



# Bioacoustic Spectral Profiling of the Endangered Salmon-Crested Cockatoo (*Cacatua moluccensis*) Using Fast Fourier Transform for Conservation Monitoring

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**Abstract:** The endangered Salmon-crested Cockatoo (*C. moluccensis*) is an endangered species endemic to Maluku and faces serious pressures due to habitat loss and illegal trade. As a species that relies heavily on vocal communication, bioacoustic analysis offers an effective, non-invasive approach to support monitoring and conservation. This study aims to analyze and characterize the spectral profile of Salmon-crested Cockatoo (*C. moluccensis*) vocalizations using the FFT algorithm. Voice recordings were conducted on individuals in their natural and captive habitats using a Zoom H5 Handy recorder. Audio data were processed through noise filtering, normalization, and segmentation stages before being analyzed using computational programming-based FFT to obtain the main spectral parameters. The results show that Salmon-crested Cockatoo (*C. moluccensis*) vocalizations have a consistent spectral structure with the main parameters being dominant frequency, bandwidth, spectral centroid, and amplitude. Spectral analysis shows variations in frequency characteristics influenced by environmental and individual conditions. The dominant frequency of Salmon-crested Cockatoo (*C. moluccensis*) behavior in its natural habitat was 1981 Hz, while in captivity it was 2497.9 Hz, both of which are within the main frequency range of  $\pm 1500 - 4000$  Hz. These different conditions show that frequency alone is not enough to explain behavior, but must be combined with context (call patterns, social interactions, and other behavioral expressions). The FFT method proved effective in identifying and characterizing vocalization patterns quantitatively. These findings indicate that FFT-based bioacoustic analysis has the potential to be developed as a non-invasive monitoring tool to support the conservation and population management of endangered endemic bird species.

**Keywords:** Bioacoustics, Bird vocalization, *Cacatua moluccensis*, Conservation monitoring, Fast Fourier Transform (FFT)

## Introduction

The Wallacea region, including the Maluku Islands, is known as one of the world's centers of biodiversity with a very high level of endemism. One endemic bird species of significant conservation value is the Salmon-Crested Cockatoo (*C. moluccensis*). This species is found naturally on Seram Island and several smaller

surrounding islands, such as Ambon, Haruku, and Saparua. A small population still survives in the protected area of Manusela National Park (Widodo 2006., Rumanta et al., 2019). In recent decades, pressure on wild populations has increased due to habitat loss and the illegal wildlife trade (Mozer & Prost, 2023).

The conservation status of the Salmon-Crested Cockatoo (*C. moluccensis*) is currently categorized as

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Vulnerable by the International Union for Conservation of Nature (IUCN Red List) and is listed on Appendix I by the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), indicating that this species faces a high risk of extinction in the wild (BirdLife International, 2024). Several recent studies have shown that the trade of several parrot species (Psittaciformes) in Indonesia remains a serious threat, despite tightened international regulations (Purwanto & Susanto, 2023; Smith et al., 2026).

As a social bird with complex vocalization capabilities, the Salmon-Crested Cockatoo (*C. moluccensis*) relies heavily on acoustic communication for social interactions, territory defense, warning of danger, and group coordination. In parrots (Psittaciformes), vocalization patterns are known to be plastic and can be influenced by the social environment, including interactions with humans in captivity (Krashennikova et al. 2024). Bioacoustic research over the past decade has shown that parameters such as dominant frequency, frequency range, call duration, and amplitude modulation patterns can be used to distinguish individuals, populations, and even specific physiological states in birds (Buxton et al. 2016; Pillay et al. 2019).

Bioacoustic approaches are increasingly evolving with advances in digital signal processing technology. One of the most commonly used methods in spectral analysis is the Fast Fourier Transform (FFT), an algorithm that efficiently transforms signals from the time domain to the frequency domain (Mutanu et al. 2022). The FFT has been widely applied in acoustic ecology studies to identify call patterns, map spectral structure, and develop automatic classification systems based on acoustic parameters (Schoeman et al. 2022). In a conservation context, this approach also supports non-invasive monitoring of wildlife populations through sound recordings in natural habitats (Nieto-Mora et al. 2023).

