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Optimizing UAV Flight Altitude and Image Overlap for RGB Image Post-Processing in Cacao Cultivation

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Abstract

The use of UAVs in agriculture provides an efficient approach for acquiring high-resolution imagery for crop monitoring and precision agriculture. This study evaluated the effects of flight altitude and image overlap on RGB photogrammetric reconstruction in a cacao plantation using a DJI Air 2S and Pix4Dmapper. A factorial design combined altitudes of 20, 25, and 30 m AGL, forward overlaps of 70%, 80%, and 90%, and side overlaps of 70% and 80%, at 5 m/s. Each configuration was flown four times over the same 1-ha plot, and image sets were processed using Initial Processing Full, Rapid, and Custom workflows. Theoretical GSD was approximately 0.57 cm/pixel at 20 m, 0.72 cm/pixel at 25 m, and 0.86 cm/pixel at 30 m. Factorial models included repetition as a blocking factor and HC3 heteroscedasticity-robust inference. In Full and Custom, altitude, forward overlap, and the Altitude × Forward and Forward × Side interactions were significant; Custom also showed a significant three-way interaction. In Rapid, only altitude and repetition were significant. Configuration T13 (30 m AGL, 90% forward overlap, and 80% side overlap) achieved the highest observed dataset quality (100%) with Full processing. This configuration provided the most favorable observed reconstruction performance while retaining sub-centimeter theoretical GSD. Without ground control points or independent checkpoints, these findings describe relative reconstruction quality rather than absolute geodetic accuracy.

Keywords: UAV, cacao, precision agriculture, Pix4D, flight optimization

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Optimización de la altitud y el solapamiento de imágenes de UAV para el posprocesamiento de imágenes RGB en el cultivo de cacao

Resumen

El uso de UAV en agricultura permite adquirir imágenes de alta resolución para el monitoreo de cultivos y la agricultura de precisión. Este estudio evaluó los efectos de la altitud de vuelo y el solapamiento de imágenes sobre la reconstrucción fotogramétrica RGB en una plantación de cacao utilizando un DJI Air 2S y Pix4Dmapper. El diseño factorial combinó altitudes de 20, 25 y 30 m AGL, solapamientos frontales de 70%, 80% y 90%, y laterales de 70% y 80%, a 5 m/s. Cada configuración se voló cuatro veces sobre la misma parcela de 1 ha, y las imágenes se procesaron mediante los flujos Initial Processing Full, Rapid y Custom. El GSD teórico fue aproximadamente 0,57 cm/píxel a 20 m, 0,72 cm/píxel a 25 m y 0,86 cm/píxel a 30 m. Los modelos factoriales incluyeron la repetición como bloque e inferencia robusta HC3. En Full y Custom fueron significativos la altitud, el solapamiento frontal y las interacciones Altitud × Frontal y Frontal × Lateral; Custom también presentó una interacción triple significativa. En Rapid solo fueron significativas la altitud y la repetición. La configuración T13 (30 m AGL, 90% frontal y 80% lateral) alcanzó la mayor calidad observada del conjunto de datos (100%) con Full. Esta configuración presentó el desempeño de reconstrucción más favorable observado, manteniendo un GSD teórico subcentimétrico. Al no disponerse de GCP ni puntos de chequeo independientes, los resultados describen calidad relativa de reconstrucción y no precisión geodésica absoluta.

Palabras clave: UAV, cacao, agricultura de precisión, Pix4D, optimización de vuelo

Otimização da altitude e da sobreposição de imagens de UAV para o pós-processamento de imagens RGB na cultura do cacau

Resumo

O uso de UAVs na agricultura permite adquirir imagens de alta resolução para o monitoramento de culturas e a agricultura de precisão. Este estudo avaliou os efeitos da altitude de voo e da sobreposição de imagens na reconstrução fotogramétrica RGB em uma plantação de cacau utilizando um DJI Air 2S e o Pix4Dmapper. O delineamento fatorial combinou altitudes de 20, 25 e 30 m AGL, sobreposições frontais de 70%, 80% e 90% e laterais de 70% e 80%, a 5 m/s. Cada configuração foi voada quatro vezes sobre a mesma parcela de 1 ha, e as imagens foram processadas pelos fluxos Initial Processing Full, Rapid e Custom. O GSD teórico foi aproximadamente 0,57 cm/pixel a 20 m, 0,72 cm/pixel a 25 m e 0,86 cm/pixel a 30 m. Os modelos fatoriais incluíram repetição como bloco e inferência robusta HC3. Em Full e Custom, altitude, sobreposição frontal e as interações Altitude × Frontal e Frontal × Lateral foram significativas; Custom também apresentou uma interação tripla significativa. Em Rapid, apenas altitude e repetição foram significativas. A configuração T13 (30 m AGL, 90% frontal e 80% lateral) atingiu a maior qualidade observada do conjunto de dados (100%) com Full. Essa configuração apresentou o desempenho de reconstrução mais favorável observado, mantendo um GSD teórico subcentimétrico. Sem pontos de controle terrestre nem pontos de verificação independentes, os resultados descrevem qualidade relativa de reconstrução, e não acurácia geodésica absoluta.

Palavras-chave: VANT, cacau, agricultura de precisão, Pix4D, otimização de voo

1. Introduction

In recent years, uncrewed aerial vehicles (UAVs) have undergone remarkable technological advancements. These devices, operated from the ground, rely on aerodynamic forces to generate lift and capture data and information through videos and photographs of specific areas. Population growth and emerging challenges in the agricultural sector are driving the adoption of advanced precision agriculture technologies. The incorporation of drones has transformed crop management, enabling more efficient resource optimization (Tu et al., 2020). In agriculture, UAVs have emerged as important tools for collecting high-resolution spatial data through photogrammetry, supporting crop monitoring and spatially informed decision-making.

Cacao is an economically important crop in Ecuador and represents a major component of the country's agricultural production. The global agricultural sector continually pursues technologies that enable efficient crop monitoring while maintaining high production quality. Using UAVs enables more efficient and accurate agricultural operations, thereby reducing field personnel workload. Such platforms rapidly cover vast regions, facilitating early problem identification and improved decision-making compared with classical methods (Tu et al., 2020).

On the other hand, the widespread adoption of new technologies in agriculture poses challenges, such as the lack of clearly defined parameters for accurately capturing drone imagery of cacao crops. There is also limited information on appropriate flight and image acquisition protocols for this crop.

Previous studies have demonstrated that UAV image quality and the accuracy of photogrammetric products are strongly influenced by flight configuration. Flight altitude, image overlap, flight direction, camera geometry, and environmental conditions can affect image alignment, tie-point matching, point-cloud density, and orthomosaic quality (Dhruva et al., 2024; Du et al., 2024; Elhadary et al., 2022; Tu et al., 2020). In particular, research conducted in perennial tree crops has shown that the interaction among flight parameters can influence the quality of three-dimensional reconstruction and derived canopy measurements, indicating that flight configurations should be evaluated according to the characteristics of the crop and the intended application (Tu et al., 2020). Recent studies have also demonstrated that variations in image overlap and flight altitude can produce measurable differences in orthomosaic quality, while radiometric inconsistencies caused by changing illumination conditions may further affect RGB photogrammetric products (Dhruva et al., 2024; Du et al., 2024; Pastucha et al., 2022).

