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Effect of Sand Layer Thickness on Heat Distribution and Effective Thermal Properties for an IoT-Monitored Artificial Heated Habitat

Khaw Zhi Xian¹, Mohd Syakirin Rusdi^{1,*}, Muhammad Hafiz Hassan¹, Muhammad Fauzinizam Razali¹

¹ School of Mechanical Engineering, Tuanku Syed Sirajuddin Engineering Campus, Universiti Sains Malaysia, 14300 Nibong Tebal, Pulau Pinang, Malaysia

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ABSTRACT

Sand layer thickness for artificially heated reptile habitats is often chosen without a clear understanding of its effect on heat distribution, creating uncertainty in balancing internal heat retention against surface basking temperature. This study investigates the effect of sand layer thickness on heat distribution and determines the effective thermal properties of a selected sand sample for an artificially heated habitat designed for *Uromastix aegyptia*. An Internet of Things (IoT)-based monitoring system using an ESP32 microcontroller, five K-type thermocouples, and a BME280 sensor was developed to acquire temperature, humidity, and ambient data in real time. Two sand thicknesses, 4.5 cm and 5.0 cm, were tested under identical heating conditions for 6.5 hours each. A one-dimensional semi-infinite conduction model was fitted to the experimental data in MATLAB to estimate the effective thermal conductivity, thermal diffusivity, and specific heat capacity. Results show that the 5.0 cm layer exhibited greater internal heat retention, with the average embedded temperature increasing from 69.6 °C for the 4.5 cm layer to 74.5 °C for the 5.0 cm layer, but recorded a lower surface basking temperature than the 4.5 cm layer, highlighting a distinction between bulk heat retention and surface thermal performance relevant to habitat design. However, selecting an appropriate sand layer thickness remains uncertain because different thicknesses can produce different heat distribution, heat retention, and surface temperature responses, while the effective thermal properties of commercially available sand may differ from published values for standardised materials.

1. Introduction

Uromastix aegyptia, known locally as the dhab or Egyptian spiny-tailed lizard, is native to the arid stretches of North Africa and the Middle East. Because it is ectothermic, it cannot generate its own body heat; every aspect of its metabolism, digestion, and growth instead depends on heat drawn from the environment [1], [2]. In the wild, this works through a natural thermal gradient — sunlight heats the sand surface while the layers beneath remain cooler, allowing the lizard to move between the two to regulate its temperature [3], [4]. Malaysia's climate does not produce these desert-level surface temperatures, which means captive care requires an artificial heating system capable of recreating a biologically realistic thermal gradient [3].

* Corresponding author.

E-mail address: syakirin@usm.my

Choosing the right sand thickness is an important design consideration because thickness determines the conduction distance and thermal mass of the bed, which together influence how heat spreads and how much heat is retained. Previous research has shown that the effective thermal conductivity of granular soils is strongly influenced by porosity, particle arrangement, and moisture content [5]. Miura et al., [6] demonstrated that the physical characteristics of sand vary with its primary properties. Dai et al., [7] further reported that the thermal diffusivity of sandy soil is affected by its physical and thermal conditions, whereas Blocka et al., [8] showed that porosity and moisture content can significantly influence the thermal conductivity and volumetric heat capacity of particulate materials. At the particle scale, heat moves through direct contact between grains as well as through the air trapped within the pores, and the arrangement of particles influences these heat-transfer pathways [9], [10]. Lee et al., [11] also demonstrated that particle size can affect the effective thermal conductivity of granular mixtures. This matters practically because commercially available sand is not a pure, standardised material: its thermal properties depend on the specific composition, particle size distribution, packing, and moisture conditions. Therefore, published values for pure SiO₂ may not accurately represent the thermal behaviour of a market-purchased sand sample [5], [6]. Using generic literature values in place of measured values may consequently lead to inaccurate predictions of heat transfer and temperature distribution within the substrate.