Various bioacoustic studies have been conducted on passerine birds (Passeriformes) and raptors, generally focusing on species identification or automatic classification based on machine learning. This study is the first quantitative study to analyze the spectral structure of Salmon-Crested Cockatoo (*C. moluccensis*) vocalizations using the FFT method approach with a direct comparison between natural habitat (*in-situ*) and captive (*ex-situ*) populations. In the recognition or identification of cockatoo vocalizations, bioacoustic approaches enable quantitative analysis of vocal signals through frequency parameters and temporal patterns. This method has rapidly evolved into a vital tool in the study of animal communication and biodiversity monitoring (Catchpole & Slater, 2018; Andrews et al., 2021). Furthermore, techniques for quantifying vocal

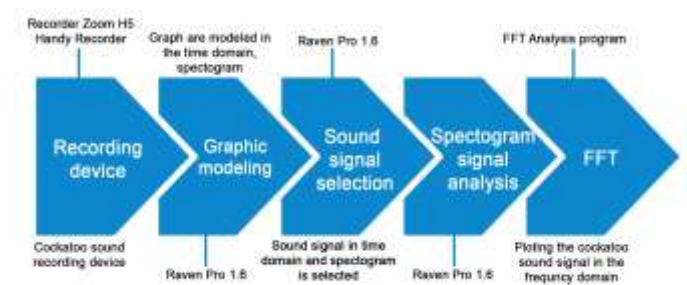
signal similarity allow for more accurate identification of communication patterns among individuals and species (Araya-Salas et al., 2025).

This study focuses on the characterization of fundamental spectral parameters as conservation acoustic biomarkers for endangered Wallacea endemic species. This approach offers a methodological contribution in the form of integrating classical FFT analysis with spectral parameter-based classification accuracy evaluation, which has the potential to be developed as a non-invasive monitoring system to support Salmon-Crested Cockatoo (*C. moluccensis*) conservation in the wild. Based on this background, this study aims to obtain and document vocalization recordings of Salmon-Crested Cockatoo (*C. moluccensis*) in natural and captive habitats, analyze frequency characteristics using the FFT algorithm, and identify key acoustic parameters that can be used as a basis for classifying vocal patterns and evaluating the accuracy level of the FFT method in distinguishing vocalization sources or conditions. This approach is expected to contribute to the development of bioacoustics as a non-invasive identification tool in the conservation of endemic birds of Wallacea.

**Method**

*Ethical Approval*

All research procedures involving sampling were non-stressful to the animals. Data collection was conducted without manipulation of bird behavior and in accordance with applicable conservation regulations in Indonesia. No capture or physical intervention was performed on the individuals being recorded. Figure 1 shows the overall stages of the research, shown in the following flowchart.



**Figure 1.** Research flowchart of bioacoustic analysis

*Location and Time of Research*

This study uses an experimental quantitative approach based on digital signal analysis. Vocalization Salmon-Crested Cockatoo (*C. moluccensis*) were recorded from two different environmental conditions (Figure 2), namely Manusela National Park (TN) as a natural habitat (*in-situ*) with coordinates

2°59'38.5"S 129°36'49.3"E, and habitat (ex-situ) in the breeding area of the Maluku Province Natural Resources Conservation Agency. The sound data obtained were analyzed using the FFT algorithm to identify the main spectral parameters.

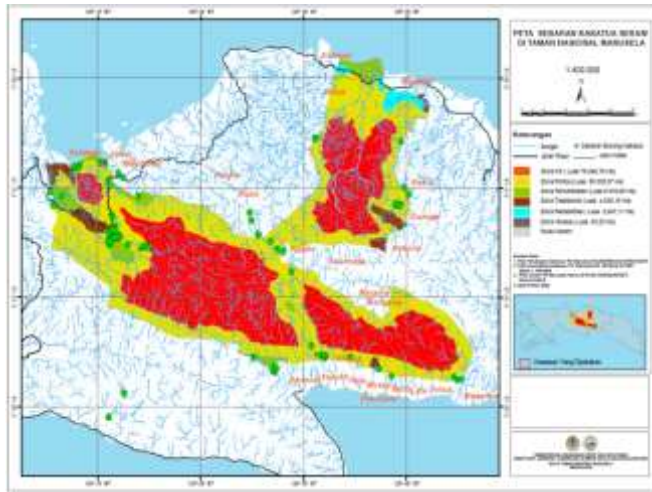


Figure 2. Location map of bioacoustic research on the Salmon-Crested Cockatoo (*C. moluccensis*)

