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Survival Responses of Two Termite Genera to Environmental Stressors as Bioindicators of Climate Change

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Abstract. *Termites are sensitive to environmental fluctuations and hold potential as bioindicators of climate change. This study evaluated the survivability of Nasutitermes and Macrotermes under controlled variations in temperature, relative humidity (RH), and CO_2 concentration. Laboratory experiments were conducted using eleven temperature levels (0–50°C), seven RH levels (40–100%), and four CO_2 concentrations (500–2000 ppm). Each treatment was replicated three times with 50 worker termites per replicate. Survivability, measured as percent survival after one hour of exposure, was analyzed by one-way ANOVA followed by Tukey's HSD test ($p < 0.05$). The results indicated that both genera exhibited sharp declines in survival under temperature extremes and elevated CO_2. Optimal survivability for Nasutitermes and Macrotermes occurred at moderate temperatures (25–35°C), relative humidity (60–80%), and ambient CO_2 levels (500 ppm), while extreme conditions significantly increased mortality. The study highlights species-specific tolerance thresholds and confirms that environmental stressors directly affect termite physiology and behavior. These results confirm termites' potential as reliable bioindicators, providing a practical tool for monitoring ecosystem responses to climate stress and informing strategies for sustainable ecosystem management.*

Keywords: *bioindicator, environmental stressors, survivability, termites*

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INTRODUCTION

Climate change, driven largely by rising atmospheric carbon dioxide (CO_2) from fossil fuel combustion and land-use change, has profound impacts on ecosystems (Haryanto & Prahara, 2019; Nurhayati et al., 2020; Susilawati, 2021).These include shifts in rainfall, extreme weather, and biodiversity loss, all of which underscore the need for reliable bioindicators to monitor ecosystem responses (Mandala et al., 2020; Myers et al., 2020; Parulian et al., 2022). The presence of termites has great potential as bioindicators of climate change due to their physiological and behavioral sensitivity to environmental changes. Their sensitivity to factors such as temperature, humidity, and CO_2 concentration makes them an ideal species for monitoring ecosystem dynamics in a sustainable manner.

Termites are increasingly recognized as effective bioindicators due to their sensitivity to variations in temperature, humidity, and CO_2 (Indrayani, 2022; van Valkengoed et al., 2024). With more than 3,100 described species across nine families and 282 genera, they occupy diverse habitats and contribute substantially to decomposition and nutrient cycling (Constantino, 2021; Krishna et al., 2013). Their adaptability reflects robust physiological and behavioral mechanisms, yet survival declines sharply under humidity below 55–65% or above 90%, with optimal activity typically at 60–90% RH (Indrayani et al., 2007). Termites also tolerate a wide thermal range, from ~4°C in high-altitude regions to >50°C in arid zones, but only when humidity prevents desiccation (Scheffrahn et al., 2015).

Although termite ecological roles as decomposers and ecosystem engineers are well documented, limited attention has been given to their physiological tolerance under combined climate stressors. In particular, little is known about how different termite genera respond simultaneously to variations in temperature, humidity, and CO_2 concentration–factors expected to fluctuate more drastically under climate change. Addressing this gap is crucial to validate termites as robust bioindicators of ecosystem health.

This study examines the survivability of two termite genera, *Nasutitermes* and *Macrotermes*, under controlled variations in temperature, humidity, and CO_2. The primary objectives are to assess the effects of temperature variations on termite survivability and identify the optimal thermal range for both genera; examine the influence of humidity levels to determine tolerance thresholds and preferred conditions; evaluate the impact of different CO_2 concentrations and explore physiological responses to elevated greenhouse gas levels; and integrate the findings across these stressors to better understand the potential of termites as bioindicators of environmental change. This study is one of the first studies to simultaneously evaluate temperature, humidity, and CO_2 tolerance in two ecologically distinct termite genera. By adopting this integrated approach, the study provides a holistic perspective on termite resilience to climate stressors and establishes a novel framework for their use as bioindicators in biodiversity conservation and ecosystem monitoring.

MATERIALS AND METHODS

Colonies of *Nasutitermes* and *Macrotermes* were collected from Pulau Sebesi, South Lampung Regency, Lampung Province, Indonesia. Sebesi Island is located between 05°55′37.43″S and 05°58′44.48″S latitude, and between 105°27′30.50″E

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and 105°30′47.54″E longitude (details are presented in Figure 1). Termite colonies were examined for the condition of their nests before being designated as research samples (as shown in Figure 2). Healthy worker termites were selected for the experiments to ensure consistency in physiological condition and response. Identification of termite genera was confirmed based on morphological characteristics using established taxonomic keys (Ahmad et al., 1958; Krishna et al., 2013; Kuswanto & Pratama, 2012).

The experiment was conducted under controlled laboratory conditions using an environmental chamber to regulate temperature, humidity, and CO_2 levels. Three environmental variables were independently manipulated to evaluate termite survivability: (1) Temperature treatment, termites were exposed to 11 temperature levels: 0, 5, 10, 15, 20, 25, 30, 35, 40, 45, and 50 (°C); (2) Humidity treatment, relative humidity was adjusted to seven levels: 40, 50, 60, 70, 80, 90, and 100 (%); and (3) CO_2 treatment, termites were exposed to four CO_2 concentrations: 500, 1000, 1500, and 2000 (ppm).

