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Research Article

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Habitat and Microclimatic Characteristics of the Maleo (*Macrocephalon maleo*) at the Ex Situ Captive Breeding Facility at PT. PAU and the Surrounding Area of PT. DSLNG Facility, Banggai Regency

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ABSTRACT

The maleo (*Macrocephalon maleo*) is an endemic bird species of Sulawesi whose conservation requires an understanding of habitat and environmental characteristics. This study aimed to characterize the ecological conditions, microclimate, nesting pits, and vegetation composition associated with two company-managed ex situ maleo conservation facilities in Banggai Regency, Central Sulawesi, Indonesia. A quantitative descriptive approach was employed through field observations conducted from February to May 2024 at facilities managed by PT Panca Amara Utama (PT PAU) and PT Donggi-Senoro LNG (PT DSLNG). At PT PAU, measurements were conducted both inside and outside the breeding enclosure, whereas observations at PT DSLNG were restricted to the external area due to access limitations. Within the PT PAU enclosure, mean air temperature, relative humidity, and sand temperature were 31.23°C, 62.13%, and 33.20°C, respectively, with a neutral sand pH of 7.0. The external area at PT PAU exhibited higher air temperatures (36.86–39.10°C), while the external area at PT DSLNG had a mean air temperature of 34.93°C, relative humidity of 60.55%, light intensity of 1,607.68 lx, and wind speed of 2.17 m/s. Two nesting pits were measured within the PT PAU enclosure, with a mean depth of 37 cm. Vegetation surveys recorded eight plant species at PT PAU and 22 species in the external area at PT DSLNG. However, differences in survey coverage precluded direct comparisons of overall species richness and internal enclosure conditions between facilities. These findings provide baseline ecological information for habitat characterization and management planning in company-managed maleo conservation areas.

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1. INTRODUCTION

The maleo (*Macrocephalon maleo*) is an endemic bird species of Sulawesi, Indonesia, with considerable ecological and conservation significance. According to the International Union for Conservation of Nature (IUCN) Red List assessment published in 2021, the species is classified as Critically Endangered (CR) under criteria A2cd+4cd, indicating an extremely high risk of extinction in the wild (BirdLife International, 2021). In Indonesia, the maleo is legally protected under Law No. 5 of 1990 concerning the Conservation of Living Natural Resources and Their Ecosystems, as amended by Law No. 32 of 2024. The species is also explicitly listed as protected wildlife under Minister of Environment and Forestry Regulation No. P.20/MENLHK/SETJEN/KUM.1/6/2018, as amended by Regulation No. P.106 /MENLHK / SETJEN/KUM.1/12/2018. Furthermore, the maleo is included in Appendix I of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES), reflecting the strict international trade controls applied to the species. The maleo exhibits a distinctive reproductive strategy in which eggs are buried in warm soil and incubated using environmental heat derived from solar radiation or geothermal sources (Mustari, 2020). Despite its protected status, maleo populations remain threatened by egg collection, habitat fragmentation, and the degradation of nesting grounds associated with land conversion, mining activities, and plantation expansion (Summers et al., 2025).

In areas affected by industrial and land-use activities, these pressures may reduce habitat availability and alter environmental conditions essential for successful reproduction. Consequently, conservation efforts require not only the protection of remaining natural habitats but also the development of scientifically informed habitat-management strategies that address the species' specific ecological and reproductive requirements.

Previous studies have established that maleo habitat suitability is closely associated with soil properties, substrate temperature, humidity, microclimatic conditions, vegetation composition, and food availability. Hafsah et al. (2009), Jamili et al. (2015), and Muhi et al. (2021) examined the ecological characteristics of natural maleo nesting habitats, particularly soil conditions, temperature, humidity, and nesting-site characteristics. These environmental factors are especially important because maleo eggs rely on external heat for incubation rather than parental body heat (Mustari, 2020). Vegetation also contributes to habitat quality by providing food resources, shade, and structural characteristics that influence habitat use. Karim et al. (2022) and Silayar et al. (2017) identified plant species associated with maleo habitats and described their potential ecological and nutritional roles. Although these studies provide valuable information on the ecological characteristics of natural maleo habitats, their findings do not fully explain how these environmental requirements are represented or maintained within company-managed ex situ conservation facilities. In particular, information remains limited regarding the combined characteristics of soil, microclimate, vegetation, and habitat-management conditions in such facilities.

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This knowledge gap is important because managed conservation environments may differ from natural habitats in their environmental characteristics and management practices. Therefore, the present study examines the ecological characteristics of a company-managed ex situ maleo conservation facility, focusing on environmental factors associated with habitat suitability. By evaluating these characteristics within a managed conservation setting, this study extends previous natural-habitat research and provides site-specific information to support habitat management and conservation planning for *M. maleo*.

In addition to conservation in natural habitats, ex situ conservation has become an important complementary approach for threatened species such as the maleo. Captive breeding facilities can provide protected environments for maintaining individuals and supporting reproductive activities when natural nesting habitats are increasingly exposed to anthropogenic pressures. Central Sulawesi is particularly important for maleo conservation because it contains several significant nesting areas, including Lore Lindu National Park, the Tompotika area, and the Bakiriang Wildlife Reserve. Banggai Regency is also an important area for maleo conservation because it contains industrial facilities operated by PT. Donggi-Senoro LNG (PT. DSLNG) and PT. Panca Amara Utama (PT. PAU), both of which have developed maleo captivity programs as part of their environmental and social responsibility initiatives. The effectiveness of these programs depends on the extent to which captivity facilities provide environmental conditions that are suitable for maleo survival and reproduction. Therefore, information on substrate characteristics, microclimatic conditions, nesting sites, and vegetation composition is necessary to support evidence-based management of ex situ facilities (Rusiyantono et al., 2011).

