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ML-Assisted Thermal Screening of Green Fin Materials for Passive Cooling under Natural Convection: An Analytical Sustainability Study

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Abstract: ***This paper presents a submission-ready journal manuscript on passive cooling using green fin materials under natural convection. A vertical plate-fin heat sink was analysed as a no-CAD, no-laboratory design problem so that the thermal logic remained reproducible and suitable for early-stage mechanical-engineering screening. Four material cases were compared: copper, aluminum, recycled aluminum, and recycled aluminum with a high-emissivity black coating. A deterministic design space of 108 configurations was generated by varying fin height, fin spacing, and base temperature while keeping the overall geometry simple enough for spreadsheet or script-based implementation. Classical heat-transfer equations were used to estimate convection, linearized radiation, fin efficiency, total heat dissipation, thermal resistance, mass, and heat dissipation per unit mass. The resulting dataset was then used to build a lightweight machine-learning layer in which linear regression served as an interpretable baseline and random forest regression acted as a nonlinear surrogate for rapid thermal-performance prediction. Graphical results show that fin height improves heat rejection with diminishing returns, fin spacing governs the trade-off between buoyancy access and fin population, and emissive surface treatment becomes increasingly valuable as the base temperature rises. Within the analysed design space, the coated recycled-aluminum configuration produced the strongest absolute thermal result, while aluminum achieved the highest weighted sustainability score under the selected multi-criteria scheme. The manuscript therefore demonstrates that a short mechanical-engineering paper can still integrate thermodynamics, material selection, sustainability reasoning, data visualization, and a modest AI layer in a form aligned to a fast-track multidisciplinary journal submission.***

Keywords: passive cooling, natural convection, recycled aluminum, sustainability assessment, random forest, heat dissipation prediction

I. INTRODUCTION

Thermal management remains a central concern in mechanical engineering because compact systems must either preserve heat, reject it, or route it without compromising reliability. For low-power electronics housings, sensing modules, LED assemblies, rooftop control boxes, and small battery-adjacent components, passive cooling is attractive because it avoids fans, noise, maintenance, and parasitic power draw. The design challenge is that passive systems depend almost entirely on geometry, material selection, and surface condition to create adequate heat rejection. The present study addresses that challenge using a modeled plate-fin heat sink under natural convection. Rather than relying on a three-dimensional CAD workflow or a laboratory prototype, the paper uses established heat-transfer relations to build a transparent design dataset that can be defended in a final-year mechanical engineering setting. The problem is broadened by environmental reasoning: the work compares conventional metallic choices with recycled aluminum and a coated recycled-aluminum alternative that benefits from improved emissivity.

A small machine-learning layer is included not as a replacement for mechanics but as a surrogate design tool. After the analytical dataset is generated, regression models are trained to predict total heat dissipation from geometry and material inputs. This creates a workflow in which physics supplies the structure and AI accelerates screening. The resulting paper therefore integrates thermal science, material choice, and modest automation within a concise journal format.

II. METHODOLOGY

A. Analytical Design Space

The reference sink consists of a 120 mm by 80 mm base plate with 5 mm thickness and straight plate fins of 2 mm thickness. Fin height was varied at 20, 30, and 40 mm; fin spacing was varied at 4, 6, and 8 mm; and base temperature was varied at 50, 60, and 70 C, with ambient air fixed at 30 C. Across four material cases, these settings yielded 108 analytically generated configurations.

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For each case, film temperature was used to estimate representative air behaviour. Natural-convection performance was calculated from a vertical-surface Rayleigh-Nusselt framework, while radiation was added through a linearized radiation coefficient. The effective heat-transfer coefficient was then used in standard straight-fin relations to evaluate fin efficiency, total heat dissipation, and overall thermal resistance. The system-level comparison was extended beyond raw thermal output by computing mass-normalized heat rejection and a weighted sustainability score.

$$Ra_L = g \beta (T_b - T_{inf}) L^3 / (\nu \alpha)$$
$$h_{rad} = \varepsilon \sigma (T_s + T_{inf})(T_s^2 + T_{inf}^2)$$
$$\eta_f = \tanh(m L_c) / (m L_c)$$
$$R_{th} = (T_b - T_{inf}) / Q_{total}$$

TABLE I: Summary of Analytical Design Variables and Material Cases

Item	Design setting
Materials	Cu; Al; Recycled Al; Recycled Al + black coat
Fin height	20, 30, 40 mm
Fin spacing	4, 6, 8 mm
Base temperature	50, 60, 70 C
Total cases	108

B. ML Prediction Framework

Once the analytical dataset had been assembled, two supervised-learning models were trained to predict total heat dissipation. Linear regression was used as an interpretable baseline, while random forest regression was selected as the nonlinear surrogate. The feature set included conductivity, density, emissivity, fin height, fin spacing, number of fins, and base temperature.