Sound Sampling and Recording

Recording was done using a digital recorder zoom H5 Handy recorder with a rate specification of 44.1 kHz to 48 kHz, dan Bit depth of 24 bits. The digital recorder has a condenser shotgun microphone with a frequency range of 20 Hz–20 kHz used to increase sensitivity to the high frequency calls typical of the species. Salmon-Crested Cockatoo (*C. moluccensis*) each recording session was conducted during the birds' peak activity periods (dawn and dusk) to capture a variety of natural vocalizations. Recordings lasted 5–10 minutes per individual, with microphones at a distance of approximately 5–15 meters in the wild and approximately 2–5 meters in captivity. Background noise such as wind and other species' sounds were recorded and considered in signal pre-processing.

Spectral Analysis Using Fast Fourier Transform (FFT)

Audio files were converted to mono and amplitude normalized. Noise reduction was performed using a band-pass filter ( $\leq 500$  Hz) to focus on the dominant frequency range of Psittaciformes vocalizations, as recommended in avian bioacoustics studies (Darras et al., 2018). Signal segmentation was performed manually to separate call units based on duration and intensity.

Spectral analysis was performed using computer application software (CAS), with the FFT algorithm and working stages shown in Figure 3. Transformation was performed on each signal segment using the equation:

$$X(k) = \sum_{n=0}^{N-1} x(n)e^{-j2\pi kn/N} \tag{1}$$

Information:

$X(n)$  is a signal in the time domain

$X(k)$  is the spectral representation in the frequency domain

$N$  is the number of samples

The FFT results were visualized in the form of a two-dimensional spectrum (amplitude vs frequency) using the Raven Pro 16 program. In addition, a computer application software (CAS)-based graphical simulation was created to display a comparison of spectral patterns between natural and captive habitat conditions.

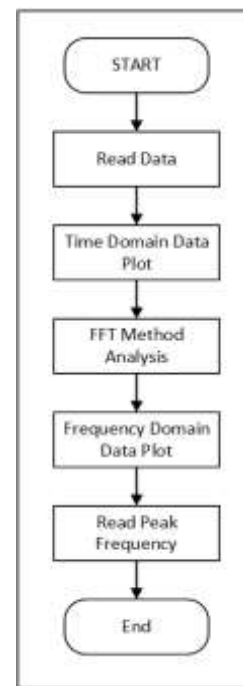


Figure 3. CAS-based FFT spectral analysis workflow diagram

Results and Discussion

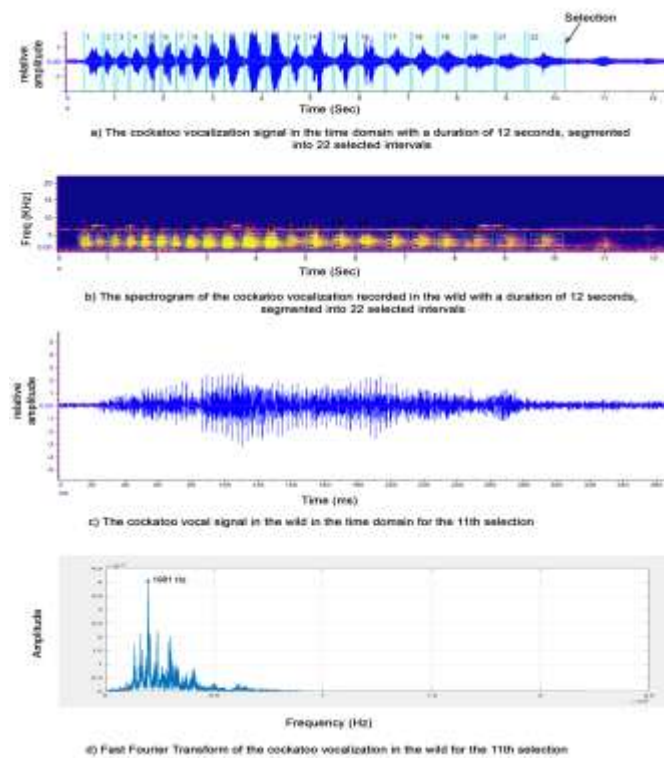
Spectral Structure of Salmon-Crested Cockatoo (*C. moluccensis*) Vocalizations

FFT-based analysis shows that Salmon-Crested Cockatoo (*C. moluccensis*) vocalizations have spectral energy concentrated in the mid-frequency range, with a dominant frequency of 1981 Hz in the wild and 2497.9 Hz in captivity. Overall, the main frequency range is in the range of  $\pm 1500$ –4000 Hz, while the full range of the detected spectrum reaches 372–8268 Hz in the wild (Figure 4) and 255–8882 Hz in captivity (Figure 5).