The sensitivity of maleo (*Macrocephalon maleo*) to human disturbance is another important consideration in ex situ conservation management, particularly for facilities located near industrial operations. Previous studies have identified human disturbance, egg collection, and habitat modification as significant threats to maleo nesting populations, potentially affecting nesting-site use and reproductive activities (Summers et al., 2023; Summers et al., 2025). In industrial environments, operational noise, vehicle movement, routine maintenance, and frequent human presence may represent additional sources of disturbance to captive maleos, although their specific effects require further investigation. Consequently, potential management measures include restricting unnecessary human access, minimizing disruptive activities near breeding enclosures, maintaining vegetated buffer zones, and monitoring behavioural responses to environmental disturbances. Such measures may help reduce disturbance exposure, but their effectiveness must be evaluated through direct observations and appropriate monitoring. In the present study, the maleo conservation facilities managed by PT. Panca Amara Utama (PT. PAU) and PT. Donggi-Senoro LNG (PT. DSLNG) are situated within industrial coastal settings. However, noise levels, human activity intensity, and behavioural indicators of stress were not directly measured. Therefore, these factors are considered relevant

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management considerations rather than variables evaluated in the present ecological characterization.

Despite the growing importance of ex situ conservation, ecological information on maleo captivity facilities in industrial coastal areas remains limited. Previous studies have primarily focused on natural habitats, while the ecological characteristics of company-managed ex situ facilities in Banggai Regency, particularly the environmental conditions within and outside these facilities, have received less attention. Specifically, information on microclimatic conditions, nesting-site characteristics, and vegetation composition in these managed environments remains insufficiently documented. Similarly, the composition and potential ecological functions of vegetation within captivity facilities have not been thoroughly described, although plant species may contribute to shading, microclimatic regulation, and food availability. These knowledge gaps highlight the need for systematic ecological characterization of company-managed ex situ facilities, particularly to document environmental variation and vegetation characteristics within and outside their boundaries. Therefore, this study focuses on describing and comparing the ecological conditions of these areas, providing baseline information that may support habitat-management planning and inform future evaluations of ex situ maleo conservation programs in industrial coastal environments.

Therefore, this study aimed to characterise the habitat of maleo (*Macrocephalon maleo*) in ex situ captivity facilities managed by PT. Panca Amara Utama and PT. Donggi-Senoro LNG in Banggai Regency, Central Sulawesi. Specifically, the study aimed to document the ecological conditions of the captivity facilities, assess microclimatic conditions inside and outside the captivity enclosures, characterize nesting-site conditions, and identify plant species and their potential ecological roles in supporting maleo conservation at both study sites.

2. MATERIALS AND METHODS

This study employed a quantitative descriptive design based on field ecological observations to characterize environmental conditions, microclimatic parameters, and vegetation composition associated with maleo (*Macrocephalon maleo* Müller, 1846) conservation facilities in Banggai Regency, Central Sulawesi, Indonesia. Fieldwork was conducted from February to May 2024 at two company-managed conservation sites: the maleo captive breeding facility operated by PT. Panca Amara Utama (PT. PAU) and the Maleo Conservation Centre managed by PT. Donggi-Senoro LNG (PT. DSLNG), both located in Uso Village, Batui District. The study sites are situated in coastal environments at elevations of approximately 4–6 m above sea level.

Ecological observations were conducted in areas accessible for field measurements. At PT. PAU, data were collected both within and outside the captive breeding enclosure, whereas observations at PT. DSLNG were restricted to areas outside the enclosure because access to the interior was not authorized. Consequently, the two sites differed in their spatial sampling coverage. The study was therefore designed to provide descriptive ecological information for the environments actually sampled, rather

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than to directly compare the internal conditions or conservation performance of the two facilities. Comparisons between observations inside and outside the enclosure were limited to PT. PAU, while data from PT. DSLNG were used to characterize the external environmental conditions surrounding its conservation facility.

Ecological and microclimatic data were collected through direct field observations and measurements. The ecological variables included the physical characteristics of maleo nesting holes, specifically depth, length, and width, while the microclimatic variables included air temperature, relative humidity, sand temperature, sand pH, light intensity, and wind speed. Measurements were conducted at three observation times, namely 09:00, 12:00, and 15:00 Central Indonesia Time (WITA), at each study site. The equipment used during field observations included labels, a Global Positioning System (GPS) device, measuring tapes, raffia string, thermometers, a Nikon D5300 camera, a lux meter, an anemometer, a digital thermohygrometer, a pH meter, and writing materials. These instruments were used to measure the physical characteristics of nesting holes and microclimatic conditions, document field observations, and record vegetation data.

Plant inventory was conducted using a complete enumeration method throughout the captive breeding area at each study site. All plant species encountered within the observation areas were recorded and identified using their scientific names. The complete enumeration method was selected because of the relatively limited size of the captive breeding areas and the objective of obtaining comprehensive information on plant species composition. Field observations and measurements were conducted systematically at each observation site and observation time to obtain comparable ecological and microclimatic data between the study sites. The maleo captive breeding facility managed by PT. Donggi-Senoro LNG (PT. DSLNG) covers an area of 0.60 hectares (ha), whereas the facility managed by PT. Panca Amara Utama (PT. PAU) covers 0.84 ha. Both sites are characterized by relatively flat coastal terrain with predominantly sandy substrates. These physical characteristics indicate that the two captive breeding facilities are situated in similar coastal environments, although they differ in size.

Ecological and microclimatic data were analysed using descriptive statistical methods. The mean, minimum, and maximum values were calculated for each measured variable at each study site and observation time. These descriptive statistics were used to describe the environmental conditions and variation of each ecological and microclimatic parameter during the observation period. The vegetation data were analysed descriptively based on the plant species recorded through the complete enumeration method to describe plant species composition at each study site. The results of the ecological, microclimatic, and vegetation observations were subsequently presented in tables and graphs to facilitate interpretation and comparison between the two study sites.