Finally, but no less important, UAV imagery has increasingly been applied to characterize cacao and cocoa-based agroforestry systems. Existing studies have frequently focused on crop characterization, structural assessment, or dataset generation using predefined flight configurations, rather than systematically comparing alternative flight configurations for RGB photogrammetric reconstruction. For example, recent UAV surveys of cocoa agroforestry systems in Côte d'Ivoire used a fixed acquisition configuration of 80 m altitude, 80% forward overlap, and 70% side overlap to generate high-resolution RGB and multispectral imagery (Lammoglia et al., 2024). However, the transferability of such configurations to other cacao production environments, UAV platforms, and image-processing objectives remains uncertain. Consequently, experimental evaluations are still needed to quantify how flight altitude and image overlap influence RGB photogrammetric reconstruction quality under controlled acquisition conditions in cacao production systems.

Therefore, the objective of this research was to experimentally evaluate flight altitude and image overlap for RGB image acquisition and photogrammetric processing using Pix4D, in order to identify suitable configurations for generating aerial mosaics to support cacao crop management.

2. Materials and Methods

2.1 Study Area

The study was conducted at the National Institute of Agricultural Research (INIAP) in the experimental plot “La Teodomira”, located in Lodana - Santa Ana, Manabí, Ecuador (1°10'02.7" S; 80°23'18.6" W). The field site corresponds to a 1-hectare cacao plantation under uniform agronomic management. In particular, this area offers a favorable environment for demonstrating the effectiveness of UAV-based RGB image acquisition across a variety of perennial crops, as the canopy structure is relatively stable and the topography is relatively flat. The plantation was approximately four years old and managed under a common agronomic regime. Detailed architectural descriptors requested for replication –tree spacing, pruning status, mean canopy height, and quantitative canopy closure– were not preserved in the archived field record and are therefore not reconstructed or estimated retrospectively.

2.2 Experimental Design

The experimental design evaluated the joint effects of flight altitude, forward image overlap, and side image overlap on RGB photogrammetric processing using a DJI Air 2S. Three flight altitudes (20, 25, and 30 m AGL), three forward overlaps (70%, 80%, and 90%), and two side overlaps (70% and 80%) formed an 18-configuration 3 × 3 × 2 factorial acquisition structure. Flight speed was fixed at 5 m/s and was not treated as an experimental factor. All acquisitions were made over the same 1-ha cacao plot between 10:00 and 14:00. Field records contained both sunny and cloudy conditions among repetitions, so the time window reduced but did not eliminate illumination variability. The complete workflow from flight planning to photogrammetric processing, quality assessment, and statistical analysis is presented in Figure 1.

Accordingly, flight treatments (T1-T18) represent the experimental acquisition configurations, whereas Full, Rapid, and Custom represent alternative photogrammetric processing workflows applied to the same acquired imagery.

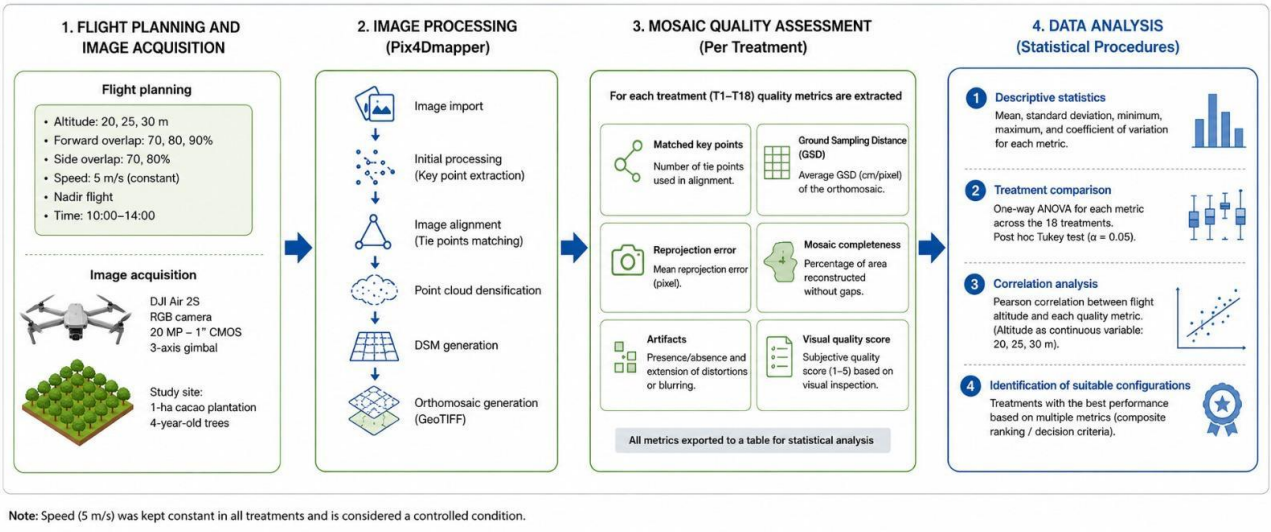


Figure 1. Experimental workflow from UAV flight planning and RGB image acquisition to photogrammetric processing, dataset-quality assessment, and statistical analysis

2.3 Equipment

The DJI Air 2S was selected as the RGB image acquisition platform because it integrates a 1-inch CMOS sensor with 20 MP effective resolution, a nominal 22-mm equivalent focal length, 2.4-µm pixel size, and a three-axis mechanical gimbal (DJI, 2021). Still images were acquired at 5472 × 3648 pixels. These characteristics provide high-resolution nadir imagery suitable for photogrammetric processing and allow consistent image acquisition across the experimental treatments. The UAV also incorporates GNSS positioning, which was used to record the approximate camera position associated with each image. The main specifications of the UAV used for image acquisition are summarized in Table 1.

Table 1. UAV specification for flights in cacao cultivation

	Specification	Details
RGB	UAV Model	DJI Air 2S
	Sensor Type	1-inch CMOS
	Image Resolution	20 MP
	Maximum Video Resolution	5.4K
	Stabilization System	3-axis mechanical gimbal
	Positioning System	GNSS (GPS + GLONASS)
	Approximate Flight Time	31 minutes
	Manufacturer	DJI - 2022

2.4 Flight Parameters

Three acquisition factors were evaluated: flight altitude, forward image overlap, and side image overlap. Altitudes were 20, 25, and 30 m AGL; forward overlap was 70%, 80%, and 90%; and side overlap was 70% and 80%. These levels produced 18 acquisition configurations (3 × 3 × 2). Flight speed was fixed at 5 m/s and therefore remained a controlled operational condition rather than an experimental factor. Theoretical GSD was calculated as GSD = H × p / f using the flight height (H), nominal pixel pitch (p = 2.4 µm), and the Air 2S camera focal length (approximately, 8.38 mm; Balestra et al., 2024), yielding approximately 0.57, 0.72, and 0.86 cm/pixel at 20, 25, and 30 m AGL, respectively. Thus, increasing altitude improved scene integration at the cost of progressively coarser spatial sampling. Parameter selection was guided by established photogrammetric considerations in which altitude, overlap, speed, sensor geometry, and acquisition conditions jointly influence image matching and reconstruction quality (Dhruva et al., 2024; Du et al., 2024; Elhadary et al., 2022; Maes, 2025; Tu et al., 2020).