The models were evaluated on an 80:20 train-test split using coefficient of determination (R2), mean absolute error (MAE), and root mean square error (RMSE). Linear regression achieved an R2 of 0.927 with an RMSE of 3.170 W, while the random forest surrogate improved performance to an R2 of 0.965 with an RMSE of 2.214 W. This arrangement keeps the AI layer limited in scope while still demonstrating how an analytical mechanical-design study can be extended into an automation-ready screening tool.

III. RESULTS AND DISCUSSION

The analytical sweep showed that passive-cooling performance is governed by coupled material and geometry effects rather than by conductivity alone. Increasing fin height improved heat rejection, but not linearly, because the added area interacts with the fin-efficiency term. Fin spacing exhibited the expected compromise between flow access and fin population. Mid-to-tight spacing improved surface area, whereas wider spacing helped buoyancy-driven motion.

The strongest absolute thermal result in the analysed design space occurred for recycled aluminum with black coating at 40 mm fin height, 4 mm spacing, and 70 C base temperature. That configuration delivered 80.51 W of heat dissipation with a thermal resistance of 0.50 K/W. The result highlights the significance of surface emissivity in fanless systems: once radiation is admitted explicitly, a lighter green material with an emissive finish can outperform an uncoated conductivity benchmark under moderate temperature conditions.

The weighted sustainability framework yielded a highest numerical score of 8.76 for an aluminum case, indicating that conventional aluminum remains highly competitive when cost, mass, and practicality are emphasized. At the same time, the coated recycled-aluminum family remains the most persuasive green upgrade because it combines high heat rejection, low density, and strong recyclability logic.

A. Thermal Behaviour Across the Design Space

Figures 1 and 2 make the coupled geometry trends explicit. At the reference 60 C base-temperature level, heat dissipation rises with fin height for all materials, but the slope is steeper for the emissive recycled-aluminum case because both convection and radiation are active contributors. The increase is not perfectly linear, which confirms that taller fins cannot be justified by area addition alone; the fin-efficiency term moderates the benefit as characteristic length grows.

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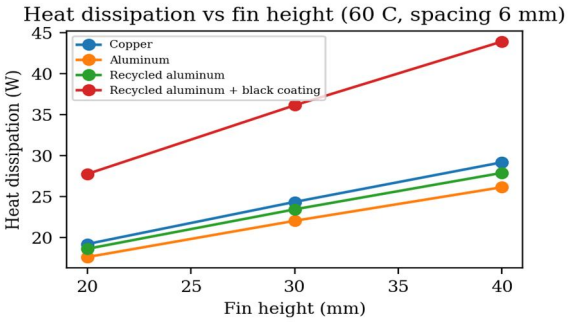


Fig. 1. Heat dissipation versus fin height at 60 C base temperature and 6 mm spacing.

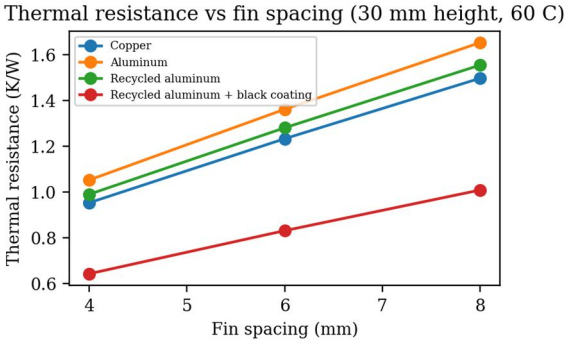


Fig. 2. Thermal resistance versus fin spacing at 30 mm fin height and 60 C base temperature.

B. Sustainability and Mass-Normalized Screening

For component selection, absolute heat rejection is not the only useful metric. Once heat dissipation is normalized by total mass, the aluminum-based families become far more competitive than copper. This distinction is important in distributed sensors, rooftop housings, lightweight enclosures, and other applications where packaging and material burden matter alongside raw thermal performance.