The spectrogram shows a relatively focused energy distribution with a consistent harmonic pattern across each call unit. This mid-frequency dominance is consistent with the general characteristics of large-

bodied members of the Psittaciformes order, which tend to produce lower frequencies than passerine birds (Passeriformes) (Bradbury & Vehrencamp, 2016). In species such as the Palm Cockatoo (*Probosciger aterrimus*), the dominant frequency is also reported to be in the 1–3 kHz range with a clear harmonic structure (Zdenek et al., 2015; Zdenek et al., 2017). This indicates that the Salmon-Crested Cockatoo (*C. moluccensis*) spectral pattern is still within the physiological range common to members of the Cacatuidae family, while also confirming that the dominant frequency parameters obtained are not recording artifacts, but rather a reflection of the species' biological characteristics.

Compared with smaller hookbills such as *Melopsittacus undulatus*, which tend to produce higher frequencies (>3–4 kHz), a morpho-acoustic gradient is observed within the order Psittaciformes. This gradient is consistent with the biomechanical principles of sound production in birds, where syrinx membrane mass and air column length determine resonance frequency (Brittan-Powell et al., 1997). Thus, the spectral position of the Salmon-Crested Cockatoo (*C. moluccensis*) in the 2–3 kHz band can be understood as a physiological consequence of its relatively large body size and vocal resonator configuration.

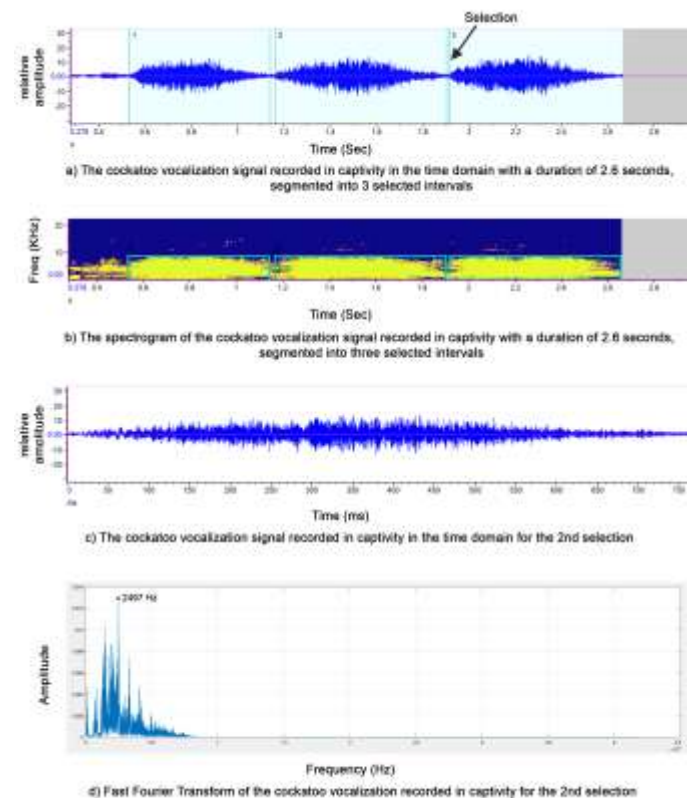


**Figure 4.** The vocal signals of the Salmon-crested Cockatoo (*C. moluccensis*) in its natural habitat are graphed in the time domain, frequency domain and in the form of a spectrogram.

From an acoustic ecology perspective, frequencies in the 2–3 kHz range offer a propagation advantage in tropical forest environments. High vegetation density

causes greater scattering and attenuation at high frequencies (>5 kHz), while frequencies that are too low are susceptible to masking by background noise such as wind or insect calls. Therefore, the mid-frequency band often represents an “optimal compromise” between transmission range and signal clarity. This principle aligns with the Acoustic Adaptation Hypothesis first proposed by Morton (1975) and has been reaffirmed in the last decade through studies of tropical acoustic landscapes, which have shown that forest birds tend to maintain signals within a frequency range that is relatively stable against vegetation disturbance (Sugai et al., 2019).

