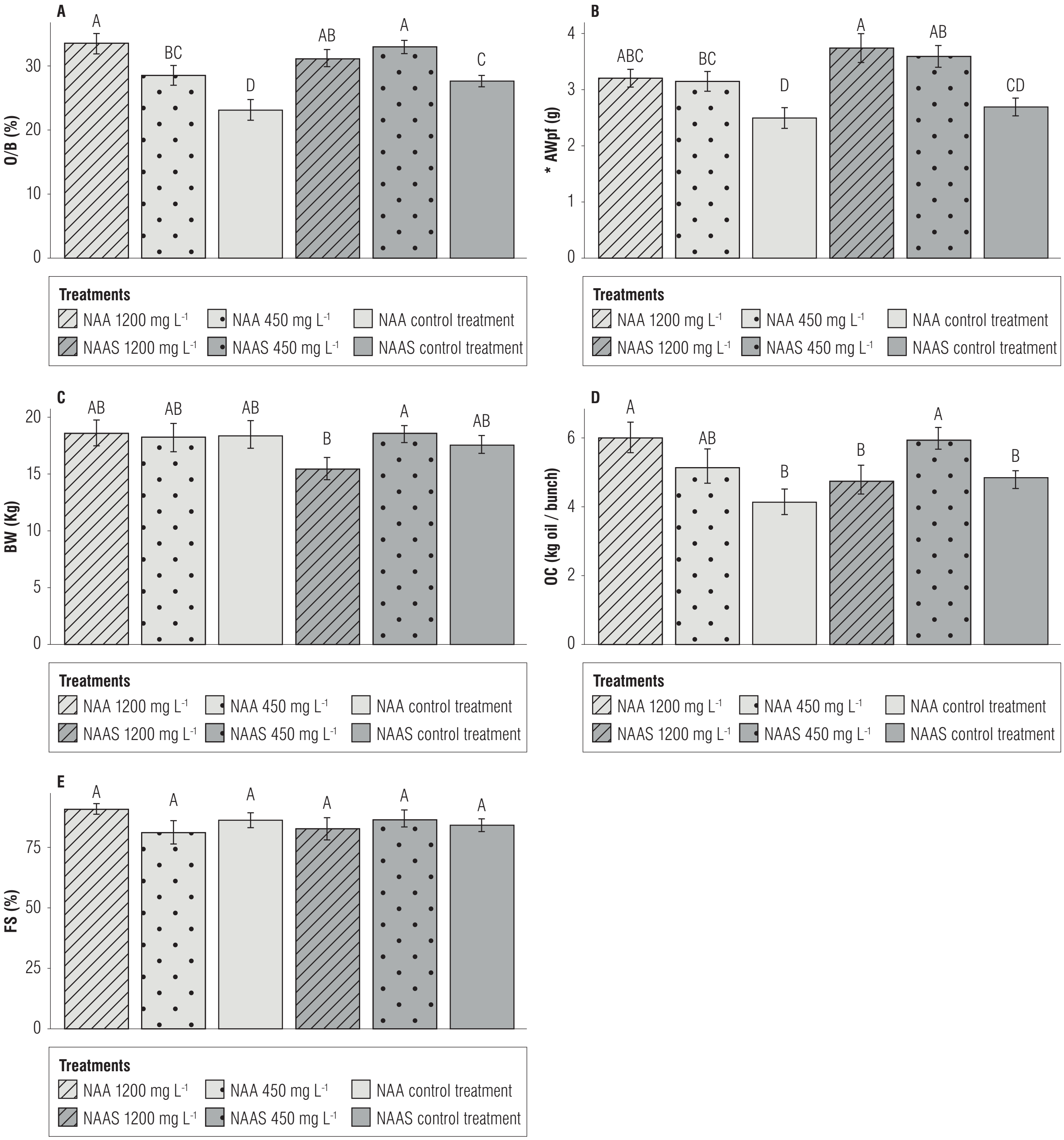

FIGURE 3. Effect of different treatments on the composition variables of oil palm bunches in the (O x G) hybrid: Naphthaleneacetic acid (NAA), sodium naphthaleneacetic acid salt (NAAS), and control treatment (assisted pollination). Vertical bars indicate the standard error. Different letters denote significant differences between treatments according to the LSD test (P<0.05) for the least significant difference. *The AWpf parameter considers the weight of normal fruits in the assisted pollination (control treatment).