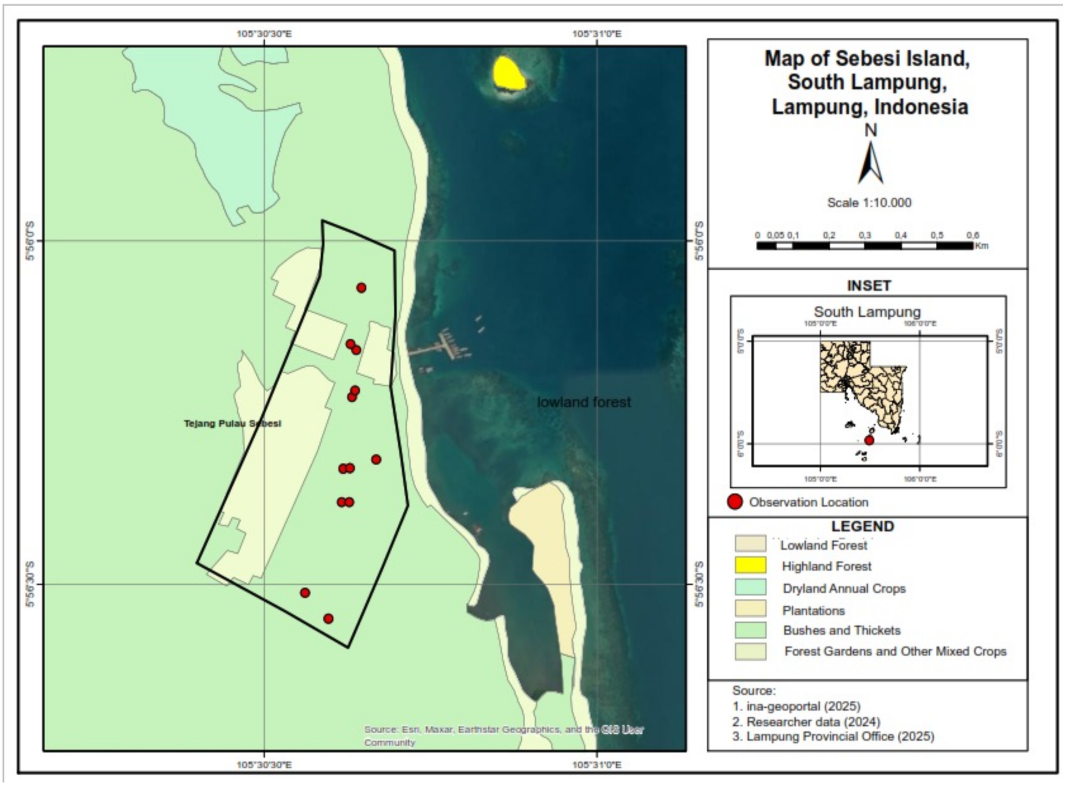

Figure 1. Map of Sebesi Island, South Lampung, Indonesia, showing the location of termite colonies (red dots) used as sampling sites within lowland forest habitats

Each treatment group consisted of 50 worker termites placed in Petri dishes with moistened filter paper to provide food and maintain microclimatic balance, with three replicates per treatment. Environmental chambers were calibrated prior to each trial, and temperature, humidity, and CO_2 were continuously monitored to ensure stability. To reduce variability, termites of similar age and size were selected, as differences in instar or body mass can influence stress tolerance. This standardization ensured that survivability outcomes reflected experimental conditions rather than age- or size-related variation. No separate laboratory control was included, as baseline field data from Pulau Sebesi (representing the microclimatic conditions of natural nests measured in this study) were used as ecological references. This approach follows the methodological recommendations to align experimental ranges with natural environmental variation (Allen, 1998; Sinclair et al., 2016). The one-hour exposure was chosen to assess acute survivability responses while minimizing starvation or handling effects. Short-term assays of comparable duration (30–120 minutes) are widely used in insect ecophysiology to determine immediate tolerance thresholds (Hoffmann et al., 2013; Terblanche & Chown, 2006). While not representing long-term outcomes, this design provides robust data on short-term physiological limits relevant to termite bioindicator potential.

Termite survivability was then calculated as the percentage of living individuals remaining after one hour of exposure, using the following formula:

$$\text{Survivability (\%)} = 100 - [(\text{Number of dead termites}/\text{Total termites}) \times 100]$$

Mortality was confirmed by the absence of movement after gentle stimulation with a fine brush. Chamber calibration was carried out to ensure that environmental variables remained fully stable before the treatments began, so that differences in survivability could be attributed solely to the experimental conditions. Termite age/size variation was controlled by selecting only healthy worker termites of uniform body size, ensuring consistency in physiological conditions across individuals. In addition, control treatments were conducted under near-natural environmental conditions as a baseline for comparison with extreme treatments.

