sciendo

Ornis Hungarica 2026. 34(1): 49–64.
DOI: 10.2478/orhu-2026-0005

Nest selection and usage of nest boxes by the Sooty Falcon *(Falco concolor)* in the Al Wajh Bank (Saudi Arabia)

Licia Calabrese[1,2,*], Bayan Alghamdi[1], Thomas Edward Collier[3], Ivor Douglas Williams[1] & Omar Al-Attas[1]

Received: March 04, 2025 – Revised: February 19, 2026 – Accepted: March 11, 2026

Calabrese, L., Alghamdi, B., Collier, T. E., Williams, I. D. & Al-Attas, O. 2026. Nest selection and usage of nest boxes by the Sooty Falcon *(Falco concolor)* in the Al Wajh Bank (Saudi Arabia). – Ornis Hungarica 34(1): 49–64. DOI: 10.2478/orhu-2026-0005

Abstract Artificial nesting sites, commonly called "nest boxes" for their shape, are used to increase animal nesting site availability in highly modified or degraded habitats, such as urban or agricultural areas, or at natural sites where nesting habitat is scarce. They are beneficial for many bird species as they provide suitable breeding sites. The objective of this study was to assess the nesting habitat preferences of the Sooty Falcon breeding in the Al Wajh Bank and to create and test different types of artificial nesting sites for this species on the field. The prototype selected was replicated and deployed in low numbers across seven islands to test the response of the species to this new nesting site. Since the prototype was successfully occupied by Sooty Falcons, the pilot study was considered successful and upscaled to 15 islands the following year. During the pilot and subsequentially on the first year of the upscale, two nest boxes were successfully occupied by breeding Sooty Falcons, making the first time in literature that this species utilizes an artificial nesting site as breeding site. This is a milestone in the Sooty Falcon conservation worldwide and will help expanding nesting habitat in degraded or nesting habitat lacking islands. This study demonstrates the potential for artificial nesting sites to enhance breeding habitats for the vulnerable Sooty Falcon. While initial occupancy rates are low, the successful fledging of nestlings in 2023 and 2024 suggests long-term promise. Continued monitoring and research are essential to refine deployment strategies and support conservation efforts for this iconic species.

Keywords: artificial nesting sites, breeding habitat, breeding success, conservation

Összefoglalás A mesterséges fészkelőhelyeket, amelyeket alakjuk miatt gyakran „fészekládáknak" neveznek, elsősorban olyan erősen átalakított vagy leromlott élőhelyeken alkalmazzák, mint a városi vagy mezőgazdasági területek, illetve olyan természetes környezetben, ahol a fészkelőhelyek korlátozottan állnak rendelkezésre. A fészekládák számos madárfaj számára hasznosak, mivel megfelelő fészkelőhelyet biztosítanak. A tanulmány célja a hamvas sólyom fészkelőhely-preferenciáinak vizsgálata az Al Wajh Bank térségében, valamint különböző típusú mesterséges fészekládák kialakítása és terepi tesztelése volt. A kiválasztott prototípust kis darabszámban hét szigeten helyezték ki, hogy felmérjék a faj új típusú fészkelőhelyre adott válaszát. Mivel a hamvas sólymok sikeresen elfoglalták a prototípust, a pilotot sikeresnek minősítették, és a projektet a következő évben 15 szigetre terjesztették ki. A kiterjesztett projekt első évében két fészekládát foglalt el sikeresen költő hamvas sólyom pár – ez az első ismert eset az irodalomban, amikor a faj mesterséges fészkelőhelyet választ költésre. Ez mérföldkő a hamvas sólyom globális védelmében, és hozzájárulhat a költőhelyek bővítéséhez olyan szigeteken, ahol az élőhely degradált vagy természetes állapotában nem alkalmas fészkelésre. A kutatás bizonyítja, hogy a mesterséges fészekládák jelentős potenciállal rendelkeznek a veszélyeztetett hamvas sólyom költőhelyeinek bővítésében. Bár a kezdeti foglalási arányok alacsonyak, a 2023-ban és 2024-ben sikeresen kirepült fiókák azt jelzik, hogy a módszer hosszú távon ígéretes lehet. A telepítési stratégiák további finomítása, valamint a folyamatos monitorozás és kutatás kulcsfontosságú a faj hatékony megőrzésében.

Kulcsszavak: mesterséges fészkelőhely, költőterület, költési siker, természetmegőrzés

[1] *Department of Environmental Protection and Regeneration, Red Sea Global (RSG-Red Sea Zone), Umluj, Saudi Arabia*
[2] *Island Biodiversity and Conservation Centre, University of Seychelles, Victoria, Seychelles*
[3] *Island Avian Surveys Ltd., Orkney, United Kingdom*
* *corresponding author, e-mail: calabrese.licia@gmail.com*

Introduction

The growth of birds of prey populations is often limited by suitable breeding habitats, which encompasses nest-site availability, food supply, weather conditions, and experience of birds (Tapia & Zuberogoitia 2018). This is particularly true for raptors selecting special breeding sites such as cliffs, burrows, or scarce trees in open land (Negro *et al.* 2007). Selection of suitable breeding habitat, in particular nesting sites, is critical as those must guarantee food and protection for extended breeding periods. Birds of prey populations may be limited by the habitats' carrying capacity due to the shortage of nesting sites (Newton 2007). Each species has its own preferences for the position, height, orientation, shelter, accessibility, and visibility of the nesting site. Such characteristics can be strict requirements or vague preferences depending on whether a species is more of a generalist or a specialist regarding its nesting site requirements. The populations of the former will be less limited by nesting site than the ones of the latter (Tapia & Zuberogoitia 2018).

Artificial nesting sites, commonly called "nest boxes" due to their shape, are used to increase animal nesting site availability in highly modified or degraded habitats, such as urban or agricultural areas, or at natural sites where nesting habitat is scarce (MacIvor 2017, Carstens *et al.* 2019, Dulisz *et al.* 2022, Gazzard & Baker 2022, Kunnasranta *et al.* 2022). They are beneficial for many bird species as they provide suitable breeding sites (Hane *et al.* 2012, Carstens *et al.* 2019, Dulisz *et al.* 2022), and there is evidence for various bird species that nest boxes facilitate, and frequently trigger, population growth (Libois *et al.* 2012, Cuatianquiz Lima & Macías Garcia 2016, Carstens *et al.* 2019, Calabrese *et al.* 2020), or mitigate anthropogenic negative actions on nesting sites (James Reynolds *et al.* 2019, Dulisz *et al.* 2022). There is much literature on the success of artificial nests used by raptors (Tapia & Zuberogoitia 2018) to increase populations and conservation benefit, especially for falcon species (Catry *et al.* 2009, Kotymán *et al.* 2015, Calabrese *et al.* 2020, Rzępała *et al.* 2023). This group tends to use from big, to relatively small nest boxes, depending on the bird size (Bux *et al*. 2008, Altwegg *et al.* 2014, Bagyura *et al.* 2024, Prommer *et al.* 2025); besides some of these species nest communally (e.g. the Lesser Kestrel *Falco naumanni*, Bux *et al.* 2008).