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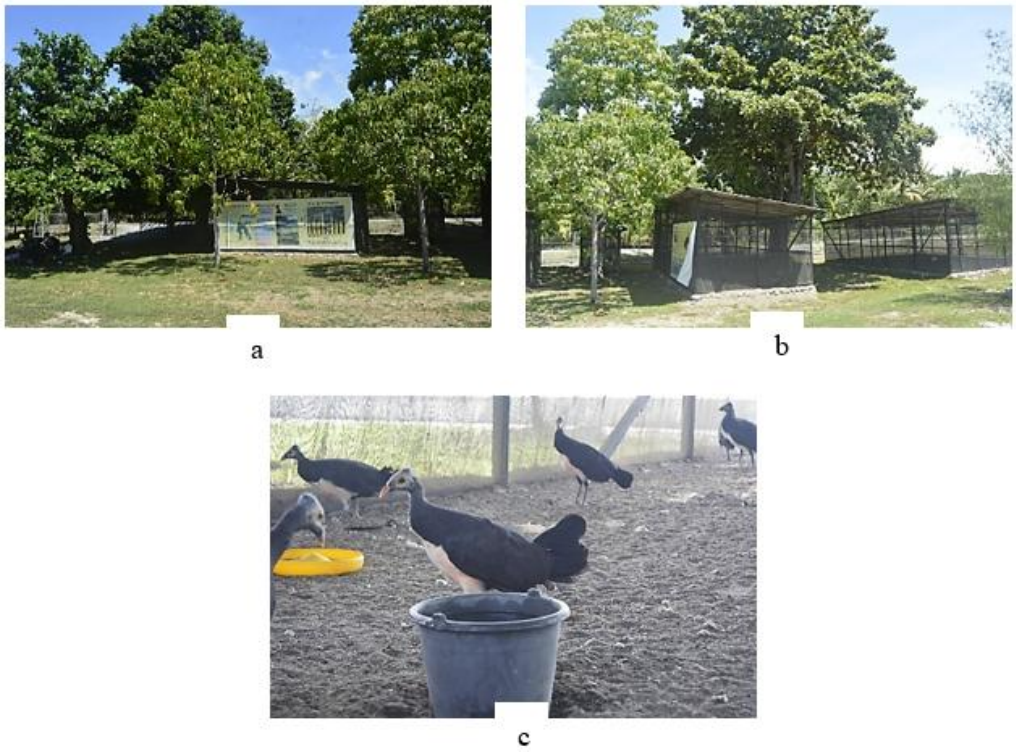


Figure 1. Captivity location (a&b) and photo of maleo bird (c) conservation PT. PAU Luwuk Banggai Central Sulawesi



Figure 2. Captivity location (a&b) and photo of maleo bird (c) conservation PT. DSLNG Luwuk Banggai Central Sulawesi

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3. RESULTS AND DISCUSSION

a. Habitat Characteristics Inside and Outside the Captivity Facilities

This study was conducted at two maleo (*Macrocephalon maleo*) breeding facilities in Banggai Regency, Central Sulawesi. The first location was the maleo breeding facility managed by PT. PAU, where observations were conducted both inside and outside the breeding enclosure. The second location was the maleo breeding facility managed by PT. DSLNG, located in Uso Village, Batui District. At the PT. DSLNG facility, data were collected only outside the breeding enclosure because access to the area inside the enclosure was restricted under the company's conservation Standard Operating Procedures (SOPs).

Both study sites are located in the coastal area of Banggai Regency, at elevations ranging from 4 to 6 m above sea level. The surrounding environments are characterized by relatively flat coastal terrain with predominantly sandy substrates. These physical characteristics suggest that both facilities share similar general coastal settings, although their environmental conditions may differ at the microhabitat level. At the PT. Panca Amara Utama (PT. PAU) captive breeding facility, four enclosures were recorded, comprising three adult enclosures and one juvenile enclosure. The three adult enclosures housed 14, nine, and 14 maleos, respectively, while the juvenile enclosure contained 16 individuals, resulting in a total of 53 maleos. At the . Donggi-Senoro LNG (PT. DSLNG) facility, five enclosures were reported, of which three breeding enclosures housed a combined total of 10 maleos and one adult enclosure contained another 10 individuals. The function and occupancy of the fifth enclosure require confirmation. Based on the reported occupancy of the four described enclosures, 20 maleos were accounted for at PT. DSLNG. Thus, the available records indicate 53 individuals at PT. PAU and 20 individuals in the four documented enclosures at PT. DSLNG. These figures represent facility population records and should not be interpreted as indicators of breeding success or conservation effectiveness.

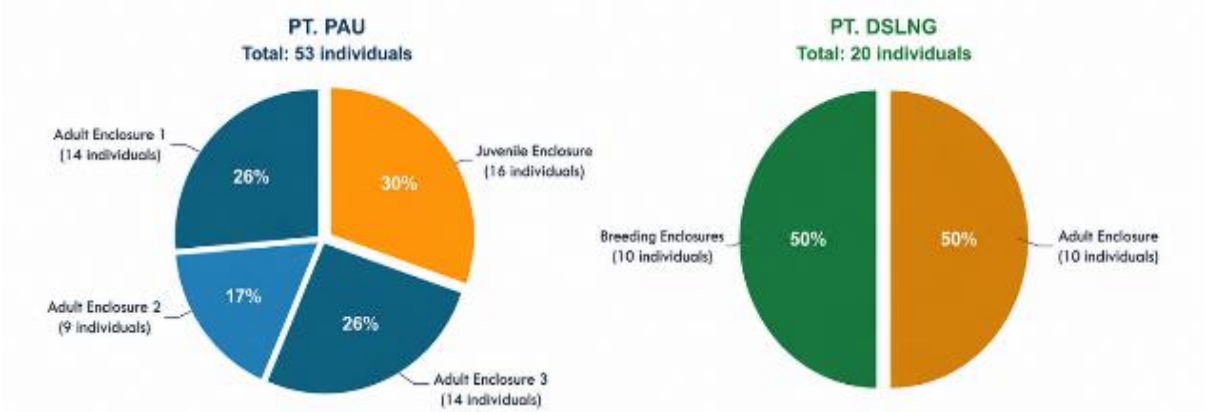


Figure 3. Percentage composition of the maleo bird population in captivity

The habitat characteristics of the maleo (*Macrocephalon maleo*) were assessed at the breeding facilities managed by PT. Panca Amara Utama (PT. PAU) and PT. Donggi-Senoro LNG (PT. DSLNG) in Banggai Regency, Central Sulawesi. PT. PAU, measurements were conducted both inside and outside the