Flight speed was maintained constant at 5 m/s for all treatments. Keeping speed fixed reduced one source of operational variability and allowed the effects of altitude and overlap to be evaluated within a common acquisition protocol. Flights used nadir imagery and were scheduled between 10:00 and 14:00. However, archived field records indicate both sunny and cloudy conditions among repetitions; therefore, illumination should be considered a partially uncontrolled environmental factor rather than a strictly constant condition.

Each of the 18 flight configurations was flown four times over the same experimental plot, resulting in 72 repeated flight acquisitions. Because all acquisitions were made over the same 1-ha site, these observations are treated as repeated acquisition or temporal/technical repetitions rather than independent spatial replicates. Repetition was incorporated into the statistical model as a blocking factor to account for between-flight variability. Table 2 presents the 18 flight configurations and the mean number of images acquired across the four repetitions of each configuration.

Table 2. Experimental flight configurations and mean number of images acquired across four repeated acquisitions

Treatment	Altitude (m)	Forward overlap (%)	Side overlap (%)	Speed (m/s)	Mean number of images (n = 4)
T1	20	90	80	5	54
T2	20	90	70	5	61
T3	20	80	80	5	73
T4	20	80	70	5	60
T5	20	70	80	5	51
T6	20	70	70	5	41
T7	25	90	80	5	69
T8	25	90	70	5	98
T9	25	80	80	5	99
T10	25	80	70	5	95
T11	25	70	80	5	81
T12	25	70	70	5	59
T13	30	90	80	5	103
T14	30	90	70	5	101
T15	30	80	80	5	101
T16	30	80	70	5	91
T17	30	70	80	5	101
T18	30	70	70	5	101

* Each flight configuration was flown four times over the same experimental plot. Values in the last column represent the mean number of images acquired across the four repeated acquisitions. Flight speed was maintained constant at 5 m/s and was not considered an experimental factor.

Each treatment represents one combination of flight altitude, forward overlap, and side overlap, with flight speed fixed at 5 m/s. Each configuration was flown four times over the same plot. For example, T1 corresponds to 20 m altitude, 90% forward overlap, 80% side overlap, and 5 m/s. The number of images reported in the final column is the mean across the four repeated acquisitions.

2.5 Flight Path Planning

Flight paths were generated in Pix4Dcapture using the flight altitude and image overlap specified for each treatment. Acquisition planning considered the relationships among flight height, ground sampling distance, and image overlap described in the PIX4D guidelines (PIX4D, n.d.). Routes followed parallel transects oriented north-south. Line spacing was automatically adjusted for each treatment according to the selected side overlap and the sensor footprint at the corresponding flight altitude.

2.6 Image Acquisition

During each flight, the UAV captured nadir RGB images covering the entire cacao plantation. Immediately after landing, image completeness and overlap were checked. The archived experimental record does not contain a complete treatment-by-treatment log of shutter speed, ISO, or exposure mode. Consequently, it cannot be demonstrated that radiometric settings remained fixed across all flights, and possible automatic-exposure responses to changing illumination are acknowledged as a source of uncontrolled variability.

2.7 GNSS Positioning and Ground Control

A handheld GNSS receiver with an estimated positional uncertainty of approximately 30 cm was used to obtain reference coordinates within the study area. No GNSS base station was established, no ground control points (GCPs) or independent checkpoints were surveyed, and GNSS-derived reference coordinates were not incorporated as ground control in Pix4Dmapper. The experiment was therefore designed to compare relative internal photogrammetric reconstruction quality among acquisition configurations, not to validate absolute horizontal or vertical geodetic accuracy. The same general georeferencing approach was used for all treatments. The absence of independent ground control remains a central limitation when interpreting spatial accuracy.

2.8 Photogrammetric Processing

The UAV flights were planned with Pix4Dcapture and the image datasets were processed in Pix4Dmapper. Flight altitude, forward overlap, side overlap, flight path geometry, and nadir camera orientation were defined during acquisition. The same acquired imagery from each treatment was then evaluated under three archived initial-processing workflow labels: Full, Rapid, and Custom. In Pix4D terminology, Full corresponds to the standard full initial-processing workflow, whereas Rapid uses a reduced image scale intended for faster processing. Custom represents a user-defined initial-processing configuration. The exact Pix4Dmapper software version and the complete archived parameter values of the Custom workflow were not available in the supplied project record and are therefore reported as a reproducibility limitation rather than reconstructed retrospectively.

The three workflows –Initial Processing Full, Initial Processing Rapid, and Initial Processing Custom– were applied to the same flight datasets. Workflow was not an acquisition factor; it represents an alternative processing condition applied after data collection. This distinction separates the 18 acquisition configurations (T1-T18) from the three post-processing workflows.

For each acquisition configuration, the corresponding image set was processed using the three workflow labels whenever a valid Pix4D quality output was generated. Missing workflow outputs were retained as missing and were not imputed.

2.9 Photogrammetric Quality Assessment

Mosaic quality was evaluated using the following metrics:

- Number of matched key points
- Ground sampling distance (GSD)
- Reprojection error
- Orthomosaic completeness
- Presence of artifacts (stretching, ghosting, blur)

A Tukey multiple-comparison test (α = 0.05) was used to identify significant differences among flight configurations.

2.10 Data Analysis

The four repeated acquisition observations for each flight configuration were considered temporal/technical repetitions rather than independent spatial replicates. The "Dataset" parameter obtained during photogrammetric processing was used as the primary quality indicator. Because each image dataset was processed using three different workflows –Initial Processing Full, Initial Processing Rapid, and Initial Processing Custom–, statistical analyses were performed separately for each processing workflow. Missing values corresponded to processing runs in which the respective workflow did not generate a valid dataset-quality output and were excluded from the corresponding ANOVA. For each workflow, differences among the 18 flight configurations were evaluated using one-way analysis of variance (ANOVA), considering flight configuration as a categorical factor. When the ANOVA indicated statistically significant differences ($p < 0.05$), Tukey's honestly significant difference (HSD) test was subsequently applied for pairwise comparisons among configuration means at $\alpha = 0.05$. (Agbangba et al., 2024; Midway et al., 2020). The assumptions underlying the parametric analysis, including residual normality and homogeneity of variance, were evaluated before the ANOVA. Pearson correlation analysis was additionally used to evaluate the linear association between flight altitude and the corresponding photogrammetric quality indicators. All statistical analyses were performed using RStudio.