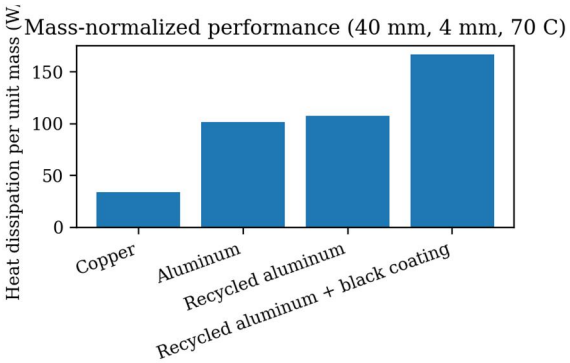


Fig. 3. Heat dissipation per unit mass for the 40 mm, 4 mm, 70 C high-duty reference case.

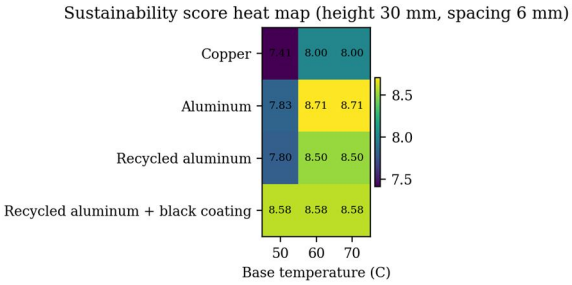


Fig. 4. Sustainability score heat map for the 30 mm fin height and 6 mm spacing reference geometry.

The sustainability comparison complements the mass-normalized view. Aluminum attains the highest numerical score under the selected weighting scheme because it balances respectable thermal behaviour with low density, practicality, and cost. However, the coated recycled-aluminum family remains the more persuasive green-upgrade strategy when the design objective is to raise thermal performance without abandoning recyclability and lower material burden.

C. Surrogate-Model Diagnostics

The machine-learning models reproduced the analytical dataset with high fidelity. Random forest achieved a higher R2 and lower error than linear regression, confirming that the design space contains nonlinear interactions among temperature, emissivity, and geometry. Feature ranking further showed that base temperature was the dominant predictor, followed by emissivity, fin spacing, fin height, conductivity, and density. These rankings are physically credible because passive heat rejection rises strongly with temperature level and radiative capability.

TABLE II: Comparative ML Performance Metrics

Model	R2	MAE (W)	RMSE (W)
Linear Regression	0.927	2.595	3.170
Random Forest	0.965	1.631	2.214

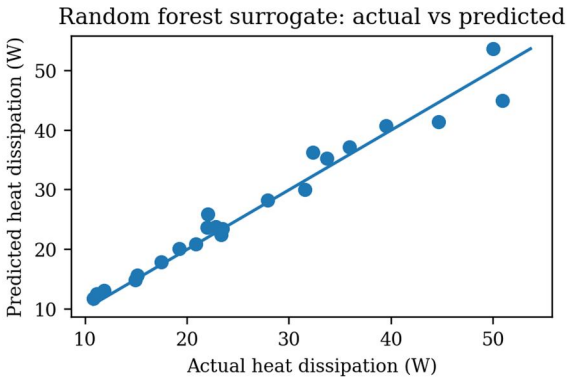


Fig. 5. Actual versus predicted heat dissipation for the random forest surrogate model.

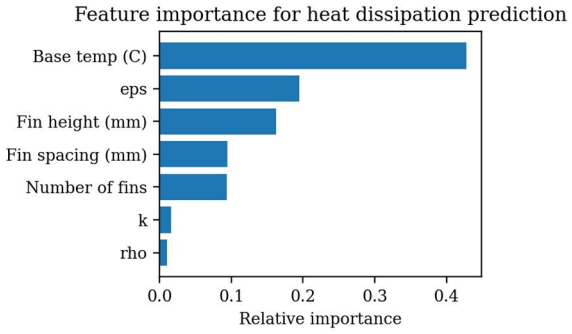


Fig. 6. Random forest feature importance for heat dissipation prediction.

IV. ENGINEERING INTERPRETATION

The results reinforce a practical idea in thermal design: surface engineering can sometimes be a more efficient lever than simply escalating to heavier materials. Copper remains a valuable conductivity benchmark, but a high-emissivity finish allows recycled aluminum to exploit both convection and radiation simultaneously. That makes it highly attractive when heat rejection, low mass, and environmental preference must be satisfied together.

The machine-learning layer also has direct design value. Because the surrogate is trained on an analytically consistent dataset, it can act as a fast estimator inside a future decision-support tool. A user could enter candidate geometry and material properties and obtain a thermal estimate immediately, with no need to manually recompute every relation. This is the correct role of AI in the present paper: not to replace first principles, but to accelerate early-stage screening.