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breeding enclosure, whereas at PT. DSLNG, data were collected only outside the enclosure because access was restricted by the company's conservation standard operating procedures.Inside the PT. PAU enclosure, nesting holes were 34-40 cm deep, with an average depth of 37 cm. Their average length and width were 130 cm and 95 cm, respectively. Air temperature inside the enclosure remained relatively stable throughout the day, averaging approximately 31.23°C. In contrast, the average temperature outside the enclosure was considerably higher, ranging from 36.86°C to 39.10°C. Relative humidity inside PT. PAU averaged 62.13%, which was higher than the average humidity outside the enclosure. Sand temperature inside the enclosure was also relatively stable, averaging approximately 33.20°C, while sand pH remained neutral at 7. Light intensity and wind speed were substantially lower inside the PT. PAU enclosure. The overall mean light intensity was approximately 774.84 lx inside and 2,474.23 lx outside the enclosure. Similarly, mean wind speed was approximately 0.69 m/s inside and 1.66 m/s outside. These findings indicate that the enclosure provided a more shaded, humid, and sheltered microclimate than the surrounding coastal environment. PT. DSLNG, environmental conditions outside the enclosure were characterized by an overall mean air temperature of approximately 34.93°C, relative humidity of 60.55%, light intensity of 1,607.68 lx, and wind speed of 2.17 m/s. Compared with the external area at PT. PAU, the PT. DSLNG site generally had lower air temperature and light intensity but higher wind speed. The data can be presented in Table 1 and Figure 4 below.

Table 1. Habitat Characteristics Inside and Outside Captivity

Location Characteristics	PT. PAU Location				PT. DSLNG Location	
	In Captivity		Out of Captivity		Out of Captivity	
	Range	Average	Range	Average	Range	Average
Hole depth (cm)	34 – 40	37	-	-	-	-
Hole size						
- Length	120 – 140	130	-	-	-	-
- width	90 – 100	95	-	-	-	-
Air temperature (°C)						
- 09.00 AM	29.5 – 34.5	31.2	32.9 – 47.4	38.27	29 - 41	33.71
- 12.00 PM	22.2 – 32.9	31.24	35.1 – 45.2	39.1	30.6 – 44.8	38.6
- 03.00 PM	28.5 - 33.5	31.25	30 – 44.6	36.86	29.2 – 34.2	32.48
Air Humidity (%)						
- 09.00 AM	46 - 81	61.3	41 – 69	52.14	37 - 95	60.45
- 12.00 PM	44 - 90	59.9	34 – 73	50.82	40 - 84	54.4
- 03.00 PM	51 - 83	65.2	37 – 93	56.68	58 - 88	66.8
Sand Temperature (°C)						
- 09.00 AM	30.1 – 37.5	33.04	-	-	-	-
- 12.00 PM	30.6 – 39.1	33.49	-	-	-	-
- 03.00 PM	29.5 – 37.2	33.07	-	-	-	-
pH						
- 09.00 AM	7	7	-	-	-	-
- 12.00 PM	7	7	-	-	-	-
- 03.00 PM	7	7	-	-	-	-
Light Intensity (lx)						
- 09.00 AM	363 - 1604	757.45	1300 – 3960	1978.45	1020 - 3250	1682
- 12.00 PM	307 - 1900	933.47	1258 – 6522	2823.32	1320 - 1985	1758.8
- 03.00 PM	300 - 1569	633.61	1255 – 7715	2620.91	1002- 1921	1382.25
Wind Speed (m/s)						
- 09.00 AM	0 - 2	0.61	0.8 – 3.1	1.86	0.6 – 7.3	1.6
- 12.00 PM	0 – 2.1	0.96	0.8 – 3.1	1.79	0.9 - 3	1.72
- 03.00 PM	0 – 1.9	0.5	0 – 3.4	1.34	0 – 5.4	3.2

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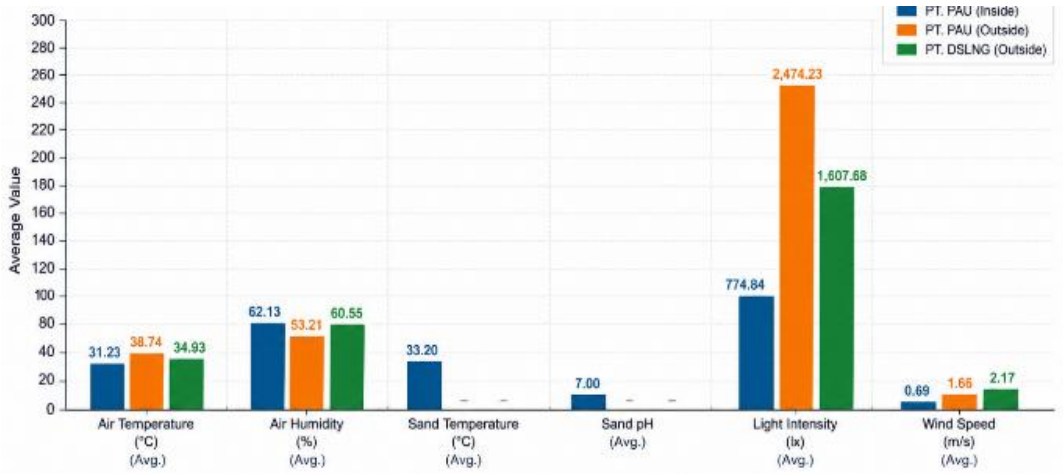