Thus, the spectral patterns of the Salmon-Crested Cockatoo (*C. moluccensis*) reflect not only the physiological limits of vocal production but also likely the result of long-term ecological selection. The stability of the energy distribution in the mid-frequency band suggests that this species' vocal signals have been evolutionarily calibrated to maximize communication effectiveness in the forest habitat of Seram Island. This combination of morphological factors, neuromuscular control, and environmental adaptation explains why the observed harmonic structure and dominant frequencies remain consistent even when recorded across different individuals and under different conditions.



**Figure 5.** The vocal signals of the Salmon-crested Cockatoo (*C. moluccensis*) in captivity are graphed in the time domain, frequency domain and as a spectrogram.

### *Bioacoustics of Salmon-crested Cockatoo (C. moluccensis) in Natural Habitat*

A 12-second recording of Salmon-Crested Cockatoo (*C. moluccensis*) vocalizations in their natural habitat yielded 22 call selection units using Raven Pro 1.6.3 software (Table 1). Each selection showed relatively consistent acoustic parameters, with an average lowest frequency of 418 Hz and a highest frequency of 7558 Hz. The average peak frequency was recorded at 2298.18 Hz, while the average duration of each call unit was 0.41 seconds. In one representative unit (selection 11), FFT analysis showed a dominant frequency of 1981 Hz with a lower limit of 372.5 Hz and an upper limit of 8268.7 Hz.

Biologically, the dominant frequency range of  $\pm 1500$ –4000 Hz obtained in this study indicates that Salmon-Crested Cockatoo (*C. moluccensis*) retains the typical vocal pattern of large members of the Order Psittaciformes. Krasheninnikova et al. (2024) reported that in an evolutionary study of vocal production in parrots, this group emphasized that they have flexible vocal control but remain within physiological limits determined by body size and vocal tract configuration. With their relatively large body mass and long vocal resonators, members of the family Cacatuidae tend to produce fundamental frequencies in the mid-band compared to small parrots such as budgerigars or grass parrots (*Melopsittacus undulatus*) (Watanabe et al., 2007).

The finding of a dominant frequency around 2 kHz is also consistent with reports from the species *Probosciger aterrimus*, which exhibits a dominant range of 1–3 kHz with a strong harmonic structure (Zdenek et al., 2015; Zdenek et al., 2017). This similarity indicates morpho-acoustic consistency within the Cacatuidae family. Functionally, calls with mid-frequency and harmonic structure are generally used as contact or long-distance calls, particularly in the context of maintaining group cohesion or communication between pairs in the forest canopy.

From an acoustic ecology perspective, the dominance of the 1981 Hz frequency in natural habitats is crucial. Tropical forests have complex vegetation structures that cause selective attenuation of high frequencies (>5 kHz) due to scattering by leaves and branches. Studies of tropical landscape acoustic monitoring have shown that the mid-frequency band (2–4 kHz) offers an optimal balance between range and resistance to signal degradation (Sugai et al., 2019; Darras et al., 2016). While lower frequencies can reach longer distances, they are often masked by background noise such as wind and insect activity. Conversely, high frequencies are sharp but rapidly attenuate under the

canopy. Therefore, the band around 2 kHz can be understood as an adaptive compromise point between transmission distance and signal clarity.

The average duration of 0.41 seconds per call unit is also behaviorally relevant. Short, repetitive calls generally serve as identity signals or to coordinate group movements. Recent studies of individual vocal signatures in social birds have shown that the combination of short duration and stable frequency enhances individual recognition within a colony (Terry et al., 2017; Kahl et al., 2021). Thus, the relatively narrow peak frequency stability across the 22 selections may indicate the presence of an individual or group identity component in the calls Salmon-Crested Cockatoo (*C. moluccensis*) wild.

When compared to several Amazon species, including the *Yellow-naped Amazon* and *Blue-fronted Amazon*, which live in South American forest habitats, their dominant frequencies tend to be in the range of 2–4 kHz with longer temporal variations for alarm calls (Bradbury et al., 2001). The pattern on Salmon-Crested Cockatoo (*C. moluccensis*) appears to be more concise in duration but still maintains a wide bandwidth (418–7558 Hz). This broad bandwidth suggests the presence of upper harmonic components that may play a role in enriching the signal information, although its greatest energy remains concentrated in the mid-band.