The Sooty Falcon *(Falco concolor)* is the only breeding falcon present in the Al-Wajh Bank Important Bird Area (IBA, Saudi Arabia), and it is listed as globally vulnerable and regionally endangered by IUCN red list (Symes *et al.* 2015). It generally nests in crevices or cavities in the upper parts of cliffs, sometimes in old nests of ravens, or in rocky/coral outcrops. On islands, it nests on the ground under overhanging rocks or under cliff ledges, but it also has been observed nesting under bushes (Gaucher *et al.* 1995, Jennings 2010); the same nest site may be reused repeatedly. Generally, it selects areas inaccessible to mammalian predators with enough shelter from the elements. Within the Al Wajh Bank, the Sooty Falcon was confirmed nesting in natural nests on nine of the 92 islands of the archipelago. These islands were found to be the only ones with suitable habitat for this species (Calabrese *et al.* 2026). Since some of these islands could be developed as part of the Saudi Vision 2030 (https://www.vision2030.gov.sa/v2030/overview/), habitat enhancement plans using nest boxes could be implemented on islands not slated for development. This would provide additional nesting sites in areas currently without suitable habitat and that will not be disturbed by future development. This will depend on how many islands will be developed in the future as plans are currently under review.

At present, there are no published studies reporting the use of nest boxes by the Sooty Falcon, however, given other falcon species are using them successfully and considering that the lagoon presents lack of breeding sites on most of the islands, we hypothesised that the Sooty Falcon is likely to select the nest boxes as breeding sites if designed and placed correctly. From literature nest box design must take into consideration the natural nesting habitat of this species and the fact that temperatures on these islands can reach 50 °C in summer – during the falcons' breeding season. The placement also has to consider favourable breeding and foraging habitat for the species (Tapia & Zuberogoitia 2018).

This study aims to i) design different types of nest boxes based on Sooty Falcon preferences and breeding ecology and test them in the field for temperature during the breeding season; ii) conduct a pilot study with the best performing design to assess the likelihood of the Sooty Falcon utilizing these artificial nesting sites, the pilot study would be considered successful whether one of the nest boxes would be used by the Sooty Falcon, in such a case an up-scaling of additional 20 nest boxes would be planned for 2024; iii) investigate Sooty Falcon nest selection by assessing characteristics of cavities occupied by breeding pairs and using such measurements to produce an alternative artificial nesting site using high-tech construction methods.

Materials and Methods

Study area

The Al-Wajh Bank IBA comprises 92 low lying sandy islands ranging from less than one to more than 1,600 ha, they are sparsely vegetated with halophyte low shrubs and ten of them include rocky outcrops from fossil coral reefs *(Figure 1)*. Out of these ten islands, only nine are known to host suitable nesting habitats for the Sooty Falcon (Calabrese *et al.* 2026). These include Quman, Breem, Sheybarah South, Ghawar, Swayhill, Mardunah, No Name, and Al Numaniat 2 and 3. In the Al Wajh Bank, the average population of Sooty Falcon counted over four years is 42 breeding pairs (Calabrese *et al.* 2026).

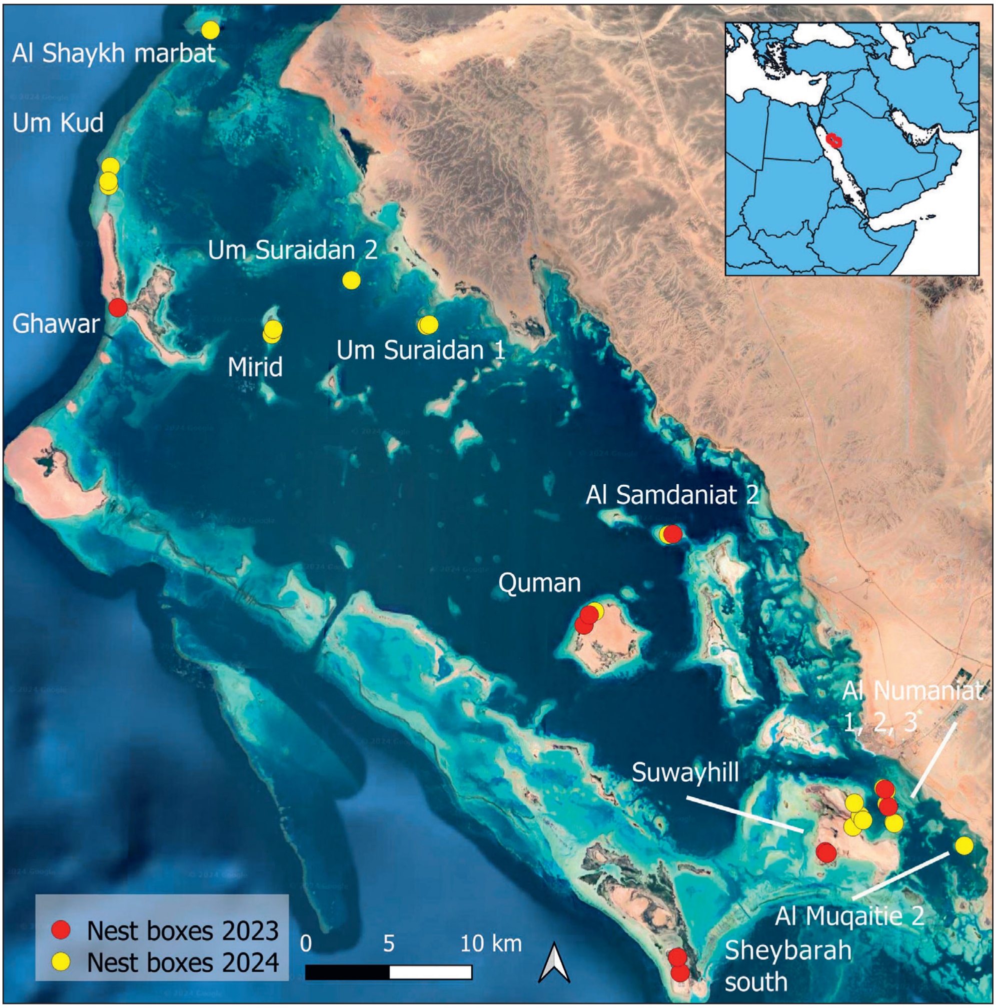


Figure 1. Study site and locations of nest boxes deployed in 2023 and 2024
1. ábra A vizsgált terület, és a 2023-ban és 2024-ben kihelyezett költőládák elhelyezkedése

Prototypes selection rationale and testing

We determined, that similarly to other artificial nesting sites, the Sooty Falcon nest box had to have a design ethologically and ecologically adapted to the species, and the construction material had to be locally available, durable, light weight, and with high temperature insulation capacity. The design of an artificial nesting site can indeed have an important effect on the life-history traits of free-ranging falcons and can affect nest box choice and the survival of the eggs or nestlings (Lambrechts *et al.* 2012). In Mediterranean breeding sites, the Eleonora's Falcon *(Falco eleonorae)*, which is considered very similar to the Sooty Falcon in terms of behaviour and natural history, selected nesting sites providing good shelter from the elements (Spina & Leonardi 2007), and was also observed using nest boxes. Therefore, an enclosed nesting site with top cover was determined to be a basic design requirement. Thermal insulation of the nest box was one of the most important features considered while selecting the material to be used for its construction, especially considering the extreme high temperatures recorded in the Arabian Peninsula.