Figure 4. Comparison graph of habitat characteristics at the captivity location

b. Physical Characteristics of Maleo Nesting Pits

Maleo (*Macrocephalon maleo*) nesting pits were observed only within the PT. Panca Amara Utama (PT. PAU) captive breeding facility. A total of two nesting pits were measured, nesting-pit dimensions were measured using a measuring tape to determine depth, length, and width. The measured pits had a mean depth of 37 cm (range: 34–40 cm), a mean length of 130 cm (range: 120–140 cm), and a mean width of 95 cm (range: 90–100 cm). These measurements indicate variation in nesting-pit dimensions within the PT. PAU facility. Compared with previous studies conducted in natural habitats, the mean nesting-pit depth at PT. PAU was shallower than the 67.78 cm reported by Hafsah et al. (2009) in Lore Lindu National Park and the 65 cm reported by Muhi et al. (2021). However, the observed depth was comparable to the range of 37–50 cm documented by Nafiu et al. (2013) in sandy habitats within Rawa Aopa Watumohai National Park. Differences in nesting-pit dimensions among locations may be associated with variation in substrate characteristics and local environmental conditions, including soil texture, temperature, moisture, and compactness. Nevertheless, these potential relationships were not directly evaluated in the present study. Therefore, the findings are interpreted as descriptive measurements of nesting-pit morphology within the PT. PAU facility, providing baseline information for future investigations into nesting behaviour and habitat characteristics in managed maleo conservation environments.

c. Air Temperature

Air temperature exhibited a consistent diurnal pattern across the observation sites, with lower temperatures in the morning at 09:00, peaking around midday at 12:00, and declining at 3:00 p.m. Within the PT. PAU captive breeding facility, the mean air temperature remained relatively stable throughout the day, ranging from 31.20 to 31.25°C. In contrast, greater daily temperature fluctuations were recorded outside the PT. PAU facility and at the PT. DSLNG site. Outside the PT. PAU captive breeding facility, the mean air temperature reached 39.10°C at 12:00, with a range of 35.1–45.2°C. This was the highest temperature recorded during

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the study. Such temperatures are extremely high and may approach or exceed the physiological tolerance limits of the maleo. Nafiu et al. (Nafiu et al., 2013), recorded air temperatures ranging from 28.3 to 29.8°C, with a mean of 28.93°C, at a maleo nesting site at 08:00. The differences between the present findings and those of previous studies may be attributable to variations in the geographical and environmental characteristics of the nesting sites. The maleo nesting areas examined in the present study were located near the coast, where exposure to solar radiation and the surrounding marine environment may contribute to higher ambient temperatures.

Temperature conditions within nesting pits influence the rate of egg incubation and hatching. As solar radiation increases during the day, the surface temperature of the nesting area also rises, consequently affecting the thermal conditions within the nesting pits (Muhi et al., 2021). In an ex situ maleo conservation study, Rusiyantono et al. (Rusiyantono et al., 2011) emphasised that proper management of environmental temperature within captive breeding facilities is an important factor determining maleo reproductive success. At the PT. DSLNG site, the mean air temperature ranged from 32.48 to 38.60°C. At 15:00, the mean temperature at PT. DSLNG was 32.48°C, considerably lower than the mean temperature of 36.86°C recorded outside the PT. PAU captive breeding facility. This finding indicates that the PT. DSLNG site had more moderate thermal conditions during the afternoon and may therefore provide a more favourable microclimate for maleo activity. Lige et al., (2026), in a study of the spatial distribution of maleo populations at three locations in Central Sulawesi, including the LNG-Batui area, identified sand temperature as one of the most influential environmental factors affecting maleo occurrence. Sand temperature is closely associated with air temperature and the intensity of solar radiation, both of which determine the thermal suitability of maleo nesting habitats.

d. Air Humidity

PT. PAU captive breeding facility, mean relative humidity ranged from 59.90 to 65.20%, whereas lower values were recorded outside the facility, ranging from 50.82 to 56.68%. The PT. DSLNG site exhibited relatively higher humidity levels, ranging from 54.40 to 66.80%, and was therefore more comparable to the conditions within the PT. PAU facility. The highest relative humidity at PT. DSLNG was recorded in the afternoon, reaching 66.80%. Air humidity plays an important role in maleo nesting ecology because it influences evaporation rates, which may subsequently affect sand temperature. It may also affect the physiological condition of adult maleos during nesting and egg-laying activities (Mainwaring et al., 2016). Higher humidity generally reduces moisture loss from the nesting substrate, whereas excessively low humidity may accelerate evaporation and alter the thermal and moisture conditions required for successful egg incubation.

In semi-natural conservation areas such as those managed by PT. PAU and PT. DSLNG, maleo eggs are incubated naturally within sandy substrates. Relative humidity levels of approximately 60–70% may provide favourable conditions for maintaining a balance between substrate moisture and gas exchange, both of

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which are essential for embryonic development. Therefore, the humidity conditions recorded within the PT. PAU facility and at the PT. DSLNG site may be considered more supportive of maleo incubation than the relatively drier conditions recorded outside the PT. PAU facility.

e. Sand Temperature

Sand temperature measurements were conducted exclusively within the PT. Panca Amara Utama (PT. PAU) captive breeding facility. Measurements were taken at a depth of 34-40 cm below the sand surface across one sampling points during morning, midday, and afternoon observation periods. The recorded mean sand temperatures ranged from 33.04 to 33.49°C, with a difference of approximately 0.45°C between the highest and lowest mean values. These results indicate relatively small differences in mean sand temperature among the observed daytime periods. However, this pattern should not be interpreted as evidence of continuous thermal stability, as nighttime temperatures and fluctuations between observation periods were not assessed. Karim et al. (2022) reported a sand temperature of approximately 32.5°C at maleo nesting sites, which was slightly lower than the values recorded at PT. PAU. Similarly, Karim et al. (2026) documented relatively comparable sand temperatures across several natural maleo habitats in Central Sulawesi. Although these findings provide a useful reference for comparing the thermal characteristics of maleo nesting environments, differences in measurement depth, observation time, and local habitat conditions should be considered when interpreting the results. Furthermore, the sand temperatures recorded in the present study represent measurements at the specified sampling depth and do not necessarily reflect temperatures experienced by eggs within nesting pits. Because egg temperatures, continuous incubation conditions, embryonic development, and hatching success were not directly monitored, the suitability of the recorded temperatures for maleo egg incubation cannot be determined from these observations alone. Therefore, the present findings provide descriptive baseline information on daytime sand-temperature conditions within the PT. PAU facility and may serve as a reference for future investigations of nesting-site thermal environments.