Discussion

The agronomic management of the interspecific hybrid (O x G) presents significant challenges for oil palm growers, particularly due to its low natural pollination rate (Corley & Tiker, 2015). This limitation has led to the widespread adoption of artificial pollination using NAA as a key strategy to ensure commercial production (Mosquera-Montoya *et al*., 2023). In this context, understanding the factors that influence the hybrid's agronomic performance is essential for optimizing its management and productivity.

Results of this study identified the key variables that determine the hybrid's agronomic performance, providing strategic information useful for strengthening selection and breeding programs. In particular, the traits that showed a significant and positive correlation with oil yield were especially relevant, as their variation in the same direction represented a strategic factor for yield optimization (Krualee *et al*., 2013; Rios *et al*., 2018; Singh *et al*., 2014). These variables included FS, BW, WPNF, and O/B, particularly when associated with parthenocarpic fruits (O/DMpf, PFBO). Altogether, these traits explained the productive behavior of the hybrid, since adequate fruit set enables subsequent fruit development (Socha *et al*., 2019), increasing fruit weight and, consequently, bunch weight. This enhances the fruit-to-bunch and oil-to-bunch ratios (Henson & Dolmat, 2004; Socha *et al*., 2019; Swaray *et al*., 2021).

Similarly, the PCA and cluster analysis enabled the identification of the variables with the most significant influence on oil yield (OC), namely the oil content in the mesocarp of normal fruits (O/DMnf) and parthenocarpic fruits (O/DMpf), as well as the average weight of parthenocarpic fruits (AWpf). In contrast to these yield-promoting variables, mesocarp moisture content and seed-related traits negatively impacted performance. An increase in moisture content is typically associated with a lower oil-to-mesocarp ratio, which also does not favor yield and is often associated with a decline in oil quality during storage (Basyuni *et al*., 2017; Romero *et al*., 2025). Likewise, the presence of seeds and endocarp in normal fruits is also considered disadvantageous, as noted by several authors (Rios *et al*., 2018; Tanya *et al*., 2021), since their absence allows for a greater proportion of the fruit to be composed of fleshy mesocarp, thereby enhancing the actual production of marketable oil (Corley & Tiker, 2015; Htwe *et al*., 2022) in spite of constraints on palm kernel oil production.

The results described above were consistent with the developed regression model (Tab. 2), in which the most statistically significant variables were bunch weight and those primarily associated with parthenocarpic fruits. Thus, parthenocarpic fruits and related variables emerge as the most critical factors for optimizing oil production in the hybrid. Several studies have demonstrated that the induction of parthenocarpic fruits through auxin application is a practice that not only ensures fruit formation but also significantly enhances crop profitability by increasing yield (Hormaza Martínez *et al*., 2010; Mosquera-Montoya *et al*., 2023; Romero *et al*., 2021).