Data were expressed as the mean percentage (±standard error) of termite survivability for each treatment. One-way analysis of variance (ANOVA) was conducted to evaluate the effects of temperature, humidity, and CO_2 concentration on termite survivability. When significant differences were detected, means were compared using Tukey’s Honestly Significant Difference (HSD) test at a significance level of $p < 0.05$. All statistical analyses were performed using SPSS v.25.

In addition to the laboratory experiments, measurements of microclimatic conditions inside the natural nests of *Nasutitermes* and *Macrotermes* were also conducted. Three nests of each genus were equipped with sensors to monitor temperature, relative humidity, and carbon dioxide (CO_2) concentration. Each sensor was carefully inserted into the central part of the nest to minimize disturbance to termite activity. Measurements were recorded continuously for 24 hours, with readings taken every three hours. The resulting data were averaged to represent the microclimatic conditions of natural nests.

Figure 2. Researchers observing termite nests: (a) *Nasutitermes* nest on tree trunk/branches; (b) *Macrotermes* mound on open ground

RESULTS AND DISCUSSION

Effects of Temperature on Termite Survival

The survivability of *Nasutitermes* and *Macrotermes* was strongly influenced by temperature variations (Table 1), showing distinct species-specific tolerance thresholds. The data indicate that *Nasutitermes* exhibited its highest survivability between 25°C and 35°C, as shown by identical superscripts in the statistical analysis, while *Macrotermes* reached maximum survivability at 30°C and 35°C. Moderate survival responses were observed for *Nasutitermes* at 15°C and 20°C and for *Macrotermes* at 20°C and 25°C, whereas both species showed markedly reduced survivability at 5°C and 10°C. At extreme temperatures (0°C, 40°C, 45°C, and 50°C), no individuals of either species survived, indicating complete mortality under both cold and heat stress. These results indicate that both *Nasutitermes* and *Macrotermes* have moderate thermal optima, reflecting the narrow temperature windows suitable for their physiological functioning (Bignell et al., 2011; Woon et al., 2019).

The differential survivability patterns can be explained by the effects of temperature on metabolic and enzymatic activities. At low temperatures (0–20°C), enzymatic reactions slow down, feeding and movement are inhibited, and energy production is reduced, leading to high mortality. Conversely, temperatures above 35°C can induce protein denaturation, oxidative stress, and cellular dysfunction, resulting in rapid declines in survivability (Chouvenc, 2020; Korb, 2003; Korb & Linsenmair, 2000; Rust & Cabrera, 1994; Wang et al., 2024).

Interestingly, *Macrotermes* displayed a slight tolerance advantage at the upper end of moderate temperatures, reaching full survivability at 35°C. This may be related to species-specific adaptations such as mound architecture and social thermoregulation that buffer environmental extremes (Korb, 2003; Neoh & Lee, 2009; Turner, 2001).

Table 1. Survivability of *Nasutitermes* and *Macrotermes* under temperature variations

Treatment of Temperature Variations (°C)	% Survivability of *Nasutitermes*	% Survivability of *Macrotermes*
0	0.0 ± 0.0[e]	0.0 ± 0.0[e]
5	7.3 ± 1.8[d]	3.0 ± 0.9[d]
10	12.3 ± 0.3[d]	6.0 ± 1.7[d]
15	33.7 ± 0.3[c]	12.7 ± 0.7[d]
20	35.3 ± 1.0[c]	21.7 ± 1.7[c]
25	100.0 ± 0.0[a]	39.0 ± 0.0[c]
30	100.0 ± 0.0[a]	100.0 ± 0.0[a]
35	100.0 ± 0.0[a]	100.0 ± 0.0[a]
40	0.0 ± 0.0[e]	0.0 ± 0.0[e]
45	0.0 ± 0.0[e]	0.0 ± 0.0[e]
50	0.0 ± 0.0[e]	0.0 ± 0.0[e]

Note: Values are presented as mean ± standard error (SE). Mean survival rate (± SE) of worker termites under different temperature treatments (n = 3). Column-wise values with different superscripts indicate significant difference ($p<0.05$)

These structural and behavioral adaptations allow *Macrotermes* to maintain internal nest conditions favorable for survival, even when ambient temperatures approach the upper physiological limits.

The complete mortality observed at extreme low (0°C) and high (45–50°C) temperatures highlights the vulnerability of both genera to climate extremes. Such thresholds are ecologically significant, as they indicate the potential impact of climate change, including heat waves or unusually cold events, on termite population (Indrayani, 2022; Woon et al., 2019, 2022). Termites' sensitivity to temperature underscores their potential role as bioindicators for monitoring ecosystem health and environmental stress (Ashton et al., 2019; Indrayani, 2022; Korb, 2003; Korb & Linsenmair, 2000).

In conclusion, these findings demonstrate that both *Nasutitermes* and *Macrotermes* have well-defined thermal tolerances, with optimal survival under moderate temperatures. Extreme temperatures outside these ranges sharply reduce survivability, providing critical information for understanding how climate change may influence termite distribution, population dynamics, and ecological functions.