In a conservation context, these relatively stable spectral characteristics have important implications. *Passive acoustic monitoring* (PAM), which has developed rapidly in the past decade, relies on parameters such as dominant frequencies and temporal patterns for the automatic detection of endangered species (Stowell, 2022). Acoustic profiles Salmon-Crested Cockatoo (*C. moluccensis*) clear and consistent data on opens up opportunities for the development of machine learning-based classification models to monitor wild populations without direct intervention. This approach is particularly relevant given the ongoing poaching and illegal trade pressures that threaten this species in the Maluku region.

Overall, the results of this study indicate that vocalization Salmon-Crested Cockatoo (*C. moluccensis*) in its natural habitat reflects the interaction between the physiological limits of sound production, social needs within the group, and the selection pressures of the tropical forest environment. The dominant frequency of around 2 kHz is not merely a numerical parameter, but rather a representation of morphological and ecological adaptations that enable effective communication in a complex acoustic landscape.

**Table 1.** Frequency data of Salmon-Crested Cockatoo (*C. moluccensis*) sounds in the natural habitat of each selection using RavenPro 1.6.3

Selection	Begin Time (s)	End Time (s)	Delta Time (s)	Low Freq (Hz)	High Freq (Hz)	Peak Freq (Hz)
1	0.35556	0.72305	0.3675	586.9	6874.9	2067.2
2	0.77046	0.99567	0.2252	518.8	6939.3	2842.4
3	1.04308	1,29200	0.2489	447	6853.4	1808.8
4	1.32163	1.61204	0.2904	447	7821.8	2411.7
5	1.64167	1.93208	0.2904	521.5	7225.8	2842.4
6	1.96171	2.25211	0.2904	372.5	7225.8	2756.2
7	2,27582	2.51288	0.2371	298	7151.4	2411.7
8	2,56622	2.86255	0.2963	298	7002.4	2153.3
9	2,89219	3,23000	0.3378	372.5	7151.4	1894.9
10	3.25371	3.63301	0.3793	372.5	8268.7	1894.9
11	3.67108	4.08001	0.4089	372.5	8268.7	1981.1
12	4,12149	4.53636	0.4149	347.2	7378.9	1981.1
13	4.56599	4.88011	0.3141	347.2	8420.7	2842.4
14	4,91567	5.44313	0.5275	434.1	8333.9	2497.8
15	5,49055	5.94689	0.4563	434.1	7639.4	2670.1
16	5,97550	6.49704	0.5215	347.2	7205.3	2928.5
17	6,53261	7.03044	0.4978	520.9	7205.3	2497.8
18	7,06562	7,56345	0.4978	434.1	7378.9	2497.8
19	7.61679	8,15612	0.5393	434.1	7205.3	1894.9
20	8,19760	8.74878	0.5512	434.1	8160.2	1894.9
21	8,79026	9,39478	0.6045	347.2	8247	1894.9
22	9.44219	10,18302	0.7408	512.8	8333.9	1894.9
Delta time (s) & Mean frequency (Hz)			0.4108	418.2	7558.7	2298.2

*Bioacoustics of Salmon-crested Cockatoo (C. moluccensis) in Captivity*

Vocalization recording Salmon-Crested Cockatoo (*C. moluccensis*) 2.6-second call of in captivity showed a relatively clearly segmented signal structure in the time domain. The selection process for three call units (Figures 5a–5c) showed that each unit had a distinct energy pattern with a defined onset and offset, indicating stable phonation control. After processing using the FFT algorithm, the second selection resulted in a dominant frequency of 2497.9 Hz (Figure 5d), which is within the typical mid-frequency band of the great cockatoo group.

Acoustically, the dominant frequency value reflects a contact call type with a mid-tone character and a relatively clear harmonic structure. In many members of the Psittaciformes, contact calls are used to maintain social cohesion, especially in groups that live in colonies or in fixed pairs. Studies on the King Cockatoo (*Probosciger aterrimus*) species indicate that calls with a dominant frequency of 1–3 kHz play a role in medium-range communication and maintaining social relationships between individuals (Heinsohn et al., 2017; Zdenek et al., 2017). The pattern obtained in Salmon-Crested Cockatoo (*C. moluccensis*) in captivity showed spectral agreement with these findings, despite the different ecological context.