Low-cost microcontrollers such as the ESP32 have made continuous, real-time environmental monitoring increasingly practical for controlled habitat applications [12]–[14]. Bandara et al., [12] demonstrated the application of IoT technology in a smart terrarium for continuous ecosystem monitoring, while Harianto et al., [13] developed an ESP32-based system for temperature and humidity monitoring. Hercog et al., [14] further demonstrated the suitability of the ESP32 for IoT device development because of its processing capability, connectivity, and flexibility for sensor integration. In the present application, these capabilities allow multiple temperature and environmental sensors to be integrated into a single low-cost monitoring system. Pairing the monitoring system with an analytical heat conduction model also allows the effective thermal properties of a given substrate to be estimated from its measured temperature response rather than assumed solely from generic material data. Ciesielski and Grodzki [15], for example, demonstrated the use of experimental temperature measurements for identifying macroscopic heat-conduction parameters in granular materials.

Beyond its immediate thermodynamic findings, this research aligns with the broader objectives outlined in the United Nations Sustainable Development Goals (SDGs). Specifically, it contributes to SDG 15 (Life on Land) by advancing the scientific understanding of artificial microclimate engineering. Precise localised temperature regulation is essential for optimising the thermal welfare and captive habitat management of specialised ectothermic species. The ability to accurately replicate and monitor critical natural thermal gradients directly supports improved ex-situ conservation and biological husbandry practices.

Furthermore, the study addresses SDG 9 (Industry, Innovation and Infrastructure) by validating a low-cost IoT instrumentation framework. By demonstrating that accessible microcontroller architectures can reliably execute real-time environmental data acquisition and signal processing, this work provides a scalable methodological approach. The integration of low-cost hardware and computational modelling establishes a replicable framework that can be adapted for broader thermal monitoring applications.

Despite established research on heat transfer and thermal properties of granular materials, limited attention has been given to experimentally evaluating the combined effect of practical sand layer thickness and effective thermal properties for artificially heated reptile habitats. In particular, commercially available sand may differ from the idealised or standardised materials commonly

considered in thermal-property studies, while the relationship between substrate thickness, heat distribution, and surface thermal performance remains application-dependent. This research therefore systematically investigates the macroscopic heat distribution and estimates the effective thermophysical properties of a granular substrate, specifically evaluating commercial sand layer thicknesses of 4.5 cm and 5.0 cm. To achieve this, the study employs a custom-engineered, ESP32-based Internet of Things (IoT) monitoring system integrated with a transient, one-dimensional semi-infinite thermal conduction model processed via MATLAB. The scope of this empirical investigation is deliberately constrained to controlled laboratory environments, utilising a strictly dry particulate medium and a constant-output planar heat source. By intentionally excluding confounding environmental variables, such as moisture-induced latent heat transfer, dynamic outdoor ambient fluctuations, and unmeasured convective currents, the experimental design isolates the fundamental conductive heat-transfer behaviour of the bulk material.

2. Methodology

2.1 Experiment

The experimental apparatus was specifically configured to simulate and monitor the localized thermal dynamics within the granular substrate. The core system comprised a stainless-steel containment vessel functioning as the physical boundary, which was filled with a commercial, market-purchased sand medium. Thermal energy was introduced into the system from the bottom boundary utilizing a resistive heating plate. To accurately map the internal spatial temperature distribution, an array of five K-type thermocouples (designated as T1 through T5) was strategically embedded within the sand matrix. These thermal sensors were aligned along a uniform horizontal plane situated exactly 4.0 cm above the primary heating surface. Their predetermined spatial coordinates corresponded to distinct heating zones to effectively capture any lateral thermal variations across the test domain. Concurrently, the external environmental boundary conditions—specifically ambient temperature and relative humidity—were continuously recorded using an integrated BME280 sensor.