3. Results

3.1 Dataset Quality Across Flight Configurations

Factorial analysis showed that acquisition-factor effects depended on the processing workflow. For Full processing, altitude, forward overlap, the Altitude × Forward-overlap interaction, and the Forward × Side-overlap interaction were significant. For Custom processing, altitude, forward overlap, Altitude × Forward, Forward × Side, and the three-way Altitude × Forward × Side interaction were significant. For Rapid processing, altitude and repetition were significant, whereas forward overlap, side overlap, and all interaction terms were not significant. These results indicate that the altitude response was not independent of image-overlap configuration in the Full and Custom workflows, while Rapid processing exhibited stronger between-repetition variability and a simpler altitude-related pattern. Robust factorial results are presented in Table 3.

The robust factorial results confirm that altitude should not be interpreted as an isolated determinant of dataset quality. In Full processing, altitude ($F(2,51) = 100.76$, $p < 0.001$), forward overlap ($F(2,51) = 12.15$, $p < 0.001$), Altitude × Forward overlap ($F(4,51) = 9.33$, $p < 0.001$), and Forward × Side overlap ($F(2,51) = 5.02$, $p = 0.010$) were significant. The three-way interaction approached but did not reach the 0.05 threshold ($F(4,51) = 2.48$, $p = 0.055$). In Custom processing, altitude ($F(2,49) = 59.06$, $p < 0.001$), forward overlap ($F(2,49) = 16.31$, $p < 0.001$),

Altitude × Forward overlap (F(4,49) = 6.79, p < 0.001), Forward × Side overlap (F(2,49) = 4.05, p = 0.023), and the Altitude × Forward × Side interaction (F(4,49) = 2.68, p = 0.042) were significant. For Rapid processing, altitude remained significant (F(2,42) = 7.02, p = 0.002), as did repetition (F(3,42) = 4.27, p = 0.010), whereas forward overlap, side overlap, and all interaction terms were non-significant.

Table 3. HC3 heteroscedasticity-robust factorial tests for dataset quality under the three photogrammetric processing workflows

Workflow	Effect	df	Robust F	p-value
Full	Repetition	3	1.13	0.344
Full	Altitude	2	100.76	<0.001
Full	Forward overlap	2	12.15	<0.001
Full	Side overlap	1	0.91	0.344
Full	Altitude × Forward	4	9.33	<0.001
Full	Altitude × Side	2	0.38	0.683
Full	Forward × Side	2	5.02	0.010
Full	Altitude × Forward × Side	4	2.48	0.055
Rapid	Repetition	3	4.27	0.010
Rapid	Altitude	2	7.02	0.002
Rapid	Forward overlap	2	0.21	0.811
Rapid	Side overlap	1	0.07	0.794
Rapid	Altitude × Forward	4	0.15	0.961
Rapid	Altitude × Side	2	0.36	0.703
Rapid	Forward × Side	2	0.15	0.862
Rapid	Altitude × Forward × Side	4	0.34	0.849
Custom	Repetition	3	1.43	0.246
Custom	Altitude	2	59.06	<0.001
Custom	Forward overlap	2	16.31	<0.001
Custom	Side overlap	1	0.01	0.908
Custom	Altitude × Forward	4	6.79	<0.001
Custom	Altitude × Side	2	0.40	0.670
Custom	Forward × Side	2	4.05	0.023
Custom	Altitude × Forward × Side	4	2.68	0.042

Denominator degrees of freedom were 51 for Full, 42 for Rapid, and 49 for Custom.

3.2 Descriptive Treatment Patterns and Altitude Associations

Significant differences among flight configurations were detected for both the Initial Processing Full (F(17,54) = 16.968, p < 0.001) and Initial Processing Custom (F(17,52) = 12.669, p < 0.001) workflows. Tukey's HSD test was subsequently used to identify differences among treatment means (Figure 2). Treatments sharing at least one letter were not significantly different, whereas treatments without a common letter differed significantly at α = 0.05.

As shown in Figure 2, dataset quality generally increased with flight altitude in both the Initial Processing Full and Initial Processing Custom workflows. For the Full workflow, mean dataset quality ranged from 39.50% for T6 at 20 m AGL to 100.00% for T13 at 30 m AGL (Figure 2a). The highest homogeneous statistical group included T13, T14, T15, T17, and T18, whereas several configurations at 20 m AGL were assigned to lower Tukey groups. A similar pattern was observed for the Custom workflow (Figure 2b), where the highest dataset-quality values occurred predominantly at 30 m AGL. T13 reached 100.00%, and T15, T14, T17, T9, T18, T10,

T16, and T8 belonged to the highest homogeneous group. Overall, these results indicate that dataset quality was generally higher at 25-30 m AGL than at 20 m, although the response varied among flight configurations.