During 2021 three nest box designs built with different materials were developed. Materials included: marine plywood (thermal insulation properties suspected to be low), concrete (thermal insulation properties unknown), and carbonate rock bricks (thermal insulation properties unknown but expected high). The wooden nest box was made in marine plywood using a design previously used for the Red-footed Falcon (Kotymán *et al.* 2015). This type of nest box has been used in different locations in Europe providing good nesting sites for this species (Kotymán *et al.* 2015, Calabrese *et al.* 2020). In those locations, the installation of the boxes was always in trees, which provide natural shade from the summer sun and in a very different climate, which is just as important as the foliage of trees. The Al Wajh Bank islands have no trees and summers are extremely hot therefore wood may not provide enough insulation from the heat. The concrete prototype had a cylindrical shape with an opening at the top and at the sides to allow air flow. This design was made by pouring concrete into a cast. The third prototype was made of carbonate bricks that were cut from fossilized coral reef rock. This material was found locally, and given its porosity, was expected to have good thermal insulation. To make one nest box, 60 bricks of the size of 20×20×5 cm and 2 of the size of 60×60×5 cm were arranged to form a squared house-like structure with a front opening and a roof, that later was modified to be overhanging to provide an awning.

The three prototypes *(Figure 2)* were installed on Quman Island from April to October 2022. TidbiT HOBO© temperature loggers were placed inside each nest box and inside a

Figure 2. Sooty Falcon nest box prototypes deployed on Quman island. From left to right: carbonate bricks nest box, concrete nest box and wooden nest box

2. ábra A Quman szigetén kihelyezett hamvas sólyom fészekláda-prototípusok. Balról jobbra: mészkő tégla, beton és fából készült fészekláda natural nest and set to record at 30-minute intervals during the Sooty Falcon breeding season. The prototype showing lowest maximum temperature, and most similar to the natural nest, was then adopted for a pilot study in which ten nest boxes were deployed in March 2023. In the pilot, nest box locations were selected to be as close as possible to foraging grounds, as far as possible from development areas and, in some cases, in proximity of existing Sooty Falcon nests (Calabrese *pers. comm.*). The orientation of the entrance was mainly north to provide maximum shade during the day and to have the cooling effect of the prevailing northerly wind. During the 2023 breeding season, temperature loggers were also placed in four natural nests and the difference in temperature between artificial and natural nests tested with t-test (Cohen 2013).

Data collection and Hackathon

Natural nests measurements

During the 2022 breeding season a total of 48 nests were found and measurements were taken from 42 of them. The nest features measured (see *Supplementary material 1 page 5* for visualization), to better capture the nest requirements of the Sooty Falcon, were: entrance orientation, height and width at the entrance, height and width of the cavity in correspondence of the location of the eggs (height and width at egg), height at the back of the cavity (height at bottom), distance from the entrance to the eggs (entrance to egg) and distance from the entrance to the back (entrance to bottom). The width at the back of the nest is not represented here because the irregular shape of the nests made it difficult to obtain a standardised measure. The Rayleigh test (Ruxton 2017), was used to test the entrance orientation. Analysis were carried out with the opensource software R (R Development Core Team 2024).

Hackathon competition

The nest features measured were used to inform the development of another nest box prototype using latest technologies at the national Industrial Hackathon organised by SIDF (Saudi Industrial Development Fund, https://eparticipation.my.gov.sa/en/co-creation/initiatives/industry-hackathon/). During this competition, local teams of biologists and engineers challenged each other to produce the best Sooty Falcon nest box prototype. The nest characteristics evaluated during the competition were: creativity and innovation, understanding of the task, quality of the materials, social, economic and environmental impact, presentation of the prototype and feasibility. The winning design was then deployed on Quman island to test its suitability for the Sooty Falcon. One temperature logger (HOBO© Pro v2) was deployed in the new prototype (Hackathon prototype) to measure temperature during the 2024 Sooty Falcon breeding season. Temperature was recorded every 30 minutes. Camera traps were deployed in front of occupied nest boxes and in front of the Hackathon prototype to assess the falcons interactions with the artificial nesting sites.

Results

Prototype selection, pilot study, and upscaling

The carbonate rock artificial nesting site had superior insulating properties, with maximum temperature similar to the natural nest and reaching the lowest maximum temperature among the prototypes – a little over 40 °C *(Figure 3)* and was therefore selected for the pilot. The wooden box exhibited the highest maximum temperatures (~50 °C), making it highly unsuitable for prevailing weather conditions. Although better than the wooden box, the concrete artificial nesting site was also discarded for its scarce insulation properties – with temperatures reaching over 45 °C. The natural nest was the coolest of all, never reaching 40 °C.

During the pilot study 10 carbonate artificial nesting sites were deployed between February and March 2023, before the arrival of the Sooty Falcons at the nesting sites from