Effects of Relative Humidity on Termite Survival

The survivability of *Nasutitermes* and *Macrotermes* was strongly influenced by relative humidity (RH) (Table 2). Consistent with the temperature response, *Nasutitermes* showed the highest survival rates at relative humidity levels between 50–80%, whereas *Macrotermes* exhibited optimal survivability under slightly higher humidity, ranging from 60–90%. These patterns, as indicated by identical superscripts in the statistical analysis, suggest that both genera perform best under moderately humid conditions but differ slightly in their upper tolerance limits. Mortality increased at lower (40%) and extreme high RH

(100%), indicating that both insufficient and excessive moisture negatively affect termite survival. These findings highlight the narrow moisture tolerance ranges that support optimal physiological and behavioral functioning (Bignell et al., 2011; Korb & Linsenmair, 2000; Woon et al., 2019, 2022).

Table 2. Survivability of *Nasutitermes* and *Macrotermes* under humidity variations

Treatment of Humidity Variations (%)	% Survivability of *Nasutitermes*	% Survivability of *Macrotermes*
40	74.3 ± 1.20[c]	76.3 ± 1.20[c]
50	98.0 ± 1.15[a]	91.0 ± 0.00[b]
60	99.3 ± 0.67[a]	97.3 ± 0.67[a]
70	100.0 ± 0.00[a]	98.7 ± 1.15[a]
80	100.0 ± 0.00[a]	100.0 ± 0.00[a]
90	78.0 ± 0.58[b]	96.7 ± 0.67[a]
100	75.7 ± 1.20[bc]	62.0 ± 1.00[d]

Note: Values are presented as mean ± standard error (SE). Mean survival rate (± SE) of worker termites under different relative humidity treatments (n = 3). Column-wise values with different superscripts indicate significant difference ($p<0.05$)

Low RH (40%) caused significant mortality, likely due to desiccation stress. Termites rely on cuticular water retention and stable microclimates to maintain homeostasis, and insufficient moisture rapidly disrupts their water balance, reducing survival (Ashton et al., 2019; Chouvenc, 2020; Eggleton, 2000; Woon et al., 2019, 2022). On the other hand, very high RH (100%) also decreased survivability, particularly in *Macrotermes*, possibly due to increased risk of fungal infection, reduced oxygen availability, or microbial proliferation within nests (Chouvenc, 2020; Woon et al., 2019, 2022).

Interestingly, *Macrotermes* showed slightly greater tolerance at high RH (90%) compared to *Nasutitermes*, suggesting species-specific adaptations such as mound ventilation, which can buffer environmental moisture extremes and maintain internal nest humidity within survivable limits (Korb, 2003; Peeters et al., 2024; Turner, 2001). Such adaptations allow *Macrotermes* to occupy habitats with higher ambient moisture, demonstrating ecological plasticity.

Relative humidity (RH) is a critical factor determining termite survival. *Cryptotermes brevis* can adapt within an RH range of 60–90% (Steward, 1983), while *Coptotermes formosanus* performs best at 90% RH and *Reticulitermes speratus* at 70–90% RH (Nakayama et al., 2004). *Reticulitermes flavipes* remains stable at moderate humidity levels of 70–80%, although its gut microbiota is susceptible to temperature fluctuations (Arango et al., 2021). In addition, *C. brevis* is sensitive to heat, and maintaining RH at 70–80% supports its survival (McDonald et al., 2022).

These results confirm that relative humidity is a key determinant of termite survival and activity. Both low and excessively high RH levels act as environmental stressors, limiting survival and potentially affecting colony development, foraging efficiency, and ecological functions. Consequently, monitoring termite responses to RH can serve as a practical approach to evaluating habitat quality and environmental stress, reinforcing their role as bioindicators in ecosystems subject to climate change (Ashton et al., 2019; Indrayani, 2022; Woon et al., 2022). In conclusion, moderate RH (60–80%) provides optimal conditions for the survival of both *Nasutitermes* and *Macrotermes*, while deviations from this range significantly reduce survivability. This reinforces the importance of moisture regulation in termite ecology and its relevance in environmental monitoring programs.

Effects of Carbon Dioxide on Termite Survival

The survivability of *Nasutitermes* and *Macrotermes* decreased progressively with increasing CO_2 concentrations (Table 3). Both *Nasutitermes* and *Macrotermes* showed similar survivability patterns across increasing CO_2 concentrations, as indicated by identical superscripts in the statistical analysis. Both species maintained full survival (100%) at 500 ppm, but survivability progressively declined at higher CO_2 levels. At 2000 ppm, survival dropped to around 50% for both genera, indicating comparable physiological tolerance to elevated CO_2 and suggesting that hypercapnic stress affects them similarly under short-term exposure conditions. This demonstrates that elevated CO_2 imposes physiological stress on termites, affecting their ability to maintain normal metabolic and respiratory functions (Bignell et al., 2011; Chouvenc, 2020; Hassan et al., 2024; Korb, 2003).