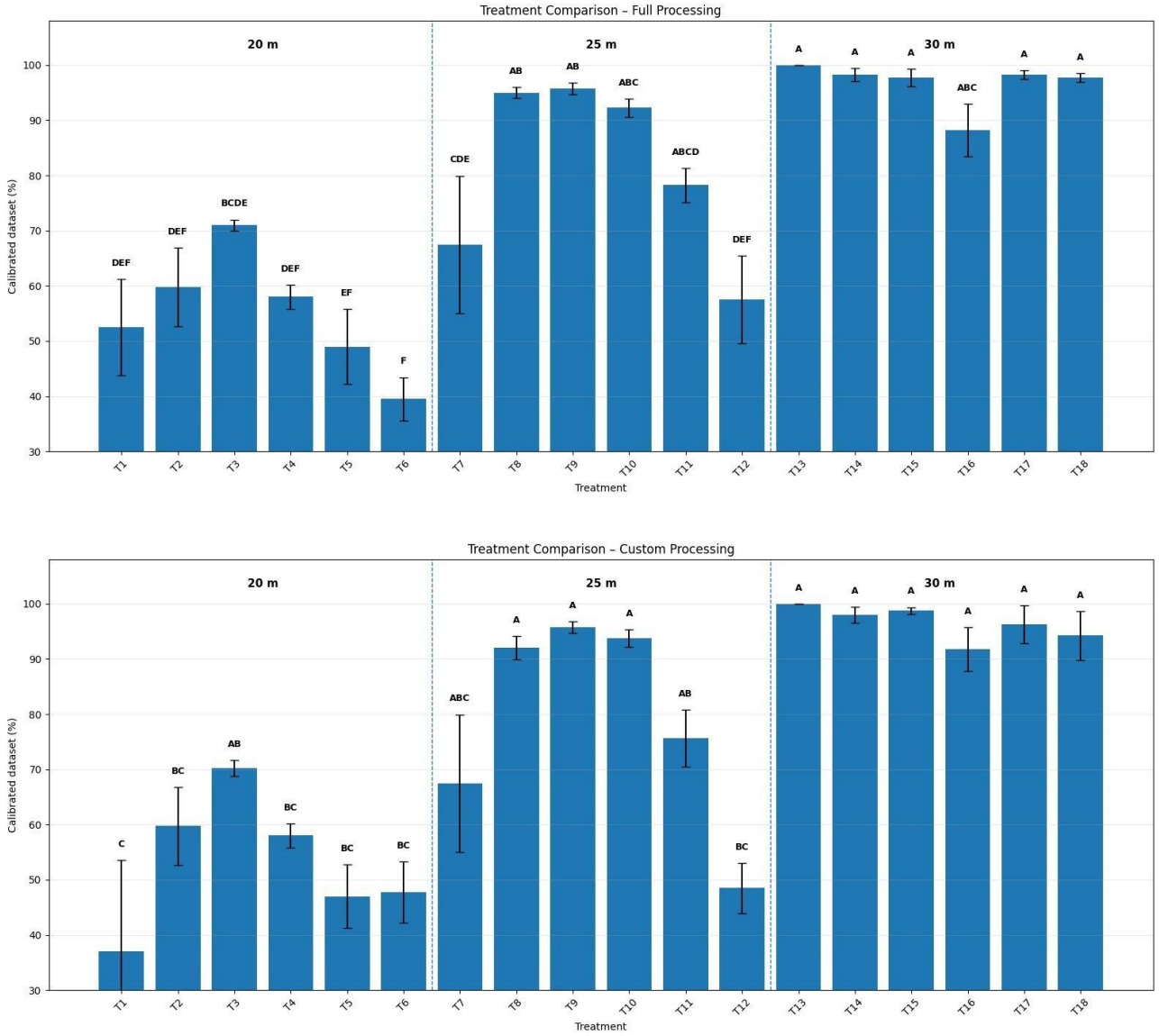


Figure 2. Dataset quality (%) across the 18 UAV flight configurations for (a) Initial Processing Full and (b) Initial Processing Custom workflows

Bars represent means ± SE (n = 4). Different letters indicate statistically significant differences according to Tukey's HSD test (α = 0.05); treatments sharing at least one letter are not significantly different.

Correlation analysis was used to assess the association between flight altitude and dataset quality across the three photogrammetric processing workflows. The relationships are presented jointly in Figure 3 to facilitate comparison among the Initial Processing Full, Rapid, and Custom workflows. Correlation analysis (Figures 3 a,b,c) revealed a positive relationship between flight altitude and mosaic quality. Flight configurations at altitudes 30 m and horizontal and vertical overlaps exceeding 80% produced sharper mosaics with more matched key points.

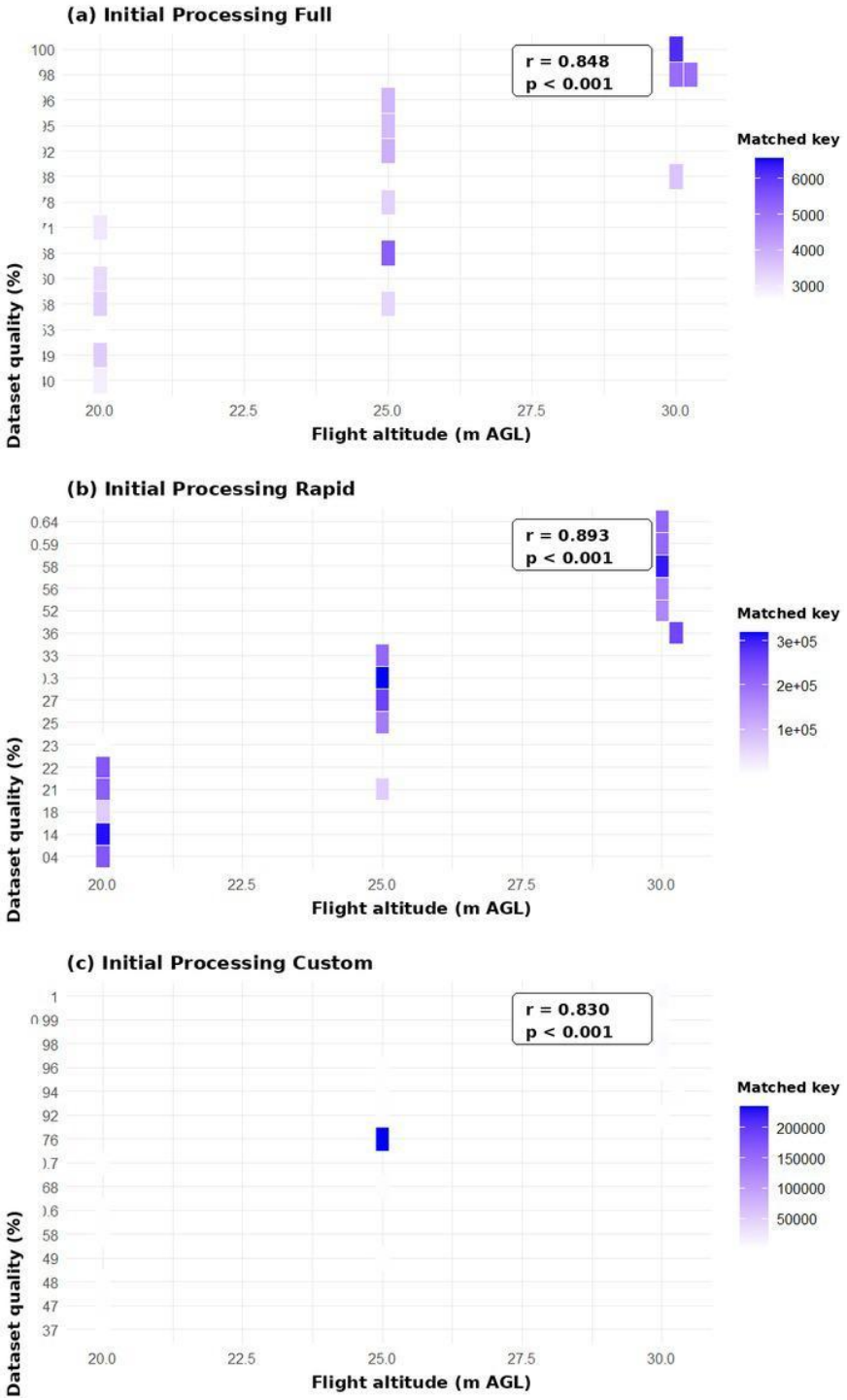


Figure 3. Relationship between flight altitude and dataset quality under the three photogrammetric processing workflows: (a) Initial Processing Full, (b) Initial Processing Rapid, and (c) Initial Processing Custom

Pearson's correlation coefficients and corresponding p-values are shown in each panel.