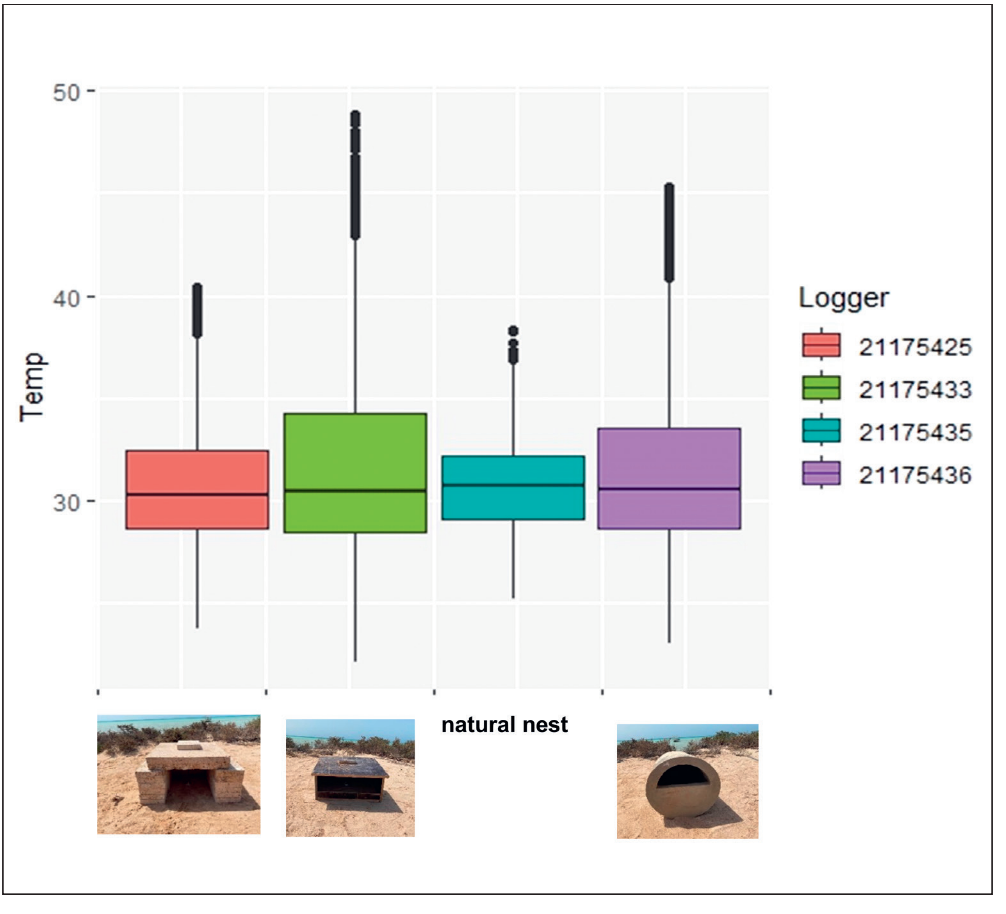


Figure 3. Boxplot comparison of temperatures recorded in prototypes deployed on Quman Island from April to October 2022.

3. ábra A Quman szigetére kihelyezett prototípusokban, 2022 április és október között mért hőmérsékletek összehasonlítása boxplot diagramon

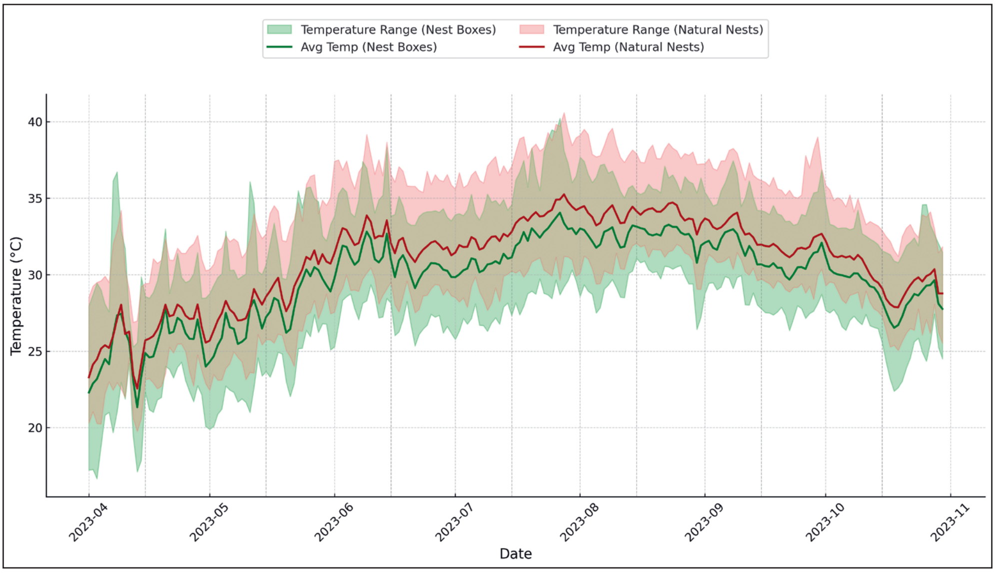


Figure 4. Average daily temperature comparison between the temperature recorded in four natural nesting sites and in the ten carbonate rock nest boxes deployed during the 2023 pilot

4. ábra Az átlagos napi hőmérsékletek összehasonlítása a négy természetes fészekben és a tíz mészkő fészekládában a 2023-as pilot során

their wintering grounds in Madagascar, which normally occurs at the beginning of April. This allowed them to explore the nest boxes during the search for nests and pair bonding period. The locations of the deployed nest boxes are shown in *Figure 1*.

The temperature recordings during the 2023 breeding season from the ten carbonate nest boxes and four natural nests are shown in *Figure 4*. Temperatures in natural nests were marginally, but statistically significantly higher than those in nest boxes ($t=4.40$, $p=1.37\times10^{-5}$).

During the pilot study one carbonate rock nest box on Sheybarah South was occupied by a breeding pair of Sooty Falcon, and they successfully raised three nestling. Given the success of the pilot study, in 2024 an up-scaling was carried out by installing additional 20 artificial nesting sites in February and March on 15 islands *(Figure 1)*, eight of which never had Sooty Falcon breeding before due to the lack of suitable habitat. The islands selected for installing nest boxes were non-development islands close to the mainland, where the Sooty Falcons nesting in Quman usually hunt (Calabrese *et al. in prep*.). In development islands, such as Sheybarah South, nest boxes were placed in areas with lack of nesting sites but close to breeding areas, and at about 500 m from the closest development activities.

In the 2024 breeding season two nest boxes were successfully occupied by Sooty Falcons, one of which was the same breeding site as in 2023, and the second one was located on Al Numaniat 1, an island where Sooty Falcon had not previously nested due to the lack of suitable habitat. Pairs breeding in nest boxes laid two eggs each. The one in Al Numaniat 1 fledged one nestling out of two. Unfortunately, the Sheybarah South nest was predated at the nestling stage by a cat, which was subsequently captured and removed.

Natural nests measurements and Hackathon

Measurements of natural Sooty Falcon nests in cavities are summarised in *Figure 5* and in *Table 1*. The orientation of the entrance was significantly dominated by entrances facing north (Test statistic: 0.354, p=0.006). We found quite a lot of variability in the height of the nests; however, it seems to be decreasing from the entrance to the bottom of the