The data acquisition (DAQ) architecture was centralized around an ESP32 microcontroller, which served as the primary processing unit. The microcontroller interfaced with the K-type thermocouples via discrete MAX6675 modules, ensuring accurate digital conversion and necessary cold-junction compensation for the thermal readings. Simultaneously, ambient environmental data from the BME280 sensor was acquired through an I²C communication protocol. The integrated sensor data stream was continuously transmitted to a host computing system operating MATLAB software. This computational environment facilitated continuous real-time data logging, dynamic visual display, and the advanced post-processing required for transient thermal analysis. The fully assembled experimental prototype utilized across all empirical trials is visually depicted in Figure 1, while Table 1 provides a comprehensive summary of the critical hardware and software components integrated into the analytical framework.

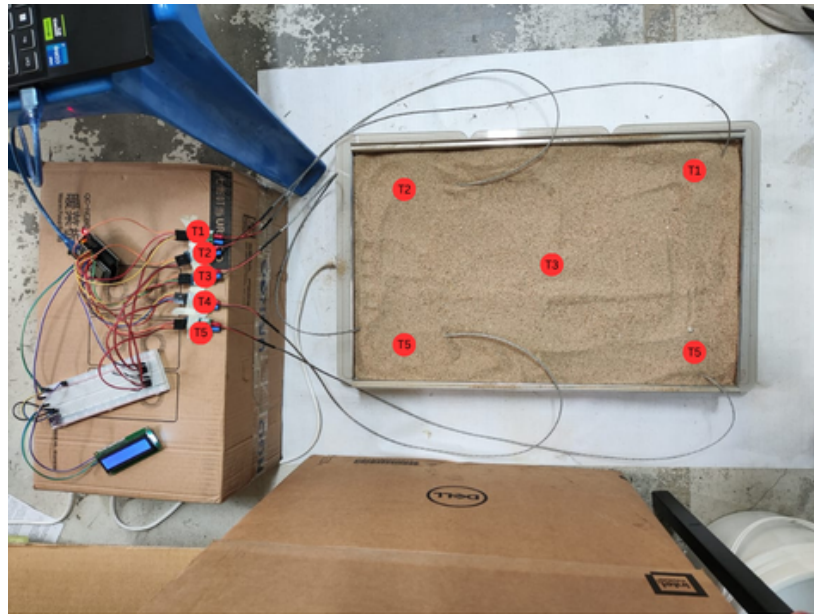


Fig. 1. Experimental setup of the IoT-monitored heated sand prototype

Table 1

Key components of the IoT-based monitoring and heating system

Component	Function
ESP32 microcontroller	Acquires sensor data and streams it to the host laptop
MAX6675 + K-type thermocouple (×5)	Measures embedded sand temperature at T1–T5
BME280 sensor	Measures ambient temperature and relative humidity
Resistive heating plate	Provides a controlled, constant heat source
Stainless-steel container	Holds the sand and maintains the required thickness
MATLAB	Logs data, fits the conduction model, and estimates thermal properties

The experimental procedure was executed systematically to ensure precise control over the substrate geometry and sensor positioning. For each trial, the stainless-steel containment vessel was positioned securely on the resistive heating plate, and the granular medium was introduced in meticulously controlled stages to minimize uneven compaction. Initially, a foundational sand layer was established to a precise depth of 4.0 cm. At this exact elevation, an array of five calibrated K-type thermocouples (T1 through T5) was embedded into the matrix along a single horizontal plane. This strategic positioning aligned the thermal sensors with predetermined spatial zones across the heating plate, establishing a consistent internal measurement datum for all subsequent evaluations. Following sensor integration, the remaining volume of sand was carefully deposited over the array to achieve the final target substrate thicknesses of either 4.5 cm or 5.0 cm, depending on the specific trial parameters.