The average frequency range from lowest to highest across the three selections (255.4–8882.4 Hz) indicates

that in addition to the dominant frequency, there are quite broad harmonic and overtone components. However, the energy concentration remains in the range of ± 1500–4000 Hz with an average dominant frequency of 2268.16 Hz. This range is still included in the “primary communication zone” of the great cockatoo, which is morpho-physiologically determined by body size and vocal tract configuration (Bradbury & Vehrencamp, 2016). Larger birds with longer air columns tend to produce lower fundamental frequencies than small hooked beaks such as *Melopsittacus undulatus*, which can reach higher frequencies with faster modulation.

In the captive context, it is interesting to note that the dominant frequency of 2497.9 Hz is slightly higher than the average obtained in the natural habitat in this study. This slight increase can be explained through two approaches. First, the acoustics of the space: the structure of the enclosure or semi-enclosed space can produce resonance and reflection effects that affect the distribution of spectral energy. Second, the behavioral and vocal plasticity aspects. Research over the past decade has shown that parrots have a high vocal learning capacity and acoustic flexibility. Krashenninnikova et al. (2024) emphasize that vocal abilities in Psittaciformes are not only related to imitation, but also to the adjustment of signal frequency and structure to the social context. In captive environments, where social density and distance between individuals are shorter, contact calls may

undergo modifications in intensity or frequency to maintain communication effectiveness.

The relationship between frequency and behavioral context was also evident during field observations. During active social interactions—for example, during play or in response to the presence of other individuals—vocalizations tended to be more varied and had richer harmonic energy. This phenomenon aligns with the findings of Bradbury et al. (2001) in the genus *Amazona* (*Yellow-naped Amazon and Blue-fronted Amazon*), which showed that spectral variation increases when birds are in dynamic social situations. Thus, the dominant frequency is not only a physical parameter, but also an indicator of behavioral context.

From an acoustic ecology perspective, the 2–3 kHz band remains an efficient range for communication, even in captive conditions. Despite not encountering the complex vegetation of tropical forests, mid-frequency signals are relatively resistant to masking by low-frequency noise (e.g., human activity or wind). Literature in the last decade on soundscape ecology confirms that many bird species maintain stable frequency bands despite environmental changes, as this range represents an optimal compromise between transmission range and signal clarity (Sugai et al., 2019).

It is important to note that although the average frequency range of 2268.16 Hz falls within the general range of great cockatoos, inter-individual variation is still possible. Factors such as body size, age, sex, and social experience can influence spectral parameters. Modern bioacoustic studies also indicate that individuals within a species can possess distinctive “acoustic signatures,” which function in individual recognition (Terry et al., 2005). Therefore, the lowest, highest, and peak frequency data for each selection (Table 2) not only illustrate the general characteristics of the species but also potentially contain individual information relevant for monitoring captive populations.

Overall, these results indicate that vocalization of Salmon-Crested Cockatoo (*C. moluccensis*) in captivity retains the typical spectral characteristics of large cockatoos, with dominant frequencies in the mid-band and a stable harmonic structure. Small differences compared to their natural habitats are more likely to reflect vocal plasticity and social context rather than physiological changes. These findings reinforce the notion that dominant frequency and bandwidth parameters can be used as reliable bioacoustic indicators in evaluating cockatoo behavior and welfare in captive environments.

**Table 2.** Sound frequency data of Salmon-Crested Cockatoo (*C. moluccensis*) in the captive habitat at each selection using the Raven Pro 1.6.3 program

Selection	Begin Time (s)	End Time (s)	Delta Time (s)	Low Freq (Hz)	High Freq (Hz)	Peak Freq (Hz)
1	0.52108	1.12945	0.6084	255.4	8939.2	1894.9
2	1.14741	1.88926	0.7418	255.4	9109.5	2497.9
3	1.90466	2.64649	0.7418	255.4	8598.6	2411.7
Delta time (s) & Mean frequency (Hz)			0.6973	255.4	8882.4	2268.2

*Ecological and Conservation Implications*

The spectral and temporal findings of this study indicate that Salmon-Crested Cockatoo (*C. moluccensis*) vocalizations have a relatively stable dominant frequency profile ( $\pm 2$ –3 kHz) with a consistent harmonic pattern, potentially serving as an acoustic signature at the species level. This stability is ecologically important because it facilitates automatic detection amidst the complexity of tropical forest soundscapes such as Manusela National Park, which are generally dominated by insects and higher-frequency passerine birds. In other words, the spectral position of Salmon-Crested Cockatoo (*C. moluccensis*) is in a fairly separate “acoustic space,” so the chance of overlapping (*acoustic masking*) is relatively low.