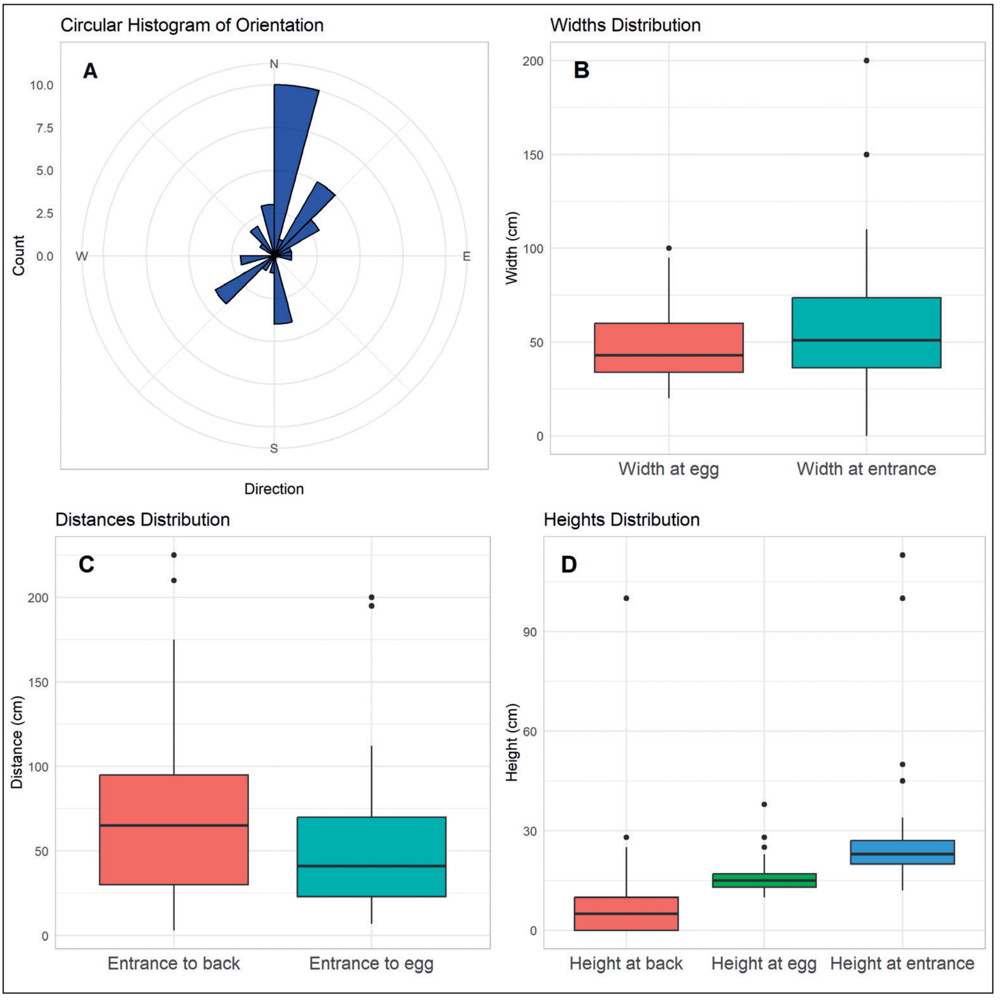


Figure 5. Outcomes summary statistic of the natural nests' measurements. A: Polar histogram representing the orientation of the natural nests (direction faced by the entrance); B: Widths distribution at the entrance of the nest and at the location of the eggs; C: Distributions of the distance from the entrance to the eggs and to the bottom of the nest respectively; D: Distribution of the height of the nest at entrance, eggs, and back level

5. ábra A természetes fészkek méreteinek összegző statisztikái. A: A természetes fészkek tájolását (a bejárat irányát) bemutató poláris hisztogram; B: A fészeküreg szélessége a bejáratnál, illetve a tojások helyénél; C: A bejárattól a tojásokig, illetve a fészeküreg hátsó faláig mért távolság; D: A fészeküreg magassága a bejáratnál, a tojások helyénél, és az üreg végében

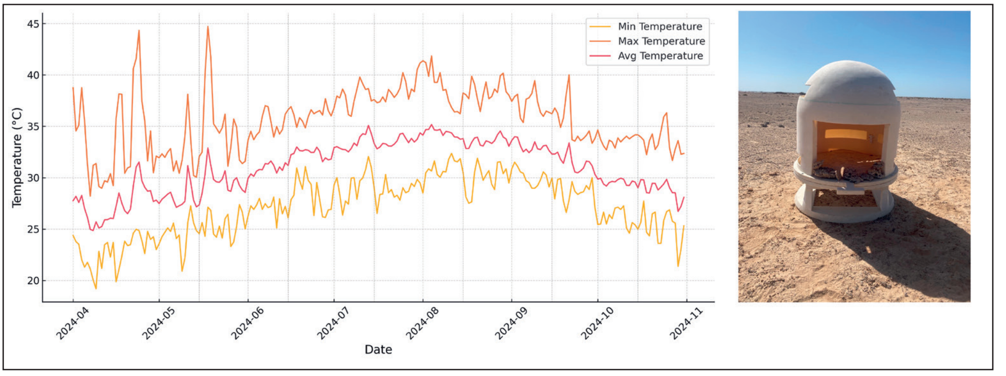


Figure 6. Minimum, average, and maximum temperature registered by the temperature logger placed in the Hackathon prototype (picture on the right) from the 1st of April to the 31st of October 2024

6. ábra A Hackathon prototípusban elhelyezett hőmérséklet-adatgyűjtő által rögzített minimum-, átlag- és maximumhőmérséklet 2024. április 1. és október 31. között (a jobb oldali fényképen látható eszköz)

Table 1. Summary statistic of the Sooty Falcon nests measurements. N = number of nests measured, SD = standard deviation, min = minimum measure, max = maximum measure. The percentages are the percentile

1. táblázat A hamvas sólyom fészkének méreteit összegző statisztikai mutatók. N = a mért fészkek száma, SD = szórás, min = legkisebb mért érték, max = legnagyobb mért érték. A százalékok a percentilisértékeket jelölik

	Orientation (°)	**Height at Entrance (cm)**	**Height at Egg (cm)**	**Height at back (cm)**	**Width at entrance (cm)**	**Width at egg (cm)**	**Entrance to egg (cm)**	**Entrance to back (cm)**
N	40	41	41	41	29	29	41	41
mean	132.13	27.85	16.22	9.37	62.76	49.55	53.76	74.22
SD	124.07	19.64	5.25	16.66	39.83	22.21	43.61	51.87
min	0	12	10	0	22	20	7	3
25%	18.75	20	13	0	37	34	23	30
50%	77.5	23	15	5	52	43	41	65
75%	232	27	17	10	75	60	70	95
max	355	113	38	100	200	100	200	225

nest (mean±SD being 27.9±19.6, 16.2±5.3 and 9.4±16.7 respectively) with the height in correspondence with the egg having a smaller variation compared with the other two levels (the height at the back and the hight at the entrance of the nest). The width of cavities seems fairly constant from entrance to the egg position (means±SD being 62.8±39.8 and 49.6±22.2 respectively). The depth of the nest from the entrance to the eggs and from the entrance to the bottom resulted to be 53.8±43.6 and 74.2±51.9 respectively, therefore in average, the egg resulted to be at about 20 cm from the bottom of the nest.

The natural nests measurements used to inform the Industrial Hackathon competition are summarized in *Supplementary material 1*, together with the challenge description.

The Hackathon prototype selected *(Figure 6)* was not occupied by a breeding pair during the 2024 season, however, a couple of Sooty Falcons started exploring it in April and continued to use it for shelter and as an eating and hunting spot throughout the breeding season. The female was often observed inside the nest box while the male was mainly perched at the entrance. The temperature recorded in the hackathon nest from April to October 2024 is shown in *Figure 6* and went over the 40 °C only three times during deployment, the first one during the second half of April, the second during the second half of May, when it reached almost 45 °C. The third time was at the beginning of August when a temperature of 42 °C was reached during the first days of Sooty Falcon egg laying. Except for these three events, the maximum temperature stayed below 40 °C for the duration of the deployment.