Once the physical test bed was assembled, the data acquisition infrastructure—driven by the ESP32 microcontroller and interfaced with a MATLAB-equipped host computing system—was initiated to continuously log the transient temperature and relative humidity profiles. To guarantee that the system fully transitioned from its initial transient heating phase into a rigorous thermal equilibrium, the heating plate was operated continuously for a duration of 6.5 hours per trial. Given the extensive stabilization period required to achieve genuine steady-state conditions, temporal

constraints limited the experimental matrix to a single, comprehensive continuous test for each discrete sand thickness. Consequently, the derived thermophysical properties reported in this study must be interpreted as effective, condition-specific operational values. Because the methodology necessitated a single prolonged trial per configuration, standard deviations and cross-trial variances could not be calculated, reflecting the specific localized performance of the granular bed under these exact experimental conditions.

2.2 Model and Data

Convective heat loss from the sand surface to the ambient air was described using Newton's law of cooling,

$$q''_{conv} = h \cdot (T_s - T_{\infty}) \quad (1)$$

where h is the convection heat transfer coefficient, T_s is the surface temperature, and T_{∞} is the ambient temperature. h was estimated from an empirical natural-convection correlation for a horizontally heated plate facing upward, evaluated using air properties interpolated at the mean film temperature.

Transient conduction within the sand layer was modelled using Fourier's second law for a one-dimensional semi-infinite medium with a uniform initial temperature and no internal heat generation:

$$T(z, t) = T_{initial} + \frac{2 \cdot q'' \cdot \sqrt{\frac{\alpha_{sand} \cdot t}{\pi}}}{k_{sand}} \cdot e^{\frac{-z^2}{4 \cdot \alpha \cdot t}} - \left(\frac{q'' \cdot z}{k_{sand}} \right) \cdot \operatorname{erfc} \left(\frac{z}{2 \cdot \sqrt{\alpha_{sand} \cdot t}} \right) \quad (2)$$

where α and k are the effective thermal diffusivity and thermal conductivity of the sand, z is depth, and t is elapsed time. Under steady state, conduction into the sand was assumed to equal convective loss from the surface, $q''_{cond} = q''_{conv}$, closing the system between the measured surface response and the heat flux supplied by the plate.

The effective specific heat capacity was then obtained from the estimated thermal diffusivity, thermal conductivity, and the measured sand density ρ :

$$c_p = \frac{k_{sand}}{\rho_{sand} \cdot \alpha_{sand}} \quad (3)$$

2.3 Model Calibration

Prior to the commencement of formal data collection, a rigorous calibration protocol was executed for all deployed environmental sensors to ensure measurement fidelity and mitigate instrumental error. The primary calibration phase utilized a standardized 0 °C ice-water bath, establishing an absolute thermodynamic reference point for the initial zero-point verification of the thermocouples. Following this baseline establishment, the integrated sensor network was systematically cross-validated against calibrated commercial reference instruments. Specifically, a UNI-T UT320A contact thermometer was employed for precise thermal corroboration, while a Testo 608-H2 reference thermohygrometer was utilized to validate both the ambient temperature and relative humidity readings.

The quantitative deviations identified during this comparative analysis were isolated to determine the inherent systematic bias of each individual sensor. These derived correction offsets, which are summarized in Table 2, were subsequently programmed directly into the microcontroller firmware. By applying these specific numerical compensations at the hardware-software interface, the data acquisition system dynamically neutralized systematic instrumental drift in real time. This critical preparatory measure ensured the highest possible measurement accuracy and signal reliability prior to the execution of the primary heat distribution experiments.

Table 2
Sensor calibration correction values applied before experiments.