The decline in survivability of *Nasutitermes* and *Macrotermes* under elevated CO_2 concentrations reflects the physiological limitations of termites in coping with hypoxic stress. Termites rely on efficient gas exchange through their tracheal system to sustain cellular respiration, and increased CO_2 levels reduce oxygen availability, leading to impaired metabolic processes. This hypoxia sensitivity is closely linked to their ecological roles, as termites function as major decomposers that brak down lignocellulosic material and recycle nutrients in ecosystems. Reduced survivability under high CO_2 conditions suggests that termite populations may become less effective in maintaining soil fertility and organic matter turnover under altered atmospheric conditions, highlighting the vulnerability of their ecological functions to environmental change (Bignell et al., 2011).

Table 3. Survivability of *Nasutitermes* and *Macrotermes* under carbon dioxide variations

Treatment of carbon dioxide variations (ppm)	% Survivability of *Nasutitermes*	% Survivability of *Macrotermes*
500	100.0 ± 0.0[a]	100.0 ± 0.0[a]
1000	72.0 ± 2.1[b]	74.7 ± 1.5[b]
1500	67.0 ± 1.7[c]	55.7 ± 0.3[c]
2000	56.0 ± 0.6[d]	53.7 ± 0.6[d]

Note: Values are presented as mean ± standard error (SE). Mean survival rate (± SE) of worker termites under different CO_2 concentration treatments (n = 3). Column-wise values with different superscripts indicate significant difference (p<0.05)

The decrease in survivability with increasing CO_2 can be attributed to reduced oxygen availability within the respiratory system, which may lead to hypoxia and impaired energy metabolism. *Macrotermes* appeared more sensitive than *Nasutitermes* at higher CO_2 concentrations, suggesting species-specific differences in respiratory efficiency, body size, or tolerance to hypoxic conditions (Chen et al., 2023; Wang et al., 2024). Such differences are ecologically significant, as they influence species distribution and niche occupancy in environments with variable gas concentrations.

The results also highlight the potential of using termites as bioindicators of CO_2-related environmental changes. Changes in CO_2 concentration in soil or nest microclimates may reflect ecosystem disturbances, including decomposition rates, soil respiration, and anthropogenic impacts (Korb, 2003; Risch et al., 2012; Woon et al., 2022). Monitoring termite survivability under varying CO_2levels provides practical insights into ecosystem health and can support climate change impact assessments. In conclusion, moderate CO_2 levels (~500 ppm) are optimal for termite survival, whereas elevated CO_2 significantly reduces survivability, especially for *Macrotermes*. These findings reinforce the value of termites as bioindicators for assessing both physiological stress and environmental quality under changing climate conditions (Ashton et al., 2019).

Microclimatic Conditions of Natural Nests

To complement the laboratory findings, microclimatic measurements were conducted directly within natural nests of *Nasutitermes* and *Macrotermes* on Sebesi Island (Table 4). The data represent mean values from three nests of each termite genus. Results show that *Macrotermes* nests exhibited slightly higher temperature, markedly higher relative humidity, and greater CO_2 concentration compared to *Nasutitermes*. All differences were statistically significant ($p<0.05$).

The observed survival responses of *Nasutitermes* and *Macrotermes* under different temperature, humidity, and CO_2 conditions were consistent with the natural nest microclimates measured in the field. As shown in Table 4, *Macrotermes* nests maintained higher humidity and CO_2 concentrations than those of *Nasutitermes*. These in situ data support the laboratory findings that *Macrotermes* exhibited optimal survivability at higher relative humidity (60–90%) and tolerated elevated CO_2levels better than *Nasutitermes*. Conversely, *Nasutitermes* colonies, which inhabit comparatively drier and cooler nests, demonstrated superior survival at moderate humidity and temperature levels.

Table 4. Microclimatic conditions in *Nasutitermes* and *Macrotermes* nests (n = 3 each)

Parameter	***Nasutitermes*** **(Mean ± SE)**	***Macrotermes*** **(Mean ± SE)**	Remarks
Temperature (°C)	27.54 ± 0.42^a	28.75 ± 0.07^b	*Macrotermes* nests exhibited significantly higher temperatures than *Nasutitermes* nests.
Relative Humidity (%)	86.38 ± 0.78^a	95.58 ± 1.20^b	*Macrotermes* maintained significantly higher humidity inside their nests.
CO_2 Concentration (ppm)	526.17 ± 2.32^a	559.50 ± 6.48^b	CO_2 levels were significantly higher in *Macrotermes* nests compared to *Nasutitermes.*

Note: Values represent mean ± SE obtained from three nests per termite genus (*Nasutitermes* and *Macrotermes*) on Sebesi Island. Different superscripts within rows denote significant differences between genera ($p < 0.05$)

This correspondence between experimental and natural conditions reinforces the ecological validity of the laboratory assays, suggesting that each genus has evolved physiological tolerances suited to its nesting environment. The integration of field microclimatic data thus provides a more comprehensive understanding of termite survival strategies under variable environmental conditions.