Our results revealed significant effects of the hormone, dose, and interaction on several analyzed variables. In particular, auxin application had a significant effect on bunch weight (BW), oil-to-bunch ratio (O/B), and the average weight of parthenocarpic fruits (AWpf). Similar results with auxin application are reported by Cayón Salinas *et al*. (2022), Romero *et al*. (2021), and Daza *et al*. (2020), who demonstrate that auxin use enhances the oil-to-dry mesocarp ratio, oil-to-bunch ratio, bunch weight, and fruit set (FS). The latter (FS) showed values exceeding the ideal fruit set threshold (> 80%) as reported by Mohd Haniff and Mohd Roslan (2002). It is essential to highlight that, although the highest dose of NAA (1200 mg L^{-1}) exhibited outstanding effects on OB and OC—also reported by Romero *et al*. (2021)—the sodium salt form of 1-naphthaleneacetic acid (NAAS) at an intermediate dose (450 mg L^{-1}) proved to be similarly effective in this study, which may be attributed to their solubility and transport properties. NAAS, being more soluble, might be absorbed more efficiently, leading to distinct physiological responses. These treatments not only increased fruit and bunch biomass but also enhanced oil production efficiency, with a clear effect on oil yield (OC) (Fig. 3). Thomas *et al*. (1973) report that in oil palms, auxins are the group of hormones primarily responsible for inducing parthenocarpic fruit formation. More recent evaluations, in which other hormones such as gibberellins and an ethylene precursor were tested, confirm that auxins were the most effective in inducing parthenocarpy, with a direct impact on yield (Cayón *et al*., 2022; Daza *et al*., 2020). Auxins promote optimal fruit development through hormonal signaling that triggers the transformation of the ovary into fruit, enhances fruit set, and stimulates cell division (Montoya *et al*., 2023; Pandolfini *et al*., 2007; Socha *et al*., 2019; Somyong *et al*., 2018). This hormone regulates key cell cycle transitions and facilitates cell elongation by acidifying the extracellular space, activating proteins such as expansins and xyloglucan endotransglucosylase/hydrolases. These proteins relax the cell wall and enable cell expansion by allowing water influx into the cell (Campanoni & Nick, 2005; Perrot-Rechenmann, 2010), and auxins can also increase sink activity. Collectively, these processes support growth and biomass accumulation in the mesocarp (Bennett & Leyser, 2014; Romero *et al*., 2021; Zhang *et al*., 2021). These findings open opportunities for further research involving the use of this molecule as a potential sustainable intensification strategy, understood as productivity improvement through efficient input use (Lerner *et al*., 2017; Sekaran *et al*., 2021).

Altogether, the results reaffirm the ability of auxins to enhance yield and profitability, considering the cost-benefit trade-off when compared to assisted pollination, due to the increase in oil output, making it a highly beneficial strategy for oil palm growers (Mosquera-Montoya *et al*., 2023).

An interesting response was observed with the highest dose of NAAS (1200 mg L^{-1}), which led to a decrease in bunch weight and oil content. This effect was likely due to the disruption caused by supra-optimal doses on hormonal homeostasis and growth regulation. At high concentrations, auxins can become toxic, and when applied exogenously, synthetic auxins are less susceptible to homeostatic control mechanisms, such as degradation, conjugation, transport, or sequestration, compared to natural auxins (Mellor *et al*., 2016; Taiz *et al*., 2017). This underscores the importance of applying appropriate doses when inducing parthenocarpic fruit formation.

These findings help clarify the behavior of the variables that explain oil yield in the hybrid in response to auxin application, highlighting their role in bunch formation and architecture, biomass accumulation, and improving oil production efficiency. This supports the progressive replacement of oil palm plantations in recent years in Colombia (Avila *et al*., 2016; Rincón *et al*., 2013; Romero *et al*., 2021), due to the hybrid's direct impact on productivity, as well as its high profitability and sustainability.

Conclusions

The variables derived from the analysis of bunch composition effectively explained the productive performance of the interspecific hybrid O × G. The developed model identified key variables that, collectively, provided valuable insights for genetic improvement programs targeting this hybrid. Applying auxins significantly enhanced crop productivity, primarily by promoting fruit set, in a similar manner to assisted pollination, and by increasing bunch biomass, especially through the induction of parthenocarpic fruits. These fruits, lacking seeds and endocarp, have a higher mesocarp proportion, resulting in increased oil content per bunch. The optimal doses were 450 mg L^{-1} of NAAS and 1200 mg L^{-1} of NAA, highlighting the importance of using appropriate concentrations to induce parthenocarpy effectively. These findings confirmed the potential of auxins as a strategy to boost oil production, with significant economic implications that enhance crop profitability and strengthen the sustainability of the oil palm sector.

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Conflict of interest statement

The authors declare that there is no conflict of interests regarding the publication of this article.

Author's contributions

KAML and ALBO designed and conducted field experiments. JEPD, KAML, and DMAM contributed to data analysis. KAML, DMAM, and HEBL prepared the draft of the manuscript. All authors reviewed and approved the final version.

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