Instrument	Correction (°C / %RH)
MAX6675 + K-type thermocouple T1	-1.50 °C
MAX6675 + K-type thermocouple T2	-2.19 °C
MAX6675 + K-type thermocouple T3	-2.13 °C
MAX6675 + K-type thermocouple T4	-2.51 °C
MAX6675 + K-type thermocouple T5	-1.87 °C
BME280 (temperature)	-0.60 °C
BME280 (humidity)	-0.48 %RH

3. Results

3.1 Steady-State Temperature Distribution

Table 3 presents a detailed comparison of the final steady-state thermal measurements acquired at the conclusion of the 6.5-hour experimental heating period for both evaluated sand layer thicknesses. An analysis of these final equilibrium states reveals a highly consistent spatial temperature gradient across the substrate. Irrespective of the overall bed thickness, the localized thermal readings strictly adhered to the following hierarchical distribution: $T_3 > T_4 > T_1 > T_5 > T_2$. The preservation of this distinct spatial pattern indicates that the fundamental macroscopic heat transfer pathways governing the system remain robust and unaffected by the variation in substrate depth. The core thermal flow dynamics within the granular matrix were unaltered by the additional thermal mass. Furthermore, the data highlight the profound influence of boundary conditions on the overall thermal profile. Thermocouple T3, which was positioned at the geometric center of the test domain, consistently registered the highest peak temperatures in all experimental trials. This localized thermal maximum is a direct consequence of its spatial isolation from the physical boundaries of the containment vessel. Situated at the furthest possible distance from the outer walls, the central region surrounding T3 experienced substantially reduced lateral heat dissipation, effectively minimizing peripheral thermal losses and facilitating maximum localized heat accumulation.

Table 3

Comparison of final recorded temperatures for the 4.5 cm and 5.0 cm sand thicknesses.

Sand thickness (cm)	T1 (°C)	T2 (°C)	T3 (°C)	T4 (°C)	T5 (°C)	Average T (°C)	Environment T (°C)
4.5	68.0	60.0	78.7	75.7	65.6	69.6	27.4
5.0	75.1	59.5	84.8	78.9	74.1	74.5	25.1

An analysis of the subsurface thermal dynamics reveals that the steady-state embedded average temperature was notably higher in the 5.0 cm sand layer (74.5 °C) compared to the 4.5 cm layer (69.6 °C). This behaviour aligns with the fundamental physical properties associated with increased substrate depth. Specifically, the additional volume provides a larger thermal mass and establishes a longer conduction path. As a result, the thicker particulate bed possesses a greater capacity to retain internal thermal energy within its deeper strata before the system reaches thermal equilibrium.

However, it is critical to distinguish this internal heat retention from the localized surface temperatures, as the uppermost boundary layer represents the primary interface for ectothermic thermoregulation. For a basking lizard, surface temperature remains the most biologically relevant metric. Counterintuitively, the enhanced internal heat storage of the thicker substrate did not manifest as a warmer basking environment. Empirical measurements demonstrated that the surface temperature across all designated observational zones was consistently lower for the 5.0 cm layer (recording 49.2 °C, 53.4 °C, and 47.9 °C for Regions 1, 2, and 3, respectively) than for the 4.5 cm layer (which recorded 50.3 °C, 55.2 °C, and 52.4 °C in the corresponding regions).

progressively transitions into a gradual asymptotic convergence toward steady-state equilibrium.