In the last decade, the approach PAM is rapidly developing as a non-invasive method for biodiversity surveys. FFT-based analysis and spectral feature extraction now form the foundation of automated monitoring systems capable of recognizing specific

vocalization patterns among thousands of hours of field recordings (Stowell, 2022). This approach is particularly relevant for species with high hunting pressure and illegal trade, such as the Salmon-Crested Cockatoo (*C. moluccensis*), as it allows population detection without the presence of researchers, potentially disrupting or increasing the risk of hunting.

Ecologically, the use of PAM also allows monitoring of population dynamics at broader spatial and temporal scales. Variations in call duration and energy intensity can be integrated as indicators of social activity, reproductive seasonality, or response to anthropogenic disturbances. Recent studies have shown that integrating dominant frequency, bandwidth, and temporal parameters into machine learning models can significantly improve species identification accuracy (Kahl et al., 2021). With a relatively constant dominant frequency in this study, the Salmon-Crested Cockatoo (*C. moluccensis*) is an ideal species for developing a deep

learning-based automatic classification model in tropical acoustic landscapes.

Furthermore, the bioacoustic approach opens up opportunities for long-term monitoring without relying on visual observations. Terry et al. (2005) state that stable vocal characteristics also have the potential to be used for individual identification in conservation contexts, which are often hindered by limited access to sites and canopy conditions in tropical rainforests. In the context of the Maluku Islands, which face habitat fragmentation and deforestation pressure, an acoustic landscape-based monitoring system can be a more sensitive tool for evaluating changes in bird communities than conventional surveys. This approach is further reinforced by the addition of automatic recording devices such as AudioMoth, which enable efficient long-term monitoring (Hill et al., 2018). The spectral baseline data generated by this study provides initial reference parameters for calibrating future automated detection algorithms. As noted by Deichmann et al. (2017), soundscape ecology analysis enables a more comprehensive evaluation of ecosystem conditions through acoustic indicators.

Thus, the ecological implications of this research go beyond mere description of vocal traits. The identified acoustic profiles not only reflect the biological traits of the species but also provide the technical foundation for a modern conservation system based on acoustic data. The integration of FFT, spectral feature extraction, and machine learning-based classification has the potential to transform Salmon-Crested Cockatoo (*C. moluccensis*) monitoring from a periodic survey approach to a continuous detection system responsive to population changes and environmental pressures.

## Conclusion

Bioacoustic analysis of Salmon-Crested Cockatoos (*C. moluccensis*) using FFT showed that the dominant vocalization frequencies in the wild (average 2298.18 Hz) and in captivity (average 2268.16 Hz) were in very similar ranges. The detected frequency range in both habitats remained within the main band of large cockatoos ( $\pm 1.5$ –4 kHz), indicating that the basic spectral characteristics were relatively stable and more influenced by morpho-physiological factors than environmental differences. Small differences in call duration (0.41 s in the wild and 0.69 s in captivity) indicated variations in behavioral context, rather than changes in fundamental acoustic structure. These findings confirm that dominant frequency and call duration parameters can be used as reliable bioacoustic indicators for non-invasive population monitoring and welfare evaluation of the endangered Salmon-Crested

Cockatoo (*C. moluccensis*), thus potentially strengthening acoustic data-driven conservation strategies.

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## Author Contributions

Conceptualization, RRL and RMK; methodology, RMK, and FM; validation, RRL and RMK; formal analysis, FM and RMK; investigation, RRL, and RMK; resources, RRL and FM; data curation, RMK; writing the original draft, RRL, and RMK; writing the review and editing, RMK; visualization, RMK and FM. All authors have read and approved the published version of this manuscript.

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## Conflicts of Interest

The authors declare no conflict of interest.

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