Similarly, Hafsah et al. (2009), reported an average nesting-pit temperature of 33.08°C in the geothermal nesting habitat of Lore Lindu National Park. This value was highly comparable to the mean sand temperatures recorded at PT. PAU, which ranged from 33.04 to 33.49°C. The similarity indicates that the thermal conditions provided within the PT. PAU captive breeding facility closely resembled those found in the maleo's natural nesting habitat. Yusuf et al. (Yusuf et al., 2025), noted that even minor changes in ground-surface temperature may influence nesting success and the survival of maleo chicks. Therefore, continuous monitoring and appropriate management of sand temperature are essential to maintain favourable incubation conditions and support the reproductive success of maleos within captive breeding facilities.

f. Sand Acidity (pH)

The sand pH within the PT. PAU captive breeding facility remained constant at 7.0, indicating neutral

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conditions, at all observation times (09:00, 12:00, and 15:00). This stable and consistent pH suggests that the nesting substrate had favourable chemical conditions for maleo egg incubation. A neutral substrate may support the physical and chemical conditions required for gas exchange and embryonic respiration (Karim et al., 2022). The findings of the present study differed from those reported in natural maleo nesting habitats. Hafsah et al. (Hafsah et al., 2009), recorded pH values ranging from 6.15 to 6.75 in Lore Lindu National Park, while Jamili et al. (Jamili et al., 2015), reported values ranging from 5.9 to 7.0 in Rawa Aopa Watumohai National Park. These previous findings indicate that natural nesting substrates may vary from slightly acidic to neutral.

The consistent pH of 7.0 recorded throughout the observation period at the PT. PAU captive breeding facility indicates that management practices were able to maintain stable substrate conditions. This stability may represent an advantage of ex situ captive breeding facilities over natural habitats, where substrate pH can fluctuate in response to rainfall, biological activity, and seasonal changes. Maintaining stable sand pH may therefore contribute to the provision of suitable incubation conditions for maleo eggs.

g. Light Intensity

Light intensity varied considerably among the observation sites. PT. PAU captive breeding facility, light intensity ranged from 633.61 to 933.47 lux, which was substantially lower than that recorded outside the PT. PAU facility, ranging from 1,978.45 to 2,823.32 lux, and at the PT. DSLNG site, ranging from 1,382.25 to 1,758.80 lux. The lower light intensity within the PT. PAU captive breeding facility indicates that the area received greater shade from vegetation and the structural components of the enclosure, thereby reducing direct exposure to solar radiation. Meanwhile, the lower light intensity recorded at PT. DSLNG compared with the area outside the PT. PAU facility suggests that the PT. DSLNG site also had relatively greater vegetation cover or other forms of shade. Puspitasari et al. (Puspitasari et al., 2023), in a study of the nesting microhabitat of the orange-footed scrubfowl (*Megapodius reinwardt*) on Satonda Island, recorded light intensities ranging from 81 to 6,189 lux at active nesting sites. This broad range indicates that members of the family Megapodiidae can tolerate considerable variation in light conditions within their nesting habitats. Although the light intensity within the PT. PAU captive breeding facility, ranging from approximately 633 to 933 lux, was lower than that recorded at the other observation sites, it remained within the range reported for active megapode nesting habitats. Therefore, the relatively shaded conditions within the facility were considered adequate to support maleo activity while also helping to maintain more stable microclimatic conditions.

h. Wind Speed

Wind speed within the PT. PAU captive breeding facility was relatively low, ranging from 0 to 2.0 m/s, with mean values between 0.50 and 0.96 m/s. Outside the PT. PAU facility, wind speed was slightly higher, ranging from 0.8 to 3.4 m/s, with mean values between 1.34 and 1.86 m/s. In contrast, wind speed at the PT. DSLNG site showed considerable variation. At 09:00, wind speed ranged from 0 to 7.3 m/s, with a mean of 1.60 m/s, whereas at 15:00, it ranged from 0

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to 5.4 m/s, with a mean of 3.20 m/s. The high variability in wind speed recorded at the PT. DSLNG site may reflect the influence of dynamic sea breezes, which vary according to time of day and local environmental conditions. In contrast, the very low wind speed within the PT. PAU captive breeding facility, with mean values below 1 m/s, provided relatively stable microclimatic conditions for maleo nesting activity.

Strong winds may interfere with nest-pit excavation and egg-laying activities, particularly by increasing disturbance at exposed nesting sites (Muhi et al., 2021). The higher mean wind speed recorded at PT. DSLNG in the afternoon, reaching 3.20 m/s, indicates greater air movement than at the PT. PAU sites. Maximum wind speeds of 7.3 m/s at 09:00 and 5.4 m/s at 15:00 may also contribute to increased convective cooling and potentially reduce the temperature of the sand surface and nesting substrate. Therefore, although moderate air movement may support ventilation and heat exchange, excessive or highly variable wind conditions may alter the microclimate of maleo nesting habitats. The relatively sheltered conditions within the PT. PAU captive breeding facility may thus help maintain more stable environmental conditions for nesting and egg incubation.

i. Differences in Plant Species Composition between PT. PAU and PT. DSLNG

Based on vegetation observations conducted in the maleo (*Macrocephalon maleo*) captive breeding habitats at PT. PAU and PT. DSLNG in Luwuk, Banggai Regency, Central Sulawesi, a total of eight plant species were identified at PT. PAU, whereas 22 plant species were recorded at PT. DSLNG. These findings indicate that the PT. DSLNG site had greater plant species richness than the PT. PAU site. The differences in plant species identified within the maleo nesting habitats at both locations are presented in Table 2 and figure 5.