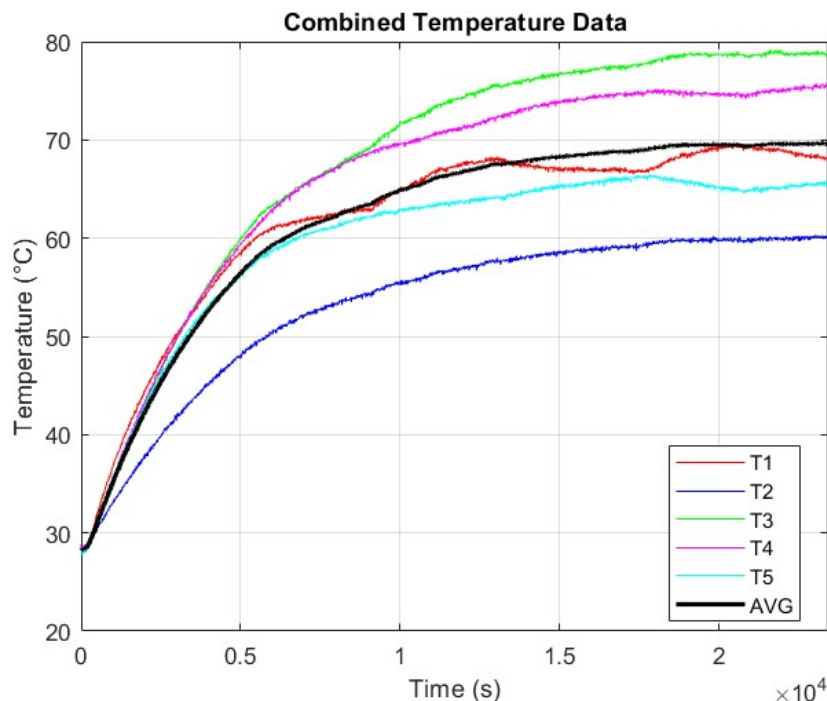


Fig. 2. Combined temperature profiles recorded at locations T1–T5 during a representative heating trial

This divergence highlights the complex heat transfer mechanisms operating within the granular bed. Although the 5.0 cm layer acts as a more substantial thermal reservoir, this stored energy remains concentrated in the lower and mid-depth horizons. The additional 0.5 cm of substrate depth

primarily increases the bulk heat capacity without sufficiently enhancing the upward conductive heat flux to overcome environmental losses. Simultaneously, the uppermost surface continues to dissipate thermal energy into the surrounding ambient air driven by natural convection. These temporal thermal dynamics are graphically represented in Figure 2, which plots the combined temperature profiles recorded by all five thermocouples. The data illustrate a characteristic biphasic heating curve for both substrate thicknesses, defined by a rapid initial thermal ascent that

3.2 Comparison of Thermal Properties

Table 4 presents a comprehensive summary of the extracted thermophysical properties across the experimental domain, specifically detailing the effective thermal conductivity (k), thermal diffusivity (α), and the model-derived effective specific heat capacity (c_p). These parameters were determined for each distinct observational region, alongside their overall spatial averages, by correlating the transient temperature response data with the analytical framework provided in Eq. (2). Analysis of the boundary conditions reveals that the convective heat transfer coefficient and the localized surface heat flux (omitted from the tabulated data) exhibited negligible deviation between the two evaluated substrate depths. This consistency confirms that the surface-level thermal exchange mechanisms were predominantly dictated by the constant thermal output of the heating apparatus and the steady-state ambient environmental conditions, functioning largely independently of the total bulk thickness of the underlying particulate bed. Conversely, the empirically derived values for k , α , and c_p demonstrated a consistent upward trend corresponding to the increased substrate thickness across all regions. Given that these parameters represent nominally intrinsic thermophysical properties of the material, this apparent geometrical dependency requires careful interpretation. The observed increase is not indicative of a fundamental physical alteration within the sand particles themselves. Rather, it is primarily attributed to compounding experimental and methodological variables inherent to physical modelling. Contributing factors likely include slight increases in localized bulk density resulting from greater granular compaction during the preparation of the 5.0 cm bed, alongside minor physical deviations in thermocouple probe positioning. Additionally, the mathematical constraints imposed by the simplifying assumptions of the one-dimensional, semi-infinite conduction model can introduce systemic scaling discrepancies when applied to a system with finite boundaries. The inherent structural complexity of the test matrix is further underscored by the pronounced region-to-region variability observed within a single constant-thickness trial. For instance, the derived specific heat capacity (c_p) within the 4.5 cm layer exhibited a significant spatial distribution, ranging from $108.86 \text{ J kg}^{-1} \text{ K}^{-1}$ to $162.78 \text{ J kg}^{-1} \text{ K}^{-1}$. Such pronounced localized fluctuations serve as a quantitative illustration of the heterogeneous, non-uniform nature of granular packing, demonstrating how microscale variations in porosity and particle-to-particle contact resistance can significantly influence the macroscopic thermal behaviour across the bed.