Discussion

During this study we successfully designed and tested three prototypes of nest boxes built with traditional methods and one using more high-tech methods. The pilot study conducted on the first three prototypes confirms the feasibility of using artificial nesting sites for Sooty Falcons. To our knowledge this is the first test of different nest box designs for the species and the first time purpose-built artificial nesting sites have been used by breeding pairs. The Sooty Falcon was observed nesting in man-made structures in the Egyptian Red Sea where eggs were found in a fishermen hut in Torfa el Mashikh and in old mining caves in Zabarjad (Habib 2019). The likelihood of Sooty Falcon breeding in artificial nesting sites was expected to be high, given the high number of successfully established artificial nesting sites for falcon species worldwide (Catry *et al.* 2009, Kotymán *et al.* 2015, Calabrese *et al.* 2020, Rzępała *et al.* 2023). This propensity to occupy artificial nesting sites could originate from the tendency of most falcon species, particularly those of the *Falco* genera, to not build their own nest – preferring instead to nest in ready-to-use cavities or other species' nests (Tapia & Zuberogoitia 2018). The species most alike Sooty Falcon, the Eleonora's Falcon was also keen on nesting in artificial nesting sites deployed in Greece (Fric & Dimallexis 2019).

The design, placement, monitoring, and maintenance of nest boxes determine environmental conditions within the nest box chamber during breeding periods (Lambrechts *et al.* 2012). We believe that key factors influencing occupancy of artificial nesting sites at our study area were mainly placement (example study on Common Kestrel *F. tinnunculus*, Rzępała *et al.* 2023) and thermal performance. The successful placements were close to the coast (therefore close to foraging areas) or close to existing breeding pairs in areas where nesting sites are scarce (Sheybarah South). Orientation of the entrance to face north, like most of the natural nests, was probably also a key factor to keep temperatures low inside the nest boxes. The success of carbonate rock boxes highlights the importance of material choice in extreme environments. Wooden nest boxes were confirmed to have poor insulation properties and would have been potentially harmful to the Sooty Falcon, as found in other studies of a similar species (Lesser Kestrel) (Catry *et al.* 2011).

Research on insulating materials for nest boxes to be deployed in extremely hot conditions was also conducted in Extremadura (Spain) within the life project ZEPAUrban on the Lesser Kestrel. The best performance material was made of a single grain-size of cork and three different proportions of cement (https://www.zepaurban.com/en/documentaci%C3%B3n/material-publicado). This established an optimum mix for the manufacture of nests providing best durability, weight, and integration performance in properties with heritage value (since cork oaks *Quercus suber* are commonly grown in Extremadura). Nest boxes built with the new material registered temperatures 10 °C lower than the same design made in concrete and were successfully occupied (https://www.zepaurban.com/en/documentaci%C3%B3n/material-publicado). The concrete nests tested in that study also experienced higher than ambient temperatures, making them potentially dangerous. Extremadura reaches very high temperatures in summer (www.aemet.es), almost as high as the Saudi Arabian Red Sea, however the non-availability of cork in Saudi Arabia led us to select the carbonate rock which is available locally. Nest boxes reaching internal high temperature could pose a threat to nestlings that may perish while in the nest as observed in Portugal during the 2009 breeding season when 22% of Lesser Kestrel nestlings breeding in nest boxes died due to acute dehydration and survivors suffered from low growth and body condition at fledging (Catry *et al.* 2011). Extreme air temperatures that surpass birds' physiological limits have more generally been shown to lead to direct mortality from dehydration (McKechnie & Wolf 2010), particularly in embryos and nestlings, which are more vulnerable to the thermal and hydric conditions of the nest (Lloyd & Martin 2004). Nestlings can indeed thermoregulate themselves only the second half of the nestling-rearing period therefore can be particularly vulnerable to weather conditions during the first half (Tapia & Zuberogoitia 2018). With increasing temperatures, climate change is likely to exacerbate the risk of overheating and nest boxes can become "ecological traps", defined as suboptimal habitats for breeding or population growth but which attracts individuals (Tapia & Zuberogoitia 2018). Therefore, materials such as wood or concrete that are commonly used in hot locations may become unsuitable in the future and may need to be replaced with higher-performance materials. The continuous development of new materials and high-tech production methods could provide more innovative solutions to this pressing issue.

We showed that artificial nesting sites could be designed and produced with new methods such as 3D printing. This should be led by measurements taken on the field, like in this study. Characteristics of such designs can be further improved to reach the optimal required for the species. The production of a lightweight and a more versatile artificial nesting site could also allow the addition of predator deterrent features and elevation from the ground. Such features may expand the suitable nesting habitat for the Sooty Falcon even inland where inaccessible cliffs are scarce or not present. The artificial nesting design that proved successful is quite heavy (150–200 kg) and more difficult to be adapted to other conditions rather than predator-free islands, needing to be placed on the ground. The fact that two nestlings were predated inside the nest box on a development island highlights the need for strict biosecurity measures in places where nesting habitat is enhanced. Arrival of predators on islands with nest boxes is a high risk of creating an ecological trap.

The success of artificial nesting sites in this study is a significant step towards the understanding about the species' requirements and provides a tool that can be used to increase suitable nesting habitat close to hunting grounds and away from development and other pressures. The fact that a nest box was occupied on an island where breeding pairs were never previously recorded due to the lack of habitat, confirms this potential. Occupancy rates are expected to increase over time, as falcons exhibit site fidelity and as new pairs exploring new nesting options find and come to utilise these new sites. Young falcons fledged from nest boxes, may also be more keen to settle in another nest box as in raptors floaters may prefer to occupy habitats similar to their natal habitat (Stamps 2001).

Despite the optimism about the potential increment of nesting sites from this study, caution is warranted about the potential for nest boxes to increase Sooty Falcon populations worldwide. Populations are experiencing a worrying decline at numerous breeding sites (Kavanagh & King 2008, Shah *et al.* 2008, Goren *et al.* 2023, McGrady *et al.* 2023) whose causes should be investigated and addressed. The Sooty Falcon, being a migratory species also faces threats at migration and wintering sites and decline of food source across their whole range is another potential concern. Recognizing those challenges, nest boxes can provide additional nesting sites in situations where suitable natural sites are not available. However, their placement and design should be carefully planned, and other conservation actions should be put in place to check and reverse the current decline of this iconic desert species.

Acknowledgements

The authors would like to thank Red Sea Global for supporting this project, which was included in one of the Saudi Green Initiatives named "SGI4: Achieving net Conservation Gain of 30% by 2024". We thank Red Sea Global - Red Sea Zone Operation team for logistic support, the Life ZEPAURBAN team for their support and collaboration, the nest boxes builders Carmen Biondo, Yasir Wusayl Aljohani, Essa Ali Alhamdi, Thomas Skinner, Edward Stubbings, Julie Riordan, Antonio Oliveira, Farah Bahkli, Arjohana Alamri. We would also thank the winners of the Industrial Hackathon Salah Alhamwi and Abdulaziz Alobaisi – The Red Nest – for producing an amazing design and Dr. Ahmed Alansari for the continuous support of this project.