The survivability patterns of *Nasutitermes* and *Macrotermes* under temperature, relative humidity, and CO_2 variations reveal that both genera exhibit species-specific tolerance thresholds. Optimal survival occurred under moderate conditions: 25–35°C for temperature, 60–80% RH for humidity, and ambient CO_2 (~500 ppm). Deviations from these ranges sharply reduced survivability, indicating that extreme environmental conditions act as physiological stressors affecting metabolism, water balance, respiration, and overall colony functioning (Chouvenc, 2020; Korb, 2003; Korb & Linsenmair, 2000; Neoh & Lee, 2009) The species-specific differences, such as *Macrotermes*' slightly broader tolerance to high humidity and moderate upper-temperature limits, likely result from nest architecture, social thermoregulation, and behavioral adaptations that buffer environmental fluctuations (Turner, 2001; Woon et al., 2019, 2022).

These findings underscore the potential of *Nasutitermes* and *Macrotermes* as bioindicators for environmental stress and ecosystem health under climate change scenarios. By responding sensitively to multiple abiotic stressors, termites provide valuable information on habitat suitability, microclimate stability, and the cumulative impacts of environmental degradation (Ashton et al., 2019; Eggleton, 2020; Indrayani, 2022). Integrating survivability assessments across temperature, humidity, and CO_2 conditions can enhance bioindicator-based monitoring programs, supporting sustainable ecosystem management, biodiversity conservation, and early detection of climate change effects on terrestrial ecosystems.

Under projected warming scenarios, regional temperatures and the frequency of extreme heat and drought events are expected to increase, with substantial implications for termite habitat suitability. The IPCC AR6 projects a global mean surface temperature increase of about 2.1–3.5°C by 2081–2100 under SSP2-4.5 (intermediate emissions) and 3.3–5.7 °C under SSP5-8.5 (high emissions), relative to 1850–1900 baselines. Such warming will be accompanied by intensified hydrological extremes, with more frequent compound events of heat and drying (IPCC, 2023). Applying these projections to our findings suggests likely shifts in termite distributions and community composition. Because survivability in both *Nasutitermes* and *Macrotermes* is tightly constrained by humidity as well as temperature, increases in temperature coupled with declining local moisture could render presently suitable habitats marginal or unsuitable—particularly for *Macrotermes*, which showed greater sensitivity to elevated CO_2 and desiccation in our assays. These range adjustments would in turn alter decomposition dynamics and nutrient cycling.

Finally, the anticipated changes in the hydrological cycle —greater atmospheric moisture overall but regionally heterogeneous precipitation and increases in drought risk— mean that relative humidity trends will not be uniform, so local outcomes for termite populations will depend strongly on regional climate trajectories and microhabitat buffering (e.g., soil moisture, canopy cover, nest architecture). Thus, while our short-term laboratory assays identify physiological thresholds that predict vulnerability, they should be integrated with regional climate projections and field monitoring to forecast realistic distributional outcomes and ecosystem service impacts under specific SSP pathways.

CONCLUSION

Nasutitermes and *Macrotermes* exhibited optimal survivability at 25–35°C, 60–80% RH, and ambient CO_2 (500 ppm). Extreme environmental conditions significantly reduced survivability, with *Macrotermes* showing slightly greater sensitivity to elevated CO_2 than *Nasutitermes*. The distinct tolerance thresholds observed support the use of both genera as bioindicators for monitoring ecosystem changes under climate stress. This study was limited by its short exposure duration and laboratory-based conditions, which may not fully reflect long-term survival or natural habitat dynamics. Future research should include longer exposure periods, different termite castes, and field validation of laboratory findings to strengthen ecological relevance and refine the application of termites as bioindicators in climate change monitoring.

AUTHOR CONTRIBUTION

This research is a collaborative effort of all authors with clear roles. **E.K** as conceptualization of research, supervision, and writing of the final draft; **A.O.S.P** data collection, writing of drafts, visualization of results; **M.D.K.H** focused on statistical analysis, data interpretation and data collection; **A.F.M., Z.A.R., F.A., N.O.A.** field data collection.

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CONFLICT OF INTEREST

The author declares that there is no conflict of interest regarding the research, writing, or publication of this article.

REFERENCES

Ahmad, F., Fouad, H., Liang, S. Y., Hu, Y., & Mo, J. C. (2021). Termites and Chinese agricultural system: applications and advances in integrated termite management and chemical control. *In Insect Science*, 28(1). DOI:10.1111/1744-7917.12726.

Allen G. Gibbs, A. K. L. A. J. A. A. (1998). Effects of Temperature on Cuticular Lipids And Water Balance In A Desert Drosophila: Is Thermal Acclimation Beneficial? *The Journal of Experimental Biology*, 201, 71–80. DOI: 10.1242/jeb.201.1.71

Arango, R. A., Schoville, S. D., Currie, C. R., & Carlos-Shanley, C. (2021). Experimental Warming Reduces Survival, Cold Tolerance, and Gut Prokaryotic Diversity of the Eastern Subterranean Termite, *Reticulitermes flavipes* (Kollar). *Frontiers in Microbiology*, 12. DOI: 10.3389/fmicb.2021.632715.

Ashton, L. A., Griffiths, H. M., Parr, C. L., Evans, T. A., Didham, R. K., Hasan, F., Teh, Y. A., Tin, H. S., Vairappan, C. S., & Eggleton, P. (2019). Termites mitigate the effects of drought in tropical rainforest. *Science*, 363(6423), 174–177. DOI: 10.1126/science.aau9565.