The three processing workflows showed a positive association between flight altitude and dataset quality within the experimental range of 20-30 m AGL (Figure 3a-c). Pearson's correlation coefficients were r = 0.848 ($p < 0.001$), r = 0.893 ($p < 0.001$), and r = 0.830 ($p < 0.001$) for Initial Processing Full, Rapid, and Custom, respectively. Although the overall ANOVA for Rapid processing did not identify significant differences among the 18 flight configurations, its treatment means exhibited a strong positive association with altitude. This distinction reflects the different analytical questions addressed by the two tests: Pearson's correlation evaluates the linear association between altitude and the treatment means, whereas ANOVA evaluates differences among the individual flight configurations. For the Full workflow, mean dataset quality increased from 54.96% at 20 m to 81.04% at 25 m and 96.71% at 30 m. A similar pattern was observed for Rapid (16.88%, 28.21%, and 54.13%) and

Custom processing (53.29%, 78.86%, and 96.50%), respectively. These results indicate a strong positive association between flight altitude and dataset quality within the experimental range, although the magnitude of the relationship varied among processing workflows.

3.3 Camera Optimization across Processing Workflows

Photogrammetric processing performance was further evaluated using the camera optimization and image-matching indicators obtained from the three processing workflows. These indicators were examined in relation to the evaluated flight configurations to identify patterns associated with flight altitude and image acquisition conditions. For example, camera optimization was positively correlated with the quality of generated mosaics (Figures 4 a-c). Processes utilizing optimal flight configurations and camera adjustments (The Initial Processing Full workflow and custom) achieved radiometric and geometric quality exceeding 90%, whereas rapid workflow, with suboptimal configurations, performed significantly worse.

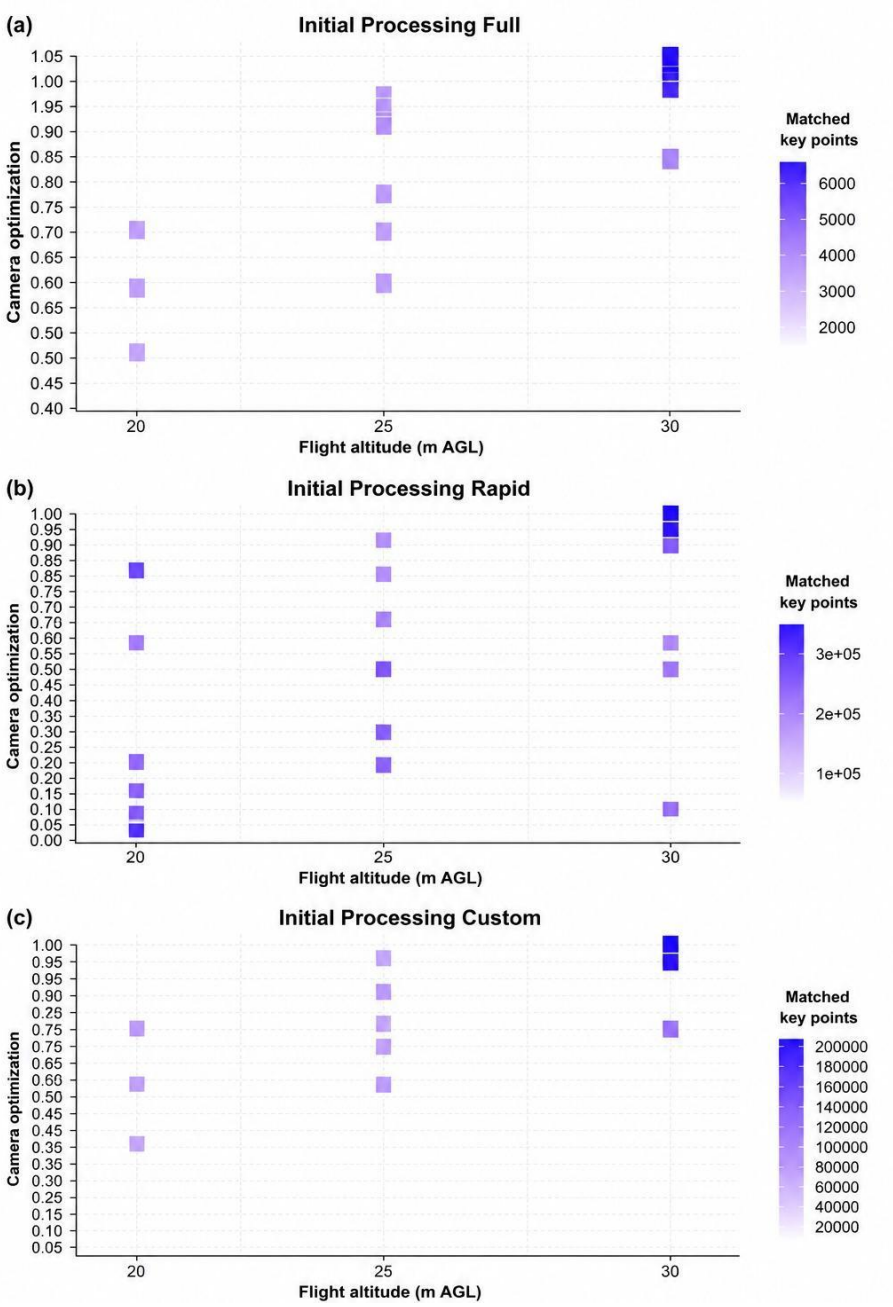


Figure 4. Relationship between flight altitude and camera optimization across the three photogrammetric processing workflows: (a) Initial Processing Full, (b) Initial Processing Rapid, and (c) Initial Processing Custom

The three processing workflows showed a generally positive relationship between flight altitude and camera optimization (Figure 4a-c). Higher optimization values were predominantly observed at 25 and 30 m AGL, although the magnitude of the response varied among flight configurations and processing workflows. Optimization values ≥0.80 were associated with greater image coincidence and lower noise and processing error, indicating more favorable image-alignment conditions. These results suggest that camera optimization varied according to the combination of flight configuration and processing workflow and should therefore be interpreted together with the other photogrammetric quality indicators.

3.4 Key-Point Matching across Processing Workflows

Image-matching performance was subsequently evaluated using the key-point matching indicator derived from the three photogrammetric processing workflows. The relationship between flight altitude and key-point matching was assessed for the Initial Processing Full, Rapid, and Custom workflows. The corresponding results are presented together in Figure 5 to facilitate comparison among processing workflows.