References

Altwegg, R., Jenkins, A. & Abadi, F. 2014. Nestboxes and immigration drive the growth of an urban Peregrine Falcon Falco peregrinus population. – Ibis 156(1): 107–115 DOI: 10.1111/ibi.12125

Bagyura, J., Haraszthy, L., Szitta, T., Solti, B., Jánossy, D., Prommer, M., Fidlóczky, J. & Horváth, M. 2024. Population trend and diet of Saker Falcons *(Falco cherrug)* in Hungary between 1980 and 2024. – Ornis Hungarica 33(1): 70–97. DOI: 10.2478/orhu-2025-0004

Bux, M., Giglio, G. & Gustin, M. 2008. Nest box provision for Lesser Kestrel *Falco naumanni* populations in the Apulia region of southern Italy. – Conservation Evidence 5: 58–61. https://conservationevidencejournal.com/reference/pdf/2281

Calabrese, L., Mucciolo, A., Zanichelli, A. & Gustin, M. 2020. Effects of nest boxes on the most important population of Red-footed Falcon *Falco vespertinus* in Italy. – Conservation Evidence 17: 35–39. https://conservationevidencejournal.com/reference/pdf/8182

Calabrese, L., Riordan, J. A., Collier,T. E., Foster, A. D., Aljohani, Y. W. M., Ahamdi, E. A. S., Williams, I. D. & Alansari, A. 2026. Sooty Falcon *(Falco concolor)* in the northern Saudi Arabian Red Sea: population assessment and conservation. – Ornis Hungarica 34(1): 31–46. DOI: 10.2478/orhu-2026-0004

Carstens, K. F., Kassanjee, R., Little, R. M., Ryan, P. G. & Hockey, P. A. R. 2019. Breeding success and population growth of Southern Ground Hornbills *Bucorvus leadbeateri* in an area supplemented with nest-boxes. – Bird Conservation International 29(4): 627–643. DOI: 10.1017/S0959270919000108

Catry, I., Alcazar, R., Franco, A. M. A. & Sutherland, W. J. 2009. Identifying the effectiveness and constraints of conservation interventions: A case study of the endangered Lesser Kestrel. – Biological Conservation 142(11): 2782–2791. DOI: 10.1016/j.biocon.2009.07.011

Catry, I., Franco, A. M. A. & Sutherland, W. J. 2011. Adapting conservation efforts to face climate change: Modifying nest-site provisioning for Lesser Kestrels. – Biological Conservation 144(3): 1111–1119. DOI: 10.1016/j.biocon.2010.12.030

Cohen, J. 2013. Statistical Power Analysis for the Behavioral Sciences (2nd ed.). – Academic Press, London DOI: 10.4324/9780203771587

Cuatianquiz Lima, C. & Macías Garcia, C. 2016. Pre- and post-experimental manipulation assessments confirm the increase in number of birds due to the addition of nest boxes. – PeerJ 4: e1806. DOI: 10.7717/peerj.1806

Dulisz, B., Stawicka, A. M., Knozowski, P., Diserens, T. A. & Nowakowski, J. J. 2022. Effectiveness of using nest boxes as a form of bird protection after building modernization. – Biodiversity and Conservation 31(1): 277–294. DOI: 10.1007/s10531-021-02334-0

Fric, J. & Dimallexis, T. 2019. Construction of Artificial Nests to Improve Nesting Habitats for Eleonora's Falcon *(Falco eleonorae)*. – Final Report. Athens, Greece

Gaucher, P., Thiollay, J.-M. & Eichaker, X. 1995. The Sooty Falcon *Falco concolor* on the Red Sea coast of Saudi Arabia: distribution numbers and conservation. – Ibis 137(1): 29–34. DOI: 10.1111/j.1474-919X.1995.tb03216.x

Gazzard, A. & Baker, P. J. 2022. What makes a house a home? Nest box use by West European Hedgehogs *(Erinaceus europaeus)* is influenced by nest box placement, resource provisioning and site-based factors. – PeerJ 10: e13662. DOI: 10.7717/peerj.13662

Goren, M., Perlman, Y. & McGrady, M. M. C. 2023. Apparent population decline of Sooty Falcon *Falco concolor* in Israel. – Sandgrouse 45(1): 84–93.

Habib, M. I. 2019. Breeding of Sooty Falcon on Egyptian Red Sea islands in 2012–17. – Dutch Birding 41: 29–36.

Hane, M. E., Kroll, A. J., Johnson, J. R., Rochelle, M. & Arnett, E. B. 2012. Experimental effects of structural enrichment on avian nest survival. – Forest Ecology and Management 282: 167–174. DOI: 10.1016/j.foreco.2012.06.037

James Reynolds, S., Ibáñez-Álamo, J. D., Sumasgutner, P. & Mainwaring, M. C. 2019. Urbanisation and nest building in birds: a review of threats and opportunities. – Journal of Ornithology 160(3): 841–860. DOI: 10.1007/s10336-019-01657-8

Jennings, M. C. 2010. Atlas of the Breeding Birds of Arabia. Fauna of Saudi Arabia 25. – Senckenberg Institute Frankfurt and the King Abdulaziz City for Science and Technology. Frankfurt and Riyadh

Kavanagh, B. & King, H. 2008. Observations from 1998–2006 on the breeding population of Sooty Falcons *Falco concolor* on the Hawar Islands, Kingdom of Bahrain. – Sandgrouse 30: 70–76.

Kotymán, L., Solt, S., Horváth, É., Palatitz, P. & Fehérvári, P. 2015. Demography, breeding success and effects of nest type in artificial colonies of Red-footed Falcons and allies. – Ornis Hungarica 23(1): 1–21. DOI: 10.1515/orhu-2015-0001

Kunnasranta, M., Niemi, M. & Auttila, M. 2022. Developing artificial nest boxes for a large aquatic mammal. – Aquatic Conservation: Marine and Freshwater Ecosystems 32(8): 1365–1371. DOI: 10.1002/aqc.3851

Lambrechts, M. M., Wiebe, K. L., Sunde, P., Solonen, T., Sergio, F., Roulin, A., Møller, A. P., López, B. C., Fargallo, J. A., Exo, K. M., Dell'Omo, G., Costantini, D., Charter, M., Butler, M. W., Bortolotti, G. R., Arlettaz, R. & Korpimäki, E. 2012. Nest box design for the study of diurnal raptors and owls is still an overlooked point in ecological, evolutionary and conservation studies: A review. – Journal of Ornithology 153(1): 23–34. DOI: 10.1007/s10336-011-0720-3

Libois, E., Gimenez, O., Oro, D., Mínguez, E., Pradel, R. & Sanz-Aguilar, A. 2012. Nest boxes: A successful management tool for the conservation of an endangered seabird. –Biological Conservation 155: 39–43. DOI: 10.1016/j.biocon.2012.05.020

Lloyd, J. D. & Martin, T. E. 2004. Nest-site preference and maternal effects on offspring growth. – Behavioural Ecology 15(5): 816–823. DOI: 10.1093/beheco/arh085

MacIvor, J. S. 2017. Cavity-nest boxes for solitary bees: a century of design and research. – Apidologie 48(3): 311–327. DOI: 10.1007/s13592-016-0477-z

McGrady, M. J., Said, T. A. L. & Neri, H. A. L. 2023. Suspected decline in the breeding population of Sooty Falcons *Falco concolor* on the islands of northern Oman. – Sandgrouse 45: 215–220.