Table 2. Plant species in the maleo captive breeding habitats at PT. PAU and PT. DSLNG

No	PT. DSLNG Captivity Location	PT. PAU Captivity Location
	Plant species	**Plant species**
1	*Aleurites moluccana*	*Mangifera sp.*
2	*Acalypha siamensis*	*Aleurites moluccana*
3	*Bucida molineti*	*Diospyros celebica*
4	*Alstonia scholaris*	*Terminalia catappa*
5	*Heliconia psittacorum*	*Casuarina Junghuhniana*
6	*Alstonia scholaris*	*Polyalthia longifolia*
7	*Nephrolepis sp.*	*Zoysia japonica*
8	*Alocasia sp.*	*Cocos sp.*
9	*Oxalis barrelieri*	
10	*Polygala paniculata*	
11	*Centrosema pubenscens*	
12	*Alocasia sp.*	
13	*Ageratum conyzoides*	
14	*Hippeastrum sp*	
15	*Heliconia psittacorum*	
16	*Asplenium nidus*	
17	*Ixora sp.*	
18	*Terminalia catappa*	
19	*Swietenai macrophylla*	
20	*Hibiscus rosa-sinensis*	
21	*Polyalthia longifolia*	
22	*Bambusa sp.*	

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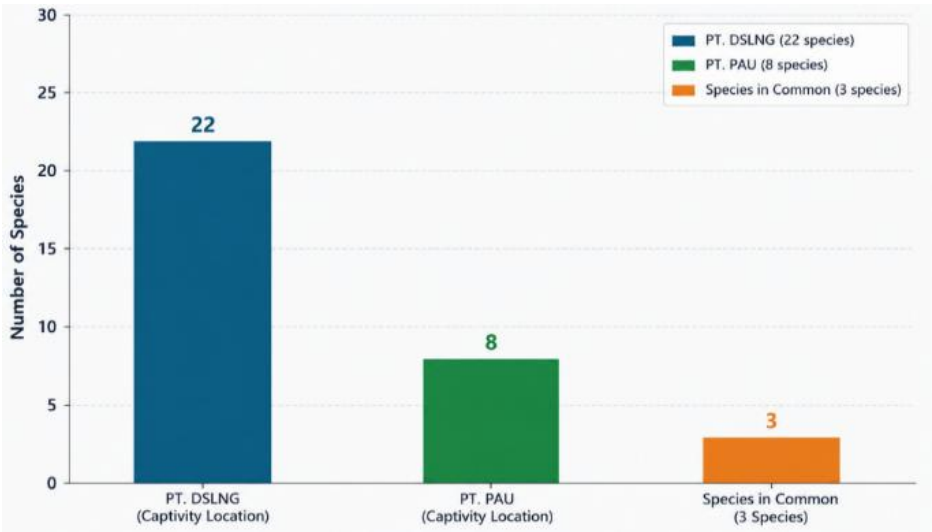


Figure 5. Comparison graph of the number of plant species in the captivity location

A total of eight plant species were recorded in the surveyed area at the PT. Panca Amara Utama (PT. PAU) captive breeding facility, whereas 22 species were identified in the surveyed area outside the PT Donggi-Senoro LNG (PT. DSLNG) enclosure. Although more plant species were recorded at PT. DSLNG, this difference should be interpreted with caution because the spatial coverage of vegetation surveys was not equivalent between the two sites. Observations at PT. PAU included areas both inside and outside the captive breeding enclosure, while those at PT DSLNG were restricted to the external environment. Therefore, the recorded species counts represent the vegetation documented within the respective surveyed areas and do not necessarily indicate differences in overall plant species richness between the two conservation facilities. Previous studies have also reported variation in vegetation composition across natural maleo habitats. Karim and Kenta (2019) identified 18 plant species at a maleo nesting site in Taima Village, Bualemo District, Banggai Regency, Central Sulawesi, where the tree, pole, sapling, and shrub strata were dominated by *Quassia indica* (29.42%), *Thespesia populnea* (11.86%), *Cycas* sp. (9.81%), and *Justicia* sp. (31.98%), respectively. Similarly, Silayar et al. (2017) documented 56 tree species in maleo habitat at Tanjung Binerean, North Sulawesi, with *Ailanthus integrifolia* (21.23%), *Cananga odorata* (12.16%), *Canarium asperum* (8.82%), and *Ficus septica* (8.32%) among the dominant species. Jamili et al. (2015) also reported plant species associated with maleo nesting areas, including *Melastoma* sp., *Dioscorea hispida, Imperata cylindrica*, and *Eupatorium* sp. Collectively, these studies illustrate variation in the vegetation composition documented across maleo habitats. Although vegetation may provide ecological functions such as food resources, roosting sites, shade, and shelter, these functions were not directly assessed in the present study and should therefore be considered potential rather than demonstrated roles. Accordingly, the findings provide descriptive information on plant species composition within the surveyed areas and establish a baseline for further investigations into the ecological functions of vegetation in

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managed maleo conservation environments.