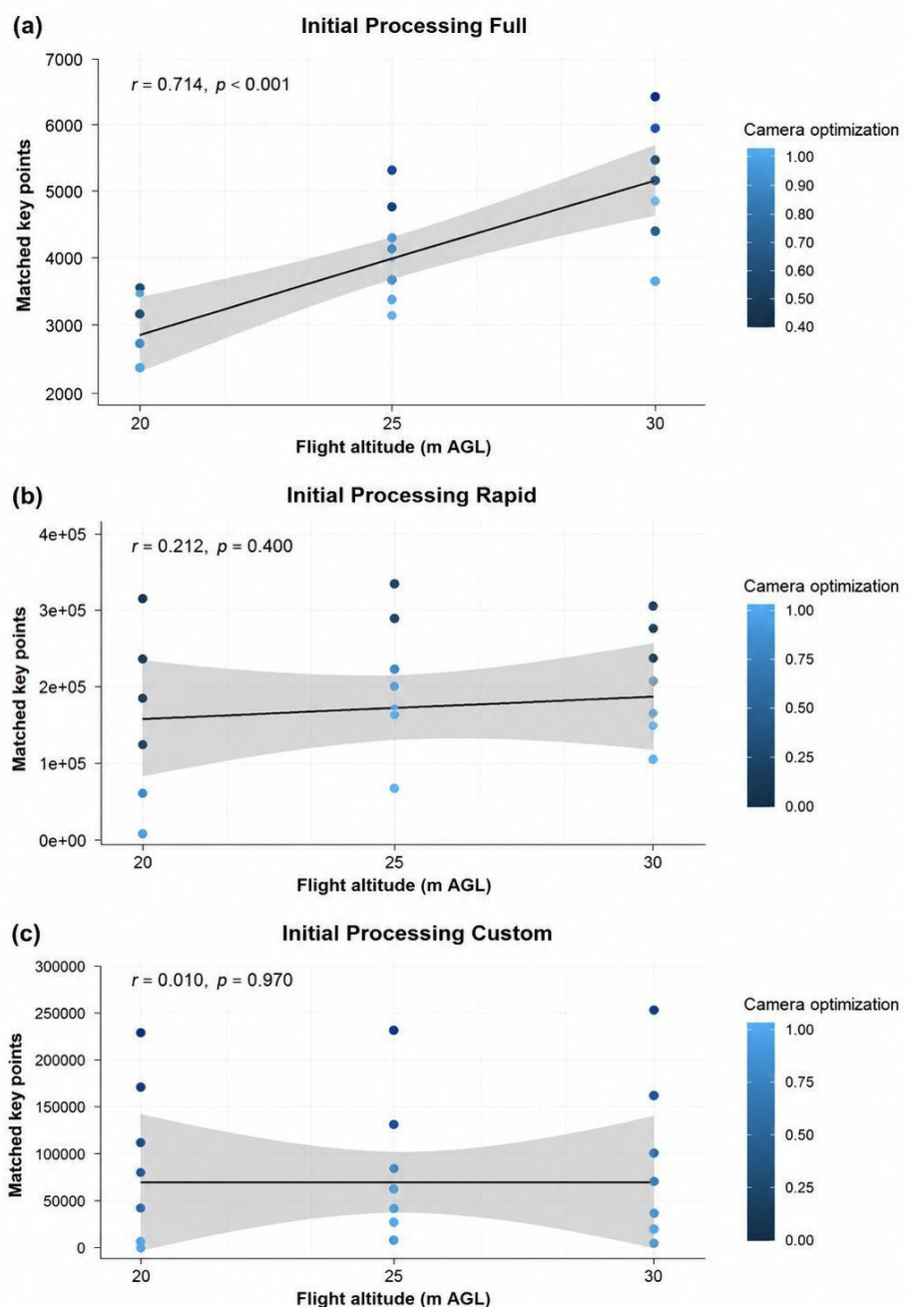


Figure 5. Relationship between flight altitude and key-point matching: (a) Initial Processing Full, (b) Initial Processing Rapid, and (c) Initial Processing Custom

The relationship between flight altitude and key-point matching differed markedly among the three processing workflows (Figure 5a-c). For the Initial Processing Full workflow, a strong positive correlation was observed between flight altitude and key-point matching ($r = 0.714$, $p < 0.001$), indicating that the number of matched key points increased consistently from 20 to 30 m AGL. In contrast, the Initial Processing Rapid workflow showed a weak and non-significant association ($r = 0.212$, $p = 0.400$), while the Initial Processing Custom workflow showed virtually no linear association ($r = 0.010$, $p = 0.970$). These results indicate that the positive relationship between flight altitude and key-point matching was primarily associated with the Full processing workflow and was not consistently reproduced by the Rapid and Custom workflows

This pattern suggests that key-point matching was influenced not only by flight altitude but also by the characteristics of the photogrammetric processing workflow and the combination of image-overlap conditions used in each flight configuration.

3.5 Integrated Assessment of Photogrammetric Quality

The integrated results show that photogrammetric performance was jointly associated with acquisition configuration and processing workflow. Dataset quality generally increased across the 20-30 m range. In Full and Custom processing, significant Altitude × Forward interactions demonstrate that the altitude response changed with image redundancy, and significant Forward × Side interactions show that overlap dimensions also acted jointly. The significant three-way interaction in Custom processing further indicates that the combined response depended on the full acquisition configuration. Rapid processing showed a significant altitude effect but no overlap interactions, together with a significant repetition effect. Consequently, suitable flight configurations should be identified from multiple quality indicators and factorial effects rather than from altitude alone.

4. Discussion of Results

4.1 Comparison with Previous UAV Photogrammetric Studies

The results of this study are broadly consistent with previous research showing that UAV flight configuration strongly influences photogrammetric data quality. Tu et al. (2020), working with horticultural tree crops, demonstrated that flight altitude, image overlap, flight direction, and solar conditions jointly affected image alignment, point-cloud generation, and orthomosaic quality, with forward overlap above 80% identified as particularly important for maintaining data quality. In the present study, the highest dataset-quality values were also predominantly associated with configurations using 90% forward overlap and 80% side overlap, particularly at 25-30 m AGL. This agreement indicates that high image redundancy can support the reconstruction of complex vegetation canopies. However, the present study adds a quantitative assessment of this relationship for cacao by evaluating three flight altitudes and five overlap combinations across three photogrammetric processing workflows. Thus, the effect of image overlap should be interpreted jointly with flight altitude and processing workflow rather than as an isolated determinant.

Our results also extend the findings of Dandois et al. (2015), who demonstrated that altitude, image overlap, and environmental conditions influence UAV-SfM reconstruction of vegetation structure. Although their study focused on forest canopies and used a different sensor and acquisition range, the strong positive associations observed in the present study between altitude and dataset quality ($r = 0.848$, $r = 0.893$, and $r = 0.830$ for Full, Rapid, and Custom processing, respectively; $p < 0.001$) indicate that higher flight altitude was systematically associated with improved dataset quality within the tested acquisition configurations. Because altitude was evaluated together with forward and side overlap, this association should not be interpreted as an independent effect of altitude.

A similar dependence of photogrammetric performance on flight height has been reported in agricultural applications. Njane et al. (2023), comparing UAV flights at 15 and 30 m over potato crops, found that flight height affected spatial resolution and the accuracy of crop-structure estimates, although the magnitude and direction of the effect depended on the variable being evaluated. In comparison, the present study evaluated three flight heights (20, 25, and 30 m AGL) and found that dataset quality generally increased across this range, whereas key-point matching showed different responses among processing workflows. This difference highlights the importance of evaluating altitude jointly with image overlap and processing conditions rather than assuming a universal optimal flight height for all agricultural UAV applications.

The present experiment further complements previous studies by evaluating 18 combinations of flight altitude and image overlap across three processing workflows, allowing dataset quality, camera optimization, and key-point matching to be assessed jointly.