McKechnie, A. E. & Wolf, B. O. 2010. Climate change increases the likelihood of catastrophic avian mortality events during extreme heat waves. – Biology Letters 6(2): 253–256. DOI: 10.1098/rsbl.2009.0702

Negro, J. J., Sarasola, J. H. & Barclay, J. 2007. Augmenting wild populations and food resources. – In: Bird, D. & Bildstein, K. (eds.) Raptor Research and Management Techniques Manual. – Raptors Research Foundation. Hancock House Publishers, Surrey, Canada, pp. 401–441.

Newton, I. 2007. Population limitation in birds: the last 100 years. – British Birds 100: 518–539.

Prommer, M., Kéry, M., Bagyura, J. & Oli, M. 2025. Repopulation of the former breeding range: spatio-temporal patterns and drivers of reproduction in the Peregrine Falcon *(Falco peregrinus)* population in Hungary. – Ibis 168(1): 63–78. DOI: 10.1111/ibi.13448

R Development Core Team, R. 2024. R: A Language and Environment for Statistical Computing. – Foundation for Statistical Computing

Ruxton, G. D. 2017. Testing for departure from uniformity and estimating mean direction for circular data. – Biology Letters 13(1): 2016.0756. DOI: 10.1098/rsbl.2016.0756

Rzępała, M., Kasprzykowski, Z., Obłoza, P., Mitrus, C. & Golawski, A. 2023. The influence of habitat and the location of nest-boxes on the occupation of boxes and breeding success of the Kestrel *Falco tinnunculus*. – The European Zoological Journal 90(1): 1–9. DOI: 10.1080/24750263.2022.2152504

Selås, V. 1997. Nest-site selection by four sympatric forest raptors in Southern Norway. – Journal of Raptor Research 31(1): 16–25.

Shah, J. N., Khan, S. B., Ahmed, S., Javed, S. & Hammadi, A. 2008. Sooty Falcon in the United Arab Emirates. – Falco 32: 16–19.

Spina, F. & Leonardi, G. 2007. Piano d'azione nazionale per il Falco della regina *(Falco eleonorae)*. No. 26. [National Action Plan for the Eleonora's Falcon *(Falco eleonorae)*]. – Ministero dell'ambiente e della tutela del territorio, Direzione conservazione della natura, Rome, Italy (in Italian)

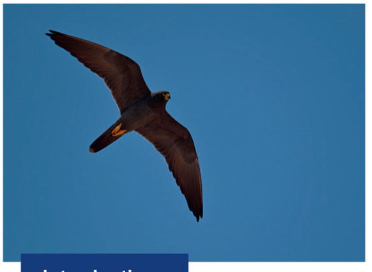
Stamps, J. A. 2001. Habitat selection by dispersers: integrating proximate and ultimate approaches. – In: Clobert, J., Danchin, E., Dhondt, A. & Nichols, J. (eds.) Dispersal. – Oxford University Press, Oxford, pp. 110–122.

Symes, A., Taylor, J., Mallon, D., Porter, R., Simms, C. & Budd, K. 2015. The Conservation Status and Distribution of the Breeding Birds of the Arabian Peninsula. – IUCN & Environment and Protected Areas Authority, Cambridge, UK. DOI: 10.2305/IUCN.CH.2015.MRA.5.en

Tapia, L. & Zuberogoitia, I. 2018. Breeding and nesting biology in raptors. – In: Sarasola, J. H., Grande, J. M. & Negro, J. J. (eds.) Birds of Prey: Biology and Conservation in the XXI. Century. – Springer International Publishing, Cham, pp. 63–94. DOI: 10.1007/978-3-319-73745-5

Supplementary material

The Application of AI tools in the Enhancement of the Natural Habitat



Introduction

There are many future advances that artificial intelligence is bringing in the field of environment. AI technologies are being used in renewable energy, pollution monitoring and more importantly conservation of natural resources.

In this year's theme we are exploring the use of high technology materials and designs (AI tools, 3D printing, etc.) to improve the habitat for a high priority bird species called Sooty Falcon.

The Challenge

The sooty falcon nests on cliffs or crevices on high mountains or islands where predators cannot access their eggs/chicks. It nests on many islands in the Red Sea, all of them with rocky outcrops. In the red sea project islands, nesting habitat is limited for sooty falcons because most of the islands consists of low land and sandy beaches and only ten of them have rocky outcrops which are the ancient coral reef. The lack of nesting habitat could potentially prevent the growth of the population of this vulnerable bird in the Red sea project area.

Current Status

Given the significance of our area as a sooty falcon breeding site, EPR (Department of environmental protection and regeneration) is currently testing ways to improve the species' habitat and breeding success. This can be done through expanding the nesting habitat by providing artificial nesting sites. Red Sea Global are trialing a variety of prototype of artificial nesting sites (also called nest boxes) constructed form different materials. A key goal is to ensure that nest box designs can replicate conditions found in natural nests, especially in terms of **temperature** and **size**.

The Goal

Provide additional nesting sites for Sooty falcon with new designs and materials.

Prototypes will be evaluated based on how close they get to the temperature recorded at natural nesting sites **(temperature loggers will be provided)** and how close they are from measurements provided (**measurements taken from natural nests).**

all designs must follow the technical specifications provided, however, creativity is encouraged and awarded in terms of nest shapes and designs.

There will be two phases:

Phase 01

Designs and prototypes will be made and tested outside in the same location in Riyadh. The temperature will be recorded inside the nest box during testing. The nest boxes with lowest temperatures and within the sizes of the natural nests will be selected as winners.

Phase 02

The winning prototypes will be tested on the natural sooty falcon habitat and the best performer in terms of temperature will be selected and replicated to provide more nesting sites.
Below are the parameters that will be used to evaluate the nest boxes.

Financial Impact

Providing additional nesting sites will not have a direct financial impact, it is more of a conservation gain for the endangered species. The economical value is still being studied financially.

Stakeholders

Academic and research institutes

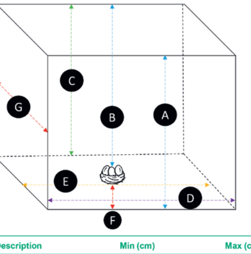
Technical specifications

Temperature

Temperature is a critical parameter for the wellbeing of adults and chicks in the nests. Below parameters recorded in two natural sooty falcon nests on Quman:

1. Max Temperature (from August to October) < 40°C
2. Average temperature: 31.2°C
3. Average temperature Natural Nest 39: 31.6 °C
4. Average temperature Natural Nest 8: 30.8 °C

Measurements



Point	Description	Min (cm)	Max (cm)
A	Height at Entrance	12	113
B	Height at Egg	10	38
C	Height at back	0	100
D	Width at entrance	22	200
E	Width at egg	20	100
F	Distance entrance to egg	7	200
G	Distance to back	3	225

Note: shape is only for illustration, it doesn't necessarily have to be a cube.