Maleos exhibit particular preferences for tree species used as roosting sites. Trees with horizontally arranged, tiered branches and relatively open canopies are generally preferred, including *Dracontomelon mangiferum*, *Koordersiodendron pinnatum*, *Vitex* sp., and *Casuarina equisetifolia* (Sabilah et al., 2022). Maleos also tend to select trees with large stem diameters or basal areas because these trees provide sufficiently strong branches for resting and foraging. However, the height of the selected trees may vary (Karim et al., 2022). Trees are an important component of bird habitats because they provide foraging areas, shelter from predators and adverse environmental conditions, materials for nest construction, and sites for nesting and breeding activities (Hidayat et al., 2026). Therefore, the presence and composition of tree species at the study sites may contribute significantly to habitat suitability and support the natural behaviour of maleos. Dense vegetation may also provide favourable habitat conditions because it offers greater protection from predators (Arista et al., 2015). Therefore, vegetation structure, including canopy cover, branch arrangement, tree diameter, and stand density, is an important component of maleo habitat suitability. *Aleurites moluccana* was the only plant species recorded at both the PT. PAU and PT. DSLNG sites. This species is also considered an important food resource in maleo ecology. Afandi et al. (Afandi et al., 2022) identified *Aleurites moluccana* seeds as one of the principal food items consumed by maleos. In addition to providing food, candlenut trees may contribute to habitat quality by creating shade that helps regulate temperature and maintain humidity within and around the captive breeding areas. Thus, the presence of *A. moluccana* at both sites may support maleo habitat requirements through both food provision and microclimatic regulation.

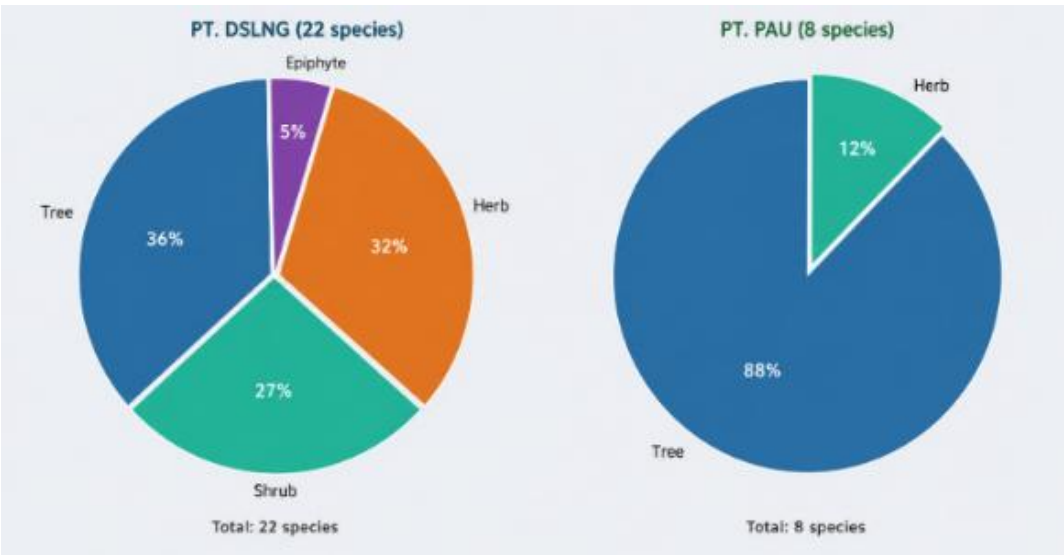


Figure 6. Proportion of plant growth at the captivity location

The vegetation composition across the two captive breeding sites collectively supports the dietary requirements and natural behaviour of the maleo. Afandi et al. (Afandi et al.,

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2022), in a study of maleo nesting behaviour in Central Sulawesi, reported that the species primarily consumes seeds and fruits. The presence of candlenut (*Aleurites moluccana*) and tropical almond (*Terminalia catappa*), which produce abundant seeds and fruits, as well as mango (*Mangifera* sp.) at the PT. PAU site, may therefore provide valuable food resources for maleos. In addition to serving as food sources, vegetation within the captive breeding areas provides shade that helps regulate air temperature and humidity. These functions contribute to a more favourable microclimate and support the welfare, feeding behaviour, and natural activities of maleos within the captive breeding facilities.

4. CONCLUSION

The maleo (*Macrocephalon maleo*) habitats at PT. PAU and PT. DSLNG exhibited different vegetation and microclimatic characteristics. Eight plant species were recorded within the PT. PAU captive breeding facility, whereas 22 species were identified in the observation area at PT. DSLNG. This finding indicates that plant species richness was higher at PT. DSLNG than at PT. PAU. Vegetation at both sites contributes to food availability, roosting opportunities, protection from predators, and the provision of shade that helps regulate habitat temperature and humidity. Candlenut (*Aleurites moluccana*) was among the important species recorded at both sites because it may serve as a food resource while also contributing to microclimatic regulation. Maleo nesting pits were found and measured only within the PT. PAU captive breeding facility. The pits had an average depth of 37 cm (range: 34-40 cm), a length of 120–140 cm, and a width of 90-100 cm. These dimensions indicate that the facility provides a suitable substrate in which maleos can perform natural digging and egg-laying behaviour.

The microclimatic conditions within the PT. PAU captive breeding facility were more stable than those recorded outside the facility. The nesting area had a mean air temperature of 31.20°C, relative humidity of 62.12%, sand temperature of 33.20°C, neutral sand pH of 7.0, light intensity of 774.84 lux, and wind speed of 0.68 m/s. The stable sand temperature, which was comparable to temperatures reported from natural nesting habitats, indicates that the nesting substrate at PT. PAU was generally favourable for maleo egg incubation. Outside the PT. PAU captive breeding facility, air temperature, light intensity, and wind speed were higher, whereas relative humidity was lower. These conditions indicate a more exposed environment with greater microclimatic variation. At the PT. DSLNG observation site, the mean air temperature was 34.93°C, relative humidity was 60.55%, light intensity was 1,607.68 lux, and wind speed was 2.17 m/s. The PT. DSLNG site therefore had relatively favourable humidity conditions, although it was characterised by greater light exposure and air movement than the area within the PT. PAU facility.

Overall, the PT. PAU captive breeding facility provided relatively stable microclimatic conditions that may support maleo nesting activity and egg incubation. In contrast, the PT. DSLNG site was characterised by greater plant species richness that may support food availability, shelter, and natural maleo behaviour. However, direct comparison

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between the two captive breeding facilities remains limited because ecological data collection within the PT. DSLNG facility was not permitted. Continuous monitoring of vegetation, sand temperature, humidity, light intensity, and wind speed is therefore required to support the effective management and ex situ conservation of the maleo.

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