V. CONCLUSION

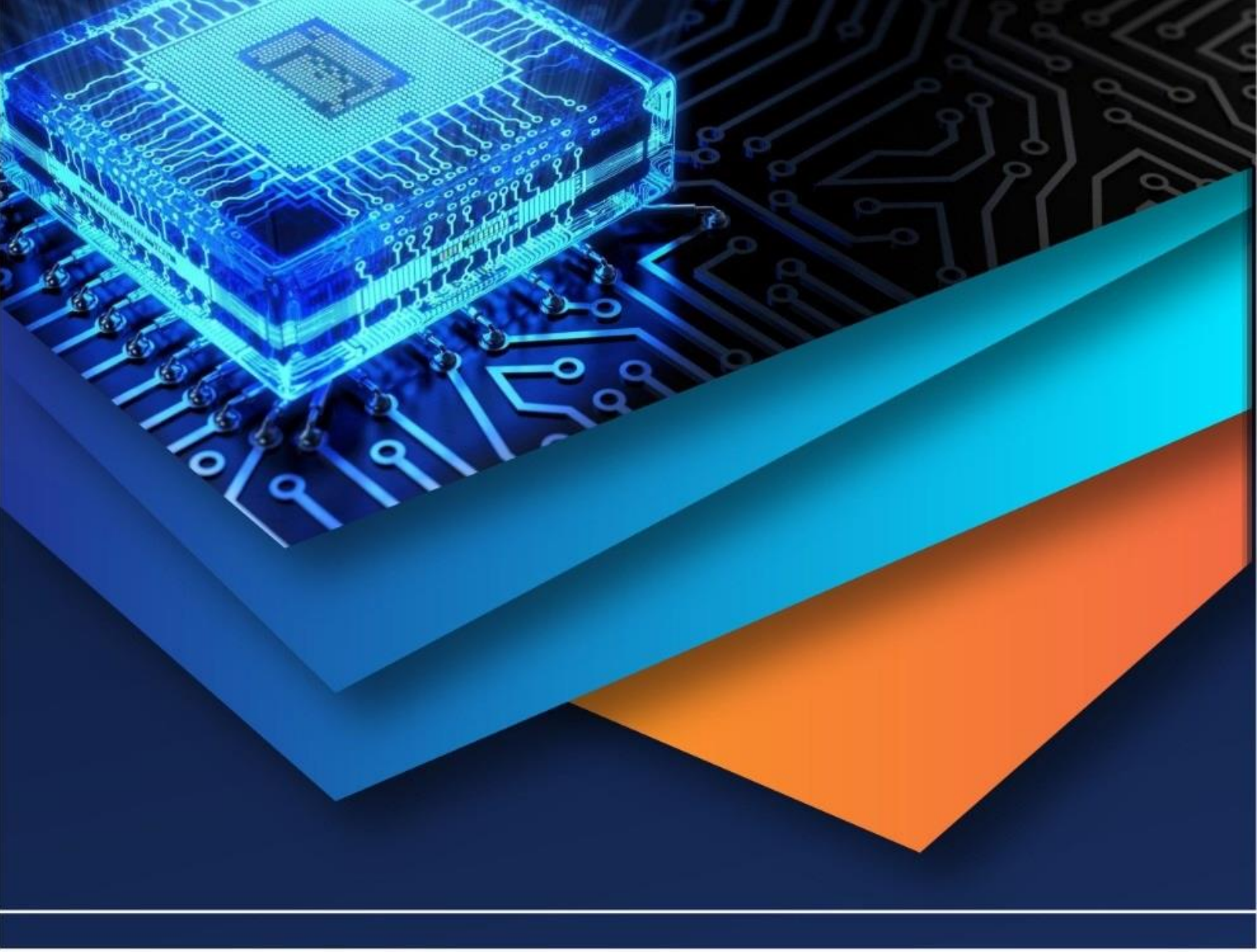
This paper reformulates a longer final-year thermal report into a concise journal-style study and shows that a no-CAD, no-laboratory workflow can still deliver technically meaningful results. Classical heat-transfer modelling produced an interpretable design space for passive cooling, while a lightweight ML layer converted that design space into a rapid prediction framework.

Within the analysed cases, the coated recycled-aluminum configuration achieved the best absolute thermal outcome, whereas aluminum secured the highest weighted sustainability score under the chosen criteria. Random forest outperformed linear regression for heat-dissipation prediction, confirming the usefulness of a small nonlinear surrogate in this type of engineering problem. Future work can extend the same framework through CAD refinement, CFD validation, prototype testing, and application-specific sustainability weighting.

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