Bignell, D. E., Roisin, Y., & Lo, N. (2011). Biology of termites: A Modern synthesis. In Biology of Termites: A Modern Synthesis. *Springer Netherlands*. DOI: 10.1007/978-90-481-3977-4.

Chen, C., Singh, A. K., Yang, B., Wang, H., & Liu, W. (2023). Effect of termite mounds on soil microbial communities and microbial processes: Implications for soil carbon and nitrogen cycling. *Geoderma*, 431. DOI: 10.1016/j.geoderma.2023.116368.

Chouvenc, T. (2020). Limited survival strategy in starving subterranean termite colonies. *Insectes Sociaux*, 67(1), 71–82. DOI: 10.1007/s00040-019-00729-5.

Constantino, R. (2021). Termite taxonomy from 2001–2021: The contribution of Zootaxa. *Zootaxa*, 4979(1), 222–223. Magnolia Press. DOI: 10.11646/zootaxa.4979.1.22.

Eggleton P, Bignell D, Hauser S, Dibog L, Norgrove L, Madong B (2002) Termite diversity across an anthropogenic disturbance gradient in the humid forest zone of West Africa. *Agric Ecosyst Environ* 90:189–202. DOI: 10.1016/S0167-8809(01)00206-7

Eggleton, P. (2020). The state of the-world's insects. *Annual Review of Environment and Resources*, 45, 61–82. Annual Reviews Inc. DOI: 10.1146/annurev-environ-012420-050035.

Haryanto, H. C., & Prahara, S. A. (2019). Perubahan Iklim, Siapa yang Bertanggung Jawab? Insight: *Jurnal Ilmiah Psikologi*, 21(2). DOI: 10.26486/psikologi.v21i2.811.

Hassan, A., Li, Z., Zhou, X., Mo, J., & Huang, Q. (2024). Termite management by entomopathogenic fungi: Recent advances and future prospects. *Current Research in Biotechnology* (Vol. 7). DOI: 10.1016/j.crbiot.2024.100183.

Hoffmann, A. A., Chown, S. L., & Clusella-Trullas, S. (2013). Upper thermal limits in terrestrial ectotherms: How constrained are they? *Functional Ecology*, 27(4), 934–949. DOI: 10.1111/j.1365-2435.2012.02036.x.

Indrayani, Y. (2022). Peran Rayap dalam Keseimbangan Ekosistem. *Prosiding Seminar Nasional Penerapan Ilmu Pengetahuan dan Teknologi*, 6(1). DOI: 10.26418/pipt.2021.50

Indrayani, Y., Yoshimura, T., Yanase, Y., Fujii, Y., & Imamura, Y. (2007). Evaluation of the temperature and relative humidity preferences of the western dry-wood termite *Incisitermes minor* (Hagen) using acoustic emission (AE) monitoring. *Journal of Wood Science*, 53(1), 76–79. DOI: 10.1007/s10086-006-0817-0.

IPCC. (2023). Summary for Policymakers. In: Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. IPCC, Geneva, Switzerland, pp. 1-34. DOI: 10.59327/IPCC/AR6-9789291691647.001.

Korb, J. (2003). Thermoregulation and ventilation of termite mounds. *Naturwissenschaften*, 90(5), 212–219. Springer Verlag. DOI: 10.1007/s00114-002-0401-4.

Korb, J., & Linsenmair, K. E. (2000). Thermoregulation of termite mounds: What role does ambient temperature and metabolism of the colony play? *Insectes Sociaux*, 47(4), 357–363. DOI: 10.1007/PL00001731.

Krishna, K., Grimaldi, D. A., & Krishna, V. (2013). Treatise on The Isoptera of The World Volum E 7 r e f e r e nc e s a n d i n de X. *Bulletin of The American Museum of Natural HISTORY* Number, 377. DOI: 10.1206/377.7.

Kuswanto, E., & Pratama, A. O. S. (2012). Sebaran dan Ukuran Koloni Sarang Rayap Pohon *Nasutitermes* sp (Isoptera: Termitidae) Di Pulau Sebesi Lampung Sebagai Sumber Belajar Biologi. *BIOEDUKASI (Jurnal Pendidikan Biologi)*, 3(2). DOI:10.24127/bioedukasi.v3i2.261.

Mandala, M., Nurhayati, D., & Dhokhikah, Y. (2020). Persepsi dan Strategi Adaptasi Masyarakat Terhadap Perubahan Iklim di Kawasan Asia Tenggara Perceptions and Strategies for Community Adaptation to Climate Change in the Southeast Asian Region. *Jurnal Lingkungan Berkelanjutan*, 1(1).

McDonald, J., Fitzgerald, C., Hassan, B., & Morrell, J. J. (2022). Thermal tolerance of an invasive drywood termite, Cryptotermes brevis (Blattodea: Kalotermitidae). *Journal of Thermal Biology*, 104. DOI: 10.1016/j.jtherbio.2022.103199.