Table 4
Model-derived effective thermal properties by region and overall average.

Region	Thickness (cm)	k (W m ⁻¹ K ⁻¹)	α (m ² s ⁻¹)	cp (J kg ⁻¹ K ⁻¹)
1	4.5	0.136	8.625×10^{-7}	108.86
1	5.0	0.472	1.324×10^{-6}	245.37
2	4.5	0.204	8.653×10^{-7}	162.78
2	5.0	0.409	1.178×10^{-6}	239.18
3	4.5	0.234	1.126×10^{-6}	143.02
3	5.0	0.389	1.400×10^{-6}	191.23
Average	4.5	0.207	1.089×10^{-6}	130.75
Average	5.0	0.509	1.651×10^{-6}	212.34

The experimentally determined effective thermal conductivity (k) values, which ranged from 0.207–0.509 W m⁻¹ K⁻¹, demonstrate strong agreement with established empirical data. These figures fall precisely within the broadly accepted range of 0.2–0.5 W m⁻¹ K⁻¹ typically reported for dry granular sand environments [5], [9]. This close concordance indicates that the analytical framework produces effective thermal conductivity values within the range reported for dry granular sand. Conversely, the model-derived effective specific heat capacity (cp) deviated significantly from standard reference metrics. The calculated values were found to be substantially lower than the approximately 850 J kg⁻¹ K⁻¹ benchmark conventionally documented for dry sand. This quantitative discrepancy can be attributed to a combination of methodological limitations and material composition. Methodologically, the specific heat capacity was not acquired through direct calorimetric measurement; rather, it was indirectly estimated as a derivative mathematical function of the extracted thermal conductivity (k) and thermal diffusivity (α). Such indirect analytical estimations inherently propagate any mathematical assumptions, simplified boundary conditions, or localized measurement variations present in the primary thermal model.

The physical characteristics of the substrate directly contribute to this divergence. The commercially sourced sand utilized in this experimental setup constitutes a heterogeneous mineralogical mixture and does not possess the chemical purity of standardized silicon dioxide (SiO₂). Because the commercial medium contains various trace minerals, impurities, and mixed particulate compositions, its bulk thermophysical response is not expected to perfectly replicate the highly idealized literature values derived from uniform, pure SiO₂ samples under rigorously controlled conditions [9], [10]. The calculated thermal parameters reported in this analysis must be carefully contextualized. Rather than viewing them as absolute, intrinsic material constants, these figures should therefore be interpreted as effective, model-dependent values representing the thermal response of the tested granular sample under the specific experimental conditions.

4. Conclusions

An ESP32-based IoT monitoring system was successfully developed and calibrated to acquire real-time sand, ambient, and humidity data for two sand layer thicknesses used in an artificial heated habitat for *Uromastix aegyptia*. The 5.0 cm sand layer exhibited higher internal temperature than the 4.5 cm layer, but recorded a lower surface basking temperature in every region, showing that increased bulk heat retention does not necessarily improve surface thermal performance for the

reptile. Effective thermal conductivity, diffusivity, and specific heat capacity were estimated from the temperature response using a one-dimensional semi-infinite conduction model in MATLAB; the obtained thermal conductivity agreed reasonably with literature values for dry sand, while the specific heat capacity was lower than reported values, reflecting the indirect estimation method and the non-standardised composition of commercial sand. These findings provide practical reference data for selecting substrate thickness in artificial reptile habitats and demonstrate a low-cost, replicable approach for characterising the effective thermal behaviour of granular materials. However, because only one prolonged trial was conducted for each sand thickness, the results should be interpreted as condition-specific effective values, and further repeated experiments are required to establish statistical variability.

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