4.2 Correlation between Altitude and Dataset Quality

The results demonstrated a consistent positive association between flight altitude and dataset quality within the experimental range of 20-30 m AGL. Within this range, 30 m provided the most favorable overall dataset quality. Mean dataset quality increased from 54.96% to 81.04% and 96.71% at 20, 25, and 30 m AGL, respectively, for the Initial Processing Full workflow, while the corresponding values for Initial Processing Custom were 53.29%, 78.86%, and 96.50%. The Rapid workflow showed the same directional response, although with substantially lower values (16.88%, 28.21%, and 54.13%, respectively). At 30 m AGL, the T13 configuration (90% forward overlap and 80% side overlap) achieved 100% dataset quality under Full processing, while T14, T15, T17, and T18 also reached values close to 98%.

Accordingly, for a cacao producer seeking to obtain a high-quality orthomosaic under acquisition and environmental conditions comparable to those evaluated in this study, a flight altitude of approximately 30 m AGL is recommended, combined with 90% forward overlap and 80% side overlap. This recommendation represents an empirical optimum within the 20-30 m AGL range tested in this experiment and should not be interpreted as a universal flight altitude for all cacao mapping applications.

4.3 Camera Optimization and Mosaic Quality

The camera optimization results showed differences among the three photogrammetric processing workflows and across the evaluated flight configurations (Figure 4a-c). Higher optimization values were generally observed at the higher flight altitudes, particularly at 25 and 30 m AGL, although the magnitude of the response varied among processing workflows.

Camera optimization was also associated with the quality of the photogrammetric products. In this study, camera optimization refers to the optimization parameters estimated during the photogrammetric processing workflow rather than to an independent camera optimization procedure. The results therefore indicate that differences in camera optimization among processing workflows were associated with differences in image alignment and dataset quality, but do not allow camera optimization to be considered an isolated causal factor.

This finding is consistent with previous photogrammetric studies showing that image geometry, acquisition configuration, and processing parameters jointly influence image alignment and reconstructed-product quality. Du et al. (2024) similarly emphasized the importance of acquisition and processing conditions when optimizing UAV photogrammetric products. In the present study, however, the observed differences in camera optimization should be interpreted as workflow-associated responses rather than evidence of an independent causal effect of camera optimization.

4.4 Environmental and Operational Factors

Flight speed was maintained constant at 5 m/s across all 18 experimental configurations and was therefore treated as a controlled parameter rather than an experimental factor. This design allowed the effects of flight altitude and image overlap to be evaluated without introducing additional variability associated with changes in flight speed. Accordingly, the differences in dataset quality, camera optimization, and key-point matching observed among treatments cannot be attributed to flight speed. Previous studies have demonstrated that flight speed can influence UAV photogrammetric quality through motion blur and image acquisition geometry, with the magnitude of these effects depending on factors such as shutter speed, GSD, and scene characteristics (Maes, 2025; Sieberth et al., 2014). Therefore, the 5 m/s value used in this experiment should be regarded as a controlled operational condition and not as an experimentally determined optimal flight speed. Also, the comparable illumination conditions used during the flights were important for minimizing radiometric variability, as changes in illumination can introduce inconsistencies in UAV-derived RGB orthomosaics (Pastucha et al., 2022).

4.5 Integrated Interpretation of Flight Configuration Effects

The combined results indicate that flight altitude should be interpreted together with image overlap and photogrammetric processing conditions when assessing UAV image quality. In the present study, increasing altitude from 20 to 30 m AGL was positively associated with dataset quality, but the response of key-point matching differed among processing workflows. This indicates that the effect of altitude was not independent of the processing procedure and image-acquisition configuration. Similar interactions among flight parameters have been reported in photogrammetric applications, where image overlap and acquisition geometry influence image matching and three-dimensional reconstruction (Dandois et al., 2015; Du et al., 2024; Tu et al., 2020). Therefore, the results support an integrated evaluation of flight configuration rather than the interpretation of altitude as an isolated determinant of photogrammetric quality.

The findings of this study not only provide critical insights for optimizing cacao cultivation but also have broader implications for other perennial crops with similar canopy structures, such as bananas, coffee, and palm oil. By identifying optimal flight parameters, this research demonstrates how UAV-RGB imagery can enhance crop-monitoring efficiency, reduce resource consumption, and support informed decision-making, particularly for smallholder farmers who rely on these crops as a primary source of income. In Ecuador, where cacao holds deep cultural and economic significance, UAV technology offers an opportunity to bridge the gap between traditional farming practices and modern precision agriculture. This integration can help farmers improve yields while preserving their agricultural heritage. Furthermore, these findings lay the groundwork for policymakers and agricultural advisors to promote the adoption of UAVs in tropical agriculture, fostering sustainable practices and driving innovation in crop management.

This study was limited to one 1-ha experimental plot and a single UAV model (DJI Air 2S). Variability in lighting and intermittent georeferencing inconsistencies (as noted in Initial Processing Rapid) may have affected some treatments. Future Work should include ground control points (GCPs), repeated measurements under strictly controlled illumination, and tests using multiple UAV platforms.

5. Conclusion

Flight altitude significantly influenced UAV photogrammetric dataset quality within the 20-30 m AGL range evaluated. Dataset quality generally increased with altitude, with mean values for the Initial Processing Full workflow increasing from 54.96% at 20 m to 81.04% at 25 m and 96.71% at 30 m AGL. A similar pattern was observed for the Initial Processing Custom workflow, with values of 53.29%, 78.86%, and 96.50%, respectively.

The highest observed dataset-quality value was obtained with T13, consisting of 30 m AGL, 90% forward overlap, and 80% side overlap, which achieved 100% dataset quality under the Initial Processing Full workflow. Other configurations at 30 m AGL also produced dataset-quality values close to 98%, indicating that high image overlap combined with 30 m AGL provided favorable conditions for photogrammetric reconstruction under the conditions evaluated.

The relationship between flight altitude and photogrammetric performance depended on the processing workflow. Dataset quality showed strong positive associations with altitude for Initial Processing Full, Rapid, and Custom ($r = 0.848$, 0.893, and 0.830, respectively; $p < 0.001$), whereas key-point matching showed a significant positive association with altitude only for the Full workflow ($r = 0.714$, $p < 0.001$). These results demonstrate that assessment of UAV flight performance should consider multiple photogrammetric quality indicators rather than relying on a single metric.

Flight speed was maintained constant at 5 m/s across all experimental configurations and therefore was not evaluated as an independent factor. Consequently, the present study does not establish an optimal flight speed. Under the controlled acquisition conditions used in this experiment, a flight altitude of 30 m AGL combined with 90% forward and 80% side overlap provided the most favorable dataset quality within the 20-30 m AGL range tested.

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Transparency of Data

Data not available: The data set that supports the results of this study is not publicly available.

Author Contribution Statement

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Conceptualization					■	■
Data curation			■	■		
Formal analysis			■	■		
Funding acquisition			■			
Investigation	■	■	■			
Methodology	■	■				
Project administration	■	■	■			■
Resources					■	
Software				■		
Supervision			■	■		
Validation			■	■		
Visualization				■		
Writing – original draft			■			
Writing – review and editing				■		

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