Myers, T. A., Maibach, E. W., Woods Placky, B., Henry, K. L., Slater, M. D., & Seitter, K. L. (2020). Impact of the climate matters program on public understanding of climate change. *Weather, Climate, and Society*, 12(4), 863–876. DOI: 10.1175/WCAS-D-20-0026.1.

Nakayama, T., Yoshimura, T., & Imamura, Y. (2004). The optimum temperature-humidity combination for the feeding activities of Japanese subterranean termites. *Journal of Wood Science*, 50(6), 530–534. DOI: 10.1007/s10086-003-0594-y.

Neoh, K. B., & Lee, C. Y. (2009). Flight activity of two sympatric termite species, *Macrotermes gilvus* and *Macrotermes carbonarius* (Termitidae: Macrotermitinae). *Environmental Entomology*, 38(6). DOI: 10.1603/022.038.0623.

Nurhayati, D., Dhokhikah, Y., & Mandala, M. (2020). Persepsi dan Strategi Adaptasi Masyarakat Terhadap Perubahan Iklim di Kawasan Asia Tenggara. *JURNAL PROTEKSI: Jurnal Lingkungan Berkelanjutan*, 1(1).

Parulian, J., Parulian Manurung, J., Boedoyo, M. S., & Sundari, S. (2022). Pajak Karbon di Indonesia dalam Upaya Mitigasi Perubahan Iklim dan Pertumbuhan Ekonomi Berkelanjutan. *Jurnal Kewarganegaraan*, 6(2). DOI: 10.31316/jk.v6i2.3171

Risch, A. C., Anderson, T. M., & Schütz, M. (2012). Soil CO_2 Emissions Associated with Termitaria in Tropical Savanna: Evidence for Hot-Spot Compensation. *Ecosystems*, 15(7), 1147–1157. DOI: 10.1007/s10021-012-9571-x.

Rust, M. K., & Cabrera, B. L. (1994). The Effects of Temperature and Humidity on the Movement of the Western Drywood Termite.

Scheffrahn, R. H., Mullins, A. J., Krecek, J., Chase, J. A., Mangold, J. R., Myles, T., Nishimura, T., Setter, R., Cannings,

R. A., Higgins, R. J., Lindgren, B. S., Constantino, R., Issa, S., & Kuswanto, E. (2015). Global elevational, latitudinal, and climatic limits for termites and the redescription of rugitermes laticollis snyder (Isoptera: Kalotermitidae) from the andean highlands. *Sociobiology*, 62(3), 426–438. DOI: 10.13102/sociobiology.v62i3.793.

Sinclair, B. J., Marshall, K. E., Sewell, M. A., Levesque, D. L., Willett, C. S., Slotsbo, S., Dong, Y., Harley, C. D. G., Marshall, D. J., Helmuth, B. S., & Huey, R. B. (2016). Can we predict ectotherm responses to climate change using thermal performance curves and body temperatures?. *Ecology Letters*, 19(11),1372–1385. Blackwell Publishing Ltd. DOI: 10.1111/ele.12686.

Steward, R. C. (1983). The Effects of Humidity, Temperature and Acclimation on The Feeding, Water Balance and Reproduction of Dry-Wood Termites (Cryptotermes). *Entomologia Experimentalis et Applicata*, 33(2), 135–144. DOI: 10.1111/j.1570-7458.1983.tb03249.x.

Susilawati, S. (2021). Dampak Perubahan Iklim Terhadap Kesehatan. *Electronic Journal Scientific of Environmental Health And Disease*, 2(1). DOI: 10.22437/esehad.v2i1.13749.

Terblanche, J. S., & Chown, S. L. (2006). The relative contributions of developmental plasticity and adult acclimation to physiological variation in the tsetse fly, *Glossina pallidipes* (Diptera, Glossinidae). *Journal of Experimental Biology*, 209(6), 1064–1073. DOI: 10.1242/jeb.02129.

Turner, J. S. (2001). On the mound of *Macrotermes michaelseni* as an organ of respiratory gas exchange. *Physiological and Biochemical Zoology*, 74(6), 798–822. DOI: 10.1086/323990.

van Valkengoed, A. M., Perlaviciute, G., & Steg, L. (2024). From believing in climate change to adapting to climate change: The role of risk perception and efficacy beliefs. *Risk Analysis*, 44(3), 553–565. DOI: 10.1111/risa.14193.

Wang, D., Yuan, C., Zhang, X., Wei, X., Yue, K., Ni, X., & Wu, F. (2024). Precipitation rather than temperature primarily drives global termite effects on litter decomposition. *Catena*, 236. DOI: 10.1016/j.catena.2023.107778.

Woon, J. S., Atkinson, D., Adu-Bredu, S., Eggleton, P., & Parr, C. L. (2022). Termites have wider thermal limits to cope with environmental conditions in savannas. *Journal of Animal Ecology*, 91(4), 766–779. DOI: 10.1111/1365-2656.13673

Woon, J. S., Boyle, M. J. W., Ewers, R. M., Chung, A., & Eggleton, P. (2019). Termite environmental tolerances are more linked to desiccation than temperature in modified tropical forests. Insectes *Sociaux*, 66(1), 57–64. DOI: 10.1007/s00040-018-0664-1