

Research Article

Sustainable Thermal Solutions: Assessing Recycled Plastic for Ceiling Insulation

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<https://doi.org/10.59652/hyvymj07>

Abstract: This study investigates the use of utilizing recycled plastics polypropylene (PP), high-density polyethylene (HDPE), and polyethylene terephthalate (PET) as alternative ceiling insulation materials. Motivated by escalating plastic pollution and the growing demand for sustainable construction practices, the research examines the thermal efficiency, durability, reliability, and user acceptability of recycled plastic-based Ceiling Plastic Insulator (CPI). A quasi-experimental research design was employed, incorporating controlled fabrication trials, thermal performance evaluation using a prototype housing model, long-term natural weathering exposure, and biological resistance testing against mold and pests. Additionally, survey data were gathered from home-owners, construction professionals, and government personnel to assess perceptions and willingness to adopt the CPI. Results indicate that among the tested materials, PP exhibited the most favorable thermal performance, recording the lowest surface temperature (34.8°C), followed by HDPE (36.1°C) and PET (39.7°C). All recycled plastics demonstrated high durability, showing no observable degradation, discoloration, or biological growth after nine months of outdoor exposure. Survey findings revealed strong positive acceptance, with 86.7% of respondents expressing willingness to use the CPI, primarily due to its potential for energy savings and environmental benefits. The study concludes that recycled plastics particularly PP and HDPE present a viable, durable, and sustainable alternative for ceiling insulation applications. Their demonstrated thermal effectiveness, resistance to environmental and biological stressors, and high user acceptability support their integration into environmentally responsible building systems. Further research is recommended to enhance fabrication methods, assess large-scale performance, and evaluate long-term installation outcomes in real residential settings.

Keywords: recycled plastic insulator; sustainable construction materials; thermal efficiency; environmental sustainability

Received: December 15, 2025

Accepted: December 26, 2025

Published: December 28, 2025



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1. Introduction

Pollution remains one of the most critical global challenges, with plastic waste emerging as a dominant contributor due to its extensive use in modern society. Plastics are widely utilized for daily human necessities because of their durability, low cost, and versatility; however, rapid population growth and increasing consumption have resulted in an unprecedented accumulation of plastic waste (Rikhter et al., 2022; Jung et al., 2023). Recent studies estimate that over 1,500 marine and terrestrial species are affected by plastic ingestion or entanglement, underscoring the scale of the environmental crisis (Safieddine et al., 2025; The Ocean Cleanup, 2024). The Philippines has been identified as one of the world's leading contributors to ocean plastic pollution, with significant quantities of plastic waste entering marine environments annually (Ramos, 2023).

This environmental challenge is further compounded by the climate impacts of plastic production and disposal. Plastics are predominantly derived from fossil fuels, and their extraction, processing, and transportation generate substantial greenhouse gas emissions (Karali et al., 2024; United Nations, n.a.). Studies from the University of Colorado Boulder and other institutions indicate that plastic production contributes millions of metric tons of carbon dioxide equivalents annually, accelerating climate change and global temperature rise

(Carlisle & Friedlander, 2016; Vászrhelyi, 2023). In the Philippine context, the Philippine Atmospheric, Geophysical and Astronomical Services Administration (PAGASA) has reported an increase in heat intensity of approximately 1.2°C due to human-induced climate change, with recorded heat index levels reaching dangerous thresholds exceeding 50°C in recent years.

These rising temperatures have intensified thermal discomfort in residential buildings, increasing reliance on mechanical cooling systems and driving higher energy consumption (Soltanzadeh et al., 2021). Effective thermal insulation has therefore become a critical requirement in sustainable building design. Conventional insulation materials such as fiberglass and foam boards are commonly used; however, they present limitations related to environmental impact, moisture retention, degradation, and potential health risks associated with airborne particles (Zhao et al., 2022; Kim et al., 2023). As a result, recent academic research has increasingly explored alternative insulation materials that are both energy-efficient and environmentally sustainable.

Recent studies have demonstrated that recycled plastic materials exhibit promising thermal properties, durability, and resistance to moisture, pests, and biological degradation (Ali et al., 2024; Jung et al., 2023). Similarly, life-cycle assessment studies have highlighted the potential of recycled plastics to reduce carbon footprints by minimizing the demand for virgin materials and diverting waste from landfills and oceans (Rikhter et al., 2022; Karali et al., 2024).

Despite these advancements, there remains a notable research gap regarding the application of recycled plastics specifically as ceiling insulation materials under tropical climatic conditions. Limited studies have systematically evaluated their thermal performance, durability, environmental resistance, and user acceptability in real-world residential settings. Addressing this gap is particularly relevant for developing countries such as the Philippines, where both plastic waste management and heat stress in buildings present urgent challenges.

The significance of this study lies in its potential to advance sustainable construction practices by assessing the feasibility of recycled plastic ceiling insulators as an alternative thermal solution. By evaluating the thermal efficiency, durability, and acceptability of recycled plastic materials, this research contributes empirical evidence that supports energy-efficient building design, plastic waste valorization, and climate-resilient housing. Ultimately, the study aligns with current academic discourse on circular economy principles and sustainable material innovation, offering practical insights for reducing energy consumption and environmental impact in residential construction.

2. Materials and Methods

The study employed a quasi-experimental research design to evaluate the development and performance of a Ceiling Plastic Insulator (CPI) fabricated from recycled plastics, specifically polypropylene (PP), high-density polyethylene (HDPE), and polyethylene terephthalate (PET). This approach enabled systematic assessment of thermal efficiency, durability, reliability, and environmental resistance under controlled fabrication trials and natural outdoor exposure.

Experimental procedures included material fabrication trials, prototype thermal performance testing, degradation assessment, and biological resistance evaluation against mold and pests. A total of 10-15 samples were used, which is appropriate for controlled comparative experiments involving repeated measurements. In addition to laboratory testing, survey questionnaires and semi-structured interviews were conducted with home-owners, construction professionals, and government personnel to assess user acceptability, perceived durability, reliability, and willingness to adopt CPI using a five-point Likert scale. The integration of experimental testing and perception-based data allowed comprehensive evaluation of both technical performance and practical applicability.

The research was conducted in Cebu City, Philippines, a major urban center characterized by rapid urbanization, high population density, and a tropical climate with average temperatures ranging from 25°C to 32°C. The city's warm and humid conditions, high energy costs, and growing demand for energy-efficient construction materials make it an appropriate setting for evaluating thermal insulation performance. Additionally, Cebu City faces significant plastic waste management challenges, highlighting the relevance of recycled plastic as a sustainable construction material. These environmental, climatic, and socioeconomic factors provide a suitable context for assessing the feasibility and applicability of recycled plastic ceiling insulation in real-world conditions.



2.1. Respondents and Sampling

The selection of respondents is crucial for ensuring the research captures a representative and comprehensive perspective on the potential for recycled plastic ceiling insulators in Cebu City. The respondents will include individuals from various sectors, consumers, industry and professionals, who can provide insights into the technical and economic feasibility of this innovation. The table below shows the categories of respondents that will be involved in the research.

Table 1. Profile distribution of respondents.

Category	Profile	Sample
Residential home-owners	Home-owners interested in sustainable insulation options	5
Construction industry professionals	Architects, engineers, contractors, builders, designers	5
Government and regulatory authorities	Building and zoning officials, DENR representatives	5

The respondents were classified into three groups: residential home-owners interested in sustainable insulation solutions, construction industry professionals (architects, engineers, contractors, builders, and designers), and government and regulatory authorities, including building officials and DENR representatives. Each category comprised five respondents, ensuring balanced representation from consumer, technical, and regulatory sectors. This distribution provided a comprehensive perspective on the technical feasibility, market demand, and regulatory considerations for recycled plastic ceiling insulators in Cebu City.

The experimental phase utilized 10-15 material samples to evaluate the thermal and durability performance of recycled plastic insulators under controlled conditions. Consistent with Roscoe's rule of thumb (Sekaran & Bougie, 2016), and supported by Cohen (1988) and Montgomery (2017), this sample size is appropriate for controlled experimental studies emphasizing repeated trials and performance comparison rather than population generalization. The selected sample size is therefore adequate to achieve the study's objectives.

2.2. Instruments

A structured survey served as the primary tool for gathering quantitative data from respondents such as home-owners, architects/engineers, and government personnel. The questionnaire used a five-point Likert scale to assess CPI in terms of: Performance, Durability, Reliability and Acceptability/willingness to adopt the survey measured user perceptions regarding heat reduction, structural integrity, pest/mold resistance, and long-term usability of the CPI.

Qualitative insights were collected through semi-structured interviews with selected individuals, including home-owners and construction professionals. This guide allowed respondents to provide deeper feedback, suggestions for improvement, and practical considerations related to installation, design, and usability of the recycled plastic insulator.

To evaluate the technical performance of the CPI, a range of experimental tools and equipment was utilized. Surface temperature measurements during thermal performance testing were obtained using an infrared thermometer, while a small-scale prototype house model was employed to simulate indoor thermal conditions under controlled exposure. A charcoal furnace and metal molder were used during fabrication trials to melt and form recycled PP, PET, and HDPE into insulation panels. In addition, observation instruments and outdoor exposure setups were implemented to assess material degradation, weather resistance, and biological resilience against pests and mold. The combined use of these instruments enabled systematic testing under natural environmental conditions, ensuring reliable evaluation of the CPI's thermal behavior and durability.

To assess the perceived need and acceptability of CPI, a weighted scoring procedure was applied using a parametric evaluation scale. The assessment focused on four key criteria: performance, reliability, durability, and willingness to adopt. Performance (30%) measured the effectiveness of the insulator in reducing heat transfer and improving indoor thermal comfort, while reliability (30%) evaluated the material's consistency and long-term functional stability. Durability (30%) examined the insulator's resistance to environmental damage and prolonged exposure conditions. Willingness to adopt (10%) reflected users' openness to



accepting and utilizing the CPI based on perceived benefits. The overall weighted mean score was calculated by averaging the weighted values across all categories, providing a quantitative basis for comparing the suitability of recycled plastic materials for ceiling insulation applications.

2.3. Data Gathering Procedures

The production of CPI involves several systematic steps to ensure that the final product meets quality, safety, and performance standards. Each stage of the process is designed to maximize material efficiency, maintain cleanliness, and achieve consistent physical property (table 2).

Table 2. Procedures of the ceiling plastic insulation fabrication.

Process	Definition
Collecting	The process begins with plastic waste collection from various sources, such as households, junk shops, and material recovery facilities (MRFs). Only recyclable thermoplastics.
Sorting	Once collected, the researchers will manually sort the plastic to separate them by type. Proper sorting ensures a consistent composition, which is critical for achieving uniform thermal resistance in the final CPI product.
Cleaning	Sorted plastics are thoroughly washed with water and mild detergent to remove dirt, food residues, and contaminants that could compromise the quality of the finished product. The cleaning process typically involves scrubbing, and rinsing.
Drying	After cleaning, plastics are air-dried to remove moisture. Proper drying is essential to prevent defects such as voids, bubbles, or reduced bonding strength during the melting stage.
Cutting/Shredding	The shredded plastics are then pre-processed by blending different types in the required ratio (e.g., HDPE or a mix of HDPE and PET depending on desired properties). to enhance durability and meet industry standards.
Melting	The shredded plastic in the molder is fed into a heating charcoal where it is heated to its melting point.

The systematic process of fabrication recycling of CPI was carried out through a structured and systematic process to ensure reliability and consistency of results. From the collection and careful sorting of recyclable thermoplastics to thorough cleaning, drying, shredding, and controlled melting, each step was designed to minimize contamination, optimize material properties, and enhance thermal performance. This methodical approach not only ensured uniformity in the fabricated CPI samples but also provided dependable data for evaluating their quality, safety, and effectiveness as sustainable insulation materials.

3. Results

This section presents the experimental findings, thermal measurements, durability assessments, and acceptability ratings collected throughout the development and evaluation of the recycled plastic ceiling insulator. Results are organized into subsections that describe the melting behavior of each plastic type, thermal performance outcomes, environmental resistance tests, and user perception scores. Tables and figures are provided to support the interpretation of data and highlight the comparative effectiveness of PET, HDPE, and PP as insulation materials.

3.1. Process and Materials Behavior Result

The findings concern the fabrication trials conducted to evaluate the process behavior and material response of recycled plastics used in the production of CPI. The focus is on observing the melting characteristics, thermal response, and overall suitability of the materials under controlled heating conditions. Through a series of experimental trials, adjustments were made to the setup and heating method to address initial failures and improve process efficiency. The outcomes discussed in this section provide insight into the challenges encountered during fabrication and the process modifications that ultimately led to successful melting and material formation.

Table 3 presents the sequential melting process trials conducted on recycled PET plastics to evaluate their heat response and process suitability for insulation panel fabrication. The results show that the first four trials were unsuccessful due to limitations related to material behavior and experimental setup. In the initial trial, PET burned and adhered to the metal surface under direct charcoal heat, producing charred residues, which indicated that PET is



highly sensitive to uncontrolled thermal exposure. The second trial similarly failed because of unstable structural support and uneven heat distribution, leading to localized overheating. In the third trial, inconsistent charcoal intensity and excessive mold thickness caused uneven melting, with portions of the material remaining partially solid. The fourth trial was unsuccessful due to insufficient charcoal supply, which prevented complete melting and emphasized the need for adequate fuel preparation and sustained heat control.

Table 3. Melting process trials for PET plastics.

Trials	Description	Results
1	The setup utilized a corrugated roof cap as the upper platform, supported by uneven stones on both sides to create an open space for heat circulation. Charcoal was ignited underneath to simulate thermal exposure similar to real environmental heat conditions.	Failed
2	The second trial of the experiment aimed to assess the thermal resistance and melting behavior of recycled PET plastic under direct heat exposure.	Failed
3	The setup consisted of a metal mold placed above a charcoal bed, designed to ensure uniform melting to avoid the product being burned.	Failed
4	The fourth trial was conducted to continue testing the melting consistency of recycled plastic materials for insulation formation using a charcoal-based heating setup. The trial aimed to ensure complete melting across the entire surface by maintaining continuous heat exposure. The setup consisted of a metal tray covered with aluminum foil placed above burning charcoal, supported by stone bases to allow airflow and heat circulation.	Failed
5	After several adjustments from previous trials, this setup incorporated all the necessary improvements ensuring stable support, even heat distribution.	Success

The fifth trial achieved a successful outcome after incorporating improvements based on earlier failures, including stable structural support and more uniform heat distribution. Although further optimization was still required, this trial demonstrated clear progress and provided critical insights that guided the successful processing of other plastics, such as HDPE and PP, in subsequent experiments.

Table 4. HDPE and PP melting trials.

Trials	Description	Results
1	In this setup, two types of recycled plastic materials PP and HDPE were tested simultaneously within a single furnace to optimize time and resource utilization. Both materials were placed in separate molders, strategically arranged inside a furnace constructed from concrete hollow blocks.	Success

The final trial (table 4) demonstrated a successful and stable fabrication setup characterized by improved structural support, uniform heat circulation, and reduced charcoal consumption. Sealing the furnace with aluminum foil minimized heat loss and promoted even thermal distribution, preventing burning and uneven melting observed in earlier trials. Even charcoal placement ensured consistent heating, allowing both PP and HDPE to melt uniformly and form smooth, well-bonded layers without deformation. The use of hollow blocks provided structural integrity and operational stability. This trial confirmed that, through effective heat management and design optimization, recycled plastics can be reliably processed into sustainable ceiling insulation materials.

3.2. Degradation Behavior of Recycled Plastic

This sub-section discusses the degradation behavior of recycled plastics used in the study, focusing on their durability and resistance to natural environmental conditions. Evaluating degradation is essential in determining the long-term performance and reliability of recycled PP, PET, and HDPE when applied as insulation or construction materials, particularly in outdoor or semi-exposed environments. Natural weathering tests were therefore conducted to assess how prolonged exposure to sunlight, rainfall, and temperature variations affects the physical condition and structural integrity of the recycled plastics.

As illustrated in figure 1, the recycled plastic samples were exposed to natural outdoor conditions from January 14, 2025, to October 19, 2025, allowing continuous interaction with sunlight, rain, and fluctuating temperatures. After nine months of exposure, visual inspection showed that the samples remained structurally stable, with no observable signs of degradation such as discoloration, cracking, surface deformation, or material embrittlement. The figure

highlights the unchanged surface appearance and form of the PP, PET, and HDPE samples before and after exposure, demonstrating their ability to withstand environmental stressors.

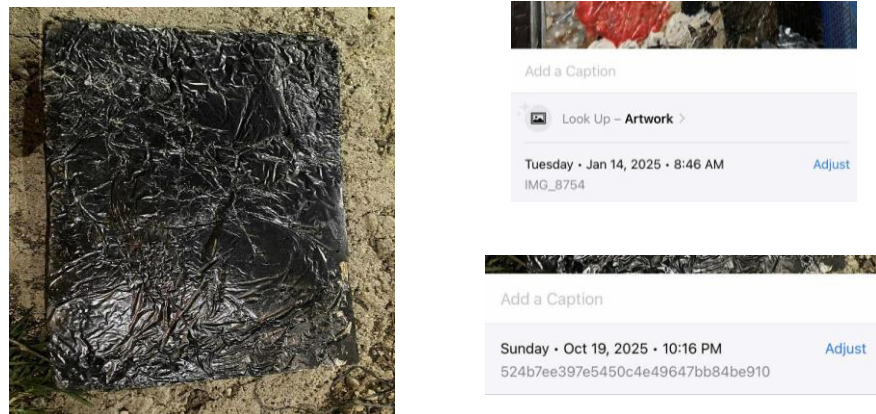


Figure 1. Examination of degradation behavior of CPI.

The absence of visible deterioration indicates strong resistance to ultraviolet (UV) radiation, moisture absorption, and thermal cycling. This performance can be attributed to the inherent chemical stability of polymer chains, which limits oxidation and photodegradation under normal outdoor conditions. The materials retained their mechanical integrity and surface quality throughout the exposure period, suggesting high durability and confirming their suitability for long-term outdoor and building insulation applications.

Table 5 summarizes the observed degradation behavior of recycled PET, HDPE, and PP after nine months of continuous outdoor exposure to natural weathering conditions, including sunlight, rainfall, and temperature fluctuations. For PET, no visible damage such as discoloration, cracking, or surface deformation was observed throughout the exposure period. This indicates that recycled PET exhibits a high level of resistance to environmental stress, particularly against UV radiation and moisture, making it suitable for long-term outdoor or semi-exposed applications.

Table 5. Degradation test results after nine months of outdoor exposure.

Material	Exposure duration	Visible damage	Interpretation
PET	9 months	None	Highly resistant
HDPE	9 months	None	No degradation
PP	9 months	None	Very stable

Similarly, HDPE showed no signs of degradation after nine months of exposure. The absence of visible damage suggests that HDPE maintained its structural integrity and surface quality despite prolonged contact with varying environmental conditions. This behavior confirms HDPE’s known resistance to moisture absorption and thermal stress, supporting its reliability as a durable material for insulation and construction-related uses. Among the materials tested, PP demonstrated the highest stability, with no observable physical changes after the full exposure period. The results indicate that PP is highly resistant to environmental aging, maintaining both its appearance and structural form.

Generally, the table confirms that all three recycled plastics PET, HDPE, and PP exhibit strong durability and resistance to natural degradation, reinforcing their potential for sustainable building applications where long-term environmental exposure is expected.

This result shows that PP, PET, and HDPE are highly durable and weather-resistant, making them reliable materials for insulation purposes. Their ability to resist sunlight, rain, and biological growth highlights their stability and long lifespan, even when recycled.

3.3. Pest and Mold Resistance

Here, we evaluate the resistance of CPI samples to biological and environmental factors that commonly affect building materials. Assessing pest and mold resistance is critical in determining the long-term performance, safety, and hygiene of insulation materials, particularly in humid and tropical climates where biological growth is prevalent. The experimental setups were designed to simulate extreme and realistic conditions that encourage

mold formation, pest activity, and moisture-related degradation, thereby providing a reliable basis for evaluating the CPI's durability and suitability for practical construction applications.

Figure 2 illustrates the three experimental setups used to evaluate the pest, mold, and moisture resistance of the CPI samples under simulated and real environmental conditions. The first setup, shown in the figure, utilizes banana peels placed inside a wooden-framed enclosure to create a humid and nutrient-rich environment that accelerates biological activity. This condition is intended to promote mold growth and attract pests, allowing for close observation of any surface changes, fungal formation, or material deterioration on the CPI samples.



Figure 2. Pest and mold testing of CPI.

The second setup in figure 2 demonstrates the immersion of CPI samples in a water-filled container to simulate prolonged exposure to damp conditions commonly encountered in poorly ventilated building spaces. This test evaluates the material's resistance to moisture absorption, swelling, softening, or structural weakening over time. The absence of visible degradation under this condition indicates that the CPI maintains its integrity even when subjected to continuous moisture.

The third setup presents the outdoor rainfall exposure, where CPI samples were placed in an open environment to experience natural weather conditions, including rain, temperature fluctuations, and environmental stress. This setup reflects real-world application scenarios and assesses the overall durability of the CPI when exposed to repeated wetting and drying cycles. Collectively, the conditions illustrated in figure 2 confirm the CPI's strong resistance to pests, mold formation, and moisture-related degradation, supporting its suitability for long-term use in building insulation systems.

Table 6 displays the environmental test setup and outcomes, indicating that none of the materials PET, HDPE, or PP showed mold growth or pest activity throughout the evaluation period. This table summarizes the results of the pest and mold resistance tests conducted on CPI samples made from PET, HDPE, and PP. Across all materials, no mold growth or pest activity was observed throughout the evaluation period, indicating consistent biological resistance under the applied test conditions.

Table 6. Pest and mold resistance assessment.

Material	Mold growth	Pest activity	Result
PET	None	None	Passed
HDPE	None	None	Passed
PP	None	None	Passed

For PET, the absence of mold and pests suggests strong resistance to moisture-related biological growth and confirms its stability under prolonged environmental exposure. HDPE similarly showed no biological activity, reflecting its low moisture absorption and non-porous surface, which limits conditions favorable for mold and pest infestation. PP also exhibited excellent performance, with intact surfaces and no visible degradation, reinforcing its high resistance to environmental and biological factors.

Moreover, the table demonstrates that all three recycled plastic materials successfully passed the biological resistance tests, supporting their suitability for long-term insulation applications, particularly in environments exposed to moisture, rainfall, and varying climatic conditions.

After several months of continuous rain and sun exposure, the panels showed no signs

of mold growth or pest infestation. Their surfaces remained intact and stable, demonstrating that the recycled plastic materials HDPE, PET, and PP are highly resistant to biological degradation and weather effects, making them suitable for long-term insulation use.

3.4. Thermal Performance of CPI

This sub-section evaluates the thermal performance of the CPI samples under peak heat conditions to determine their effectiveness in reducing heat transfer. Thermal performance is a critical parameter in insulation studies, as it directly influences indoor comfort, energy efficiency, and building thermal regulation. By examining the temperature response of the materials during periods of maximum solar exposure, the study aims to assess how well the CPI materials mitigate heat accumulation and withstand extreme thermal conditions commonly experienced in real-world building environments.

The thermal performance of the CPI samples was evaluated by measuring surface temperatures between 11:00 AM and 3:00 PM, a period corresponding to the peak solar radiation and ambient temperature of the day (figure 3). This interval was specifically chosen because it represents the worst-case thermal conditions that building surfaces typically experience. According to Hu et al. (2025), cumulative solar heating during the morning often leads to the highest outdoor and surface temperatures in the early afternoon. Similarly, some other findings (Xi et al., 2025) indicate that daily maximum temperatures generally occur between 12:00 PM and 3:00 PM. By conducting measurements within this timeframe, the study ensured that the collected data accurately reflects the maximum heat stress that indoor and outdoor surfaces could encounter.



Figure 3. Thermal performance for CPI.

During testing, the CPI samples were exposed to direct sunlight, and their surface temperatures were recorded to evaluate heat retention, absorption, and distribution. The data provide insights into the insulation efficiency of each material, showing how effectively they reduce heat transfer compared to non-insulated surfaces. High-performing materials maintain lower surface temperatures under the same conditions, indicating better thermal resistance and enhanced ability to protect indoor environments from excessive heat. Conversely, materials with higher surface temperatures absorb and transmit more heat, signaling lower insulation efficiency.

Table 7 presents the thermal performance of PET, HDPE, and PP when tested as CPI under peak heat exposure from 11:00 AM to 3:00 PM. As shown in the table, PP recorded the lowest surface temperature at 34.8°C, indicating the highest thermal efficiency among the three materials. where PP consistently demonstrated better heat resistance and more stable insulation behavior compared to PET and HDPE. The lower temperature reading suggests that PP effectively reduces heat transfer, making it the most suitable insulation material.

Table 7. Thermal performance comparison of PET, HDPE, and PP.

Plastic type	Surface temperature (°C)	Thermal efficiency rating	Interpretation
PET	39.7°C	Low	Absorbs and retains heat; poor insulation
HDPE	36.1°C	Moderate	Better insulation than PET
PP	34.8°C	High	Best insulation; most effective in reducing heat

The recorded surface temperatures of each material from 11:00 AM to 3:00 PM, highlighting PP as the most effective insulator based on its significantly lower temperature readings HDPE showed a moderate temperature of 36.1°C, which is significantly lower than

PET and indicates a fair level of insulation capability. This aligns with earlier experimental results, where HDPE melted uniformly and formed a stable panel structure, reinforcing its moderate thermal performance.

In contrast, PET recorded the highest surface temperature at 39.7°C, suggesting poor thermal efficiency. This is consistent with its behavior during production, where PET showed high sensitivity to heat, uneven melting, and a tendency to burn easily. The higher temperature reading confirms that PET is less effective at reducing heat and therefore provides minimal insulation benefit. Moreover, the data indicate that PP offers the best thermal insulation performance, followed by HDPE, whereas PET is the least effective. These findings reinforce PP's potential as the most competitive material for sustainable ceiling insulation applications compared to existing commercial products.

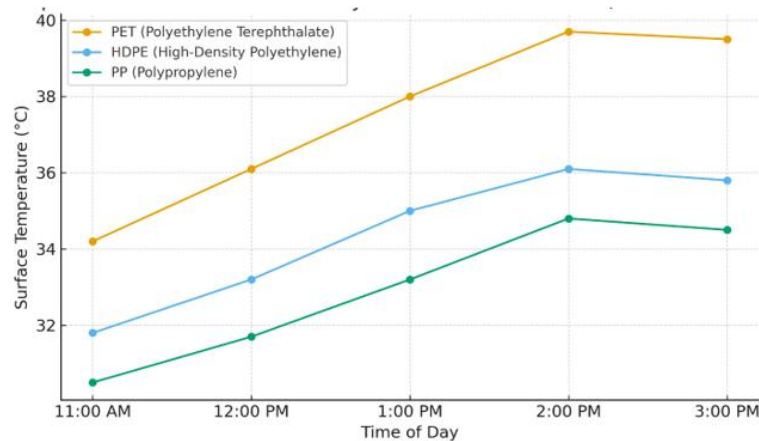


Figure 4. Thermal performance of recycled plastic insulators PET, HDPE, and PP.

The line chart (figure 4) represents the thermal performance of recycled plastic insulators PET, HDPE, and PP tested from 11:00AM to 3:00 PM, corresponding to the peak hours of solar radiation. During this period, the temperature of each material increased gradually as exposure time and solar intensity rise. PET exhibited the highest surface temperature (39.7°C), which can be attributed to its higher density and greater thermal conductivity. This allows PET to absorb and retain more heat that resulting higher recorded temperature. HDPE reached a moderate temperature of (36.1°C), reflecting its relatively lower thermal conductivity and improved insulation behavior compared to PET. In contrast, PP recorded the lowest surface temperature (34.8°C), indicating superior thermal insulation due to its lower thermal conductivity, therefore this suggests that PP provides the most effective thermal performance among the tested materials by minimizing heat transfer and maintaining cooler surface temperature under prolonged heat exposure.

3.5. Performance Testing with or without the Use of CPI

This section presents the evaluation of the practical performance of CPI in reducing indoor heat accumulation. Performance testing is essential to validate laboratory findings under simulated real-world conditions, providing tangible evidence of the material's effectiveness in thermal management. By comparing structures with and without the recycled plastic insulation, the study assesses how well the CPI mitigates heat transfer, improves indoor comfort, and demonstrates its potential application in energy-efficient building designs.

The performance testing of the CPI was conducted using a popsicle-stick prototype house to simulate a small-scale building and evaluate the practical effectiveness of the recycled plastic insulation in controlling indoor temperatures. This approach allows for a direct comparison between an uninsulated structure and one equipped with CPI under identical environmental conditions, providing a realistic measure of thermal performance.

During the peak heat hours between 11:00 AM and 3:00 PM, the uninsulated prototype reached a maximum internal temperature of 41°C, demonstrating that without insulation, the interior is highly susceptible to heat buildup due to direct solar exposure. In contrast, the prototype with recycled plastic insulation maintained a significantly lower internal temperature of 34.8°C, showing a temperature reduction of more than 6°C. This substantial difference highlights the insulation's ability to minimize heat transfer from the external environment into the interior, thereby reducing the impact of solar radiation and improving indoor thermal comfort.



Figure 5. Thermal performance testing.

The results (figure 5) indicate that the CPI materials made from recycled PET, HDPE, and PP are effective in enhancing insulation performance even under intense heat conditions. By keeping indoor temperatures lower, the CPI not only improves comfort but also has the potential to reduce energy consumption in buildings by decreasing the need for active cooling systems. This demonstrates the practical applicability of recycled plastic insulators in sustainable building design, especially in regions with high ambient temperatures.

3.6. The degree of acceptability of CPI in the dimensions of quality and willingness

This sub-section evaluates the overall acceptability of CPI materials based on key dimensions such as durability, reliability, performance, and user willingness to adopt the product. Assessing acceptability is essential to understand not only the technical effectiveness of the materials but also their potential adoption and preference among users. By combining quantitative scores with weighted calculations, the study provides a comprehensive measure of how each recycled plastic type PET, HDPE, and PP performs in terms of both quality and user acceptance, guiding decisions for practical application in insulation systems.

The weighted score computations (table 8) show that PP achieved the highest overall rating among the three materials, with a weighted score of 4.36 (87.2%). This was followed by HDPE with 4.11 (82.2%), while PET ranked lowest at 3.56 (71.2%). These results indicate that PP demonstrates superior durability, reliability, performance, and user willingness compared to PET and HDPE, making it the most effective and competitive option for insulation applications.

Table 8. The calculation of weighted mean.

Plastic type	Durability (Score × 0.30)	Reliability (Score × 0.30)	Performance (Score × 0.30)	Willingness (Score × 0.10)	Total weighted score	% of max (×20)
PET	$4.2 \times 0.30 = 1.26$	$3.4 \times 0.30 = 1.02$	$3.1 \times 0.30 = 0.93$	$3.5 \times 0.10 = 0.35$	3.56	71.2%
HDPE	$4.5 \times 0.30 = 1.35$	$4.0 \times 0.30 = 1.20$	$3.8 \times 0.30 = 1.14$	$4.2 \times 0.10 = 0.42$	4.11	82.2%
PP	$4.7 \times 0.30 = 1.41$	$4.3 \times 0.30 = 1.29$	$4.0 \times 0.30 = 1.20$	$4.6 \times 0.10 = 0.46$	4.36	87.2%

Table 9 presents the weighted mean scores of three recycled plastics PET, HDPE, and PP evaluated across durability, reliability, performance, and willingness to adopt. Scores were weighted at 30% each for durability, reliability, and performance, and 10% for willingness, resulting in an overall ranking of material competitiveness for ceiling insulation applications. Based on the experimental results, the recycled plastic that demonstrated the highest potential to compete with existing insulation products is PP. Among the materials tested, PP showed the most stable melting behavior, produced uniform and durable insulation panels, and recorded the lowest surface temperature during thermal performance testing. This indicates superior heat resistance and effective insulation capability. PP also showed strong resistance to weathering, mold growth, and pest activity during long-term exposure, confirming its durability in real environmental conditions. Survey responses supported these findings, with PP receiving the highest ratings in performance, reliability, and overall acceptability. These combined results show that PP is the most effective plastic for ceiling insulation and has the



strongest potential to compete with commercially available insulation materials.

Table 9. Weighted acceptability scores of PET, HDPE, and PP showing their effectiveness.

Plastic type	Durability	Reliability	Performance	Willingness	Weighted score	% of max (×20)	Rank
PET	4.2	3.4	3.1	3.5	3.56	71.2%	3
HDPE	4.5	4.0	3.8	4.2	4.11	82.2%	2
PP	4.7	4.3	4.0	4.6	4.36	87.2%	1

At the same time, table 10 presents the comparative acceptability scores of recycled plastic materials used as CPI. The ratings summarize respondents evaluations of material quality across key dimensions, including durability, reliability, performance, and user willingness to adopt CPI. It shows the degree of acceptability of the CPI across four major criteria: durability, reliability, performance, and willingness to adopt based on respondent evaluations. As reflected in the data, PP consistently received the highest ratings in all dimensions, indicating strong user confidence and alignment with the experimental findings. PP recorded the highest durability and highest overall acceptability, which support the material’s demonstrated resistance to degradation, pests, and mold during long-term exposure testing described in the study. Moreover, PP’s very good performance rating is consistent with thermal experiment results, where PP achieved the lowest temperature reading (34.8°C) compared to PET and HDPE, indicating superior insulation capability.

Table 10. Acceptability ratings of CPI and its overall acceptability.

Category	PET	HDPE	PP
Durability rating	Moderate	High	Highest
Reliability rating	Moderate	High	High
Performance rating	Fair	Good	Very good
Willingness to adapt CPI	Medium	High	Very high
Overall acceptability	Moderate	High	Highest

HDPE also showed strong acceptability, receiving high ratings in durability and reliability and performing better than PET in thermal performance and material stability. On the other hand, PET received only moderate to fair ratings, reflecting its limitations in practical use. This aligns with the results from the melting trials, where PET required multiple attempts due to heat sensitivity and uneven melting behavior. Therefore, the table demonstrates that PP is the most acceptable material for CPI applications, supported by both experimental performance and respondent preference, making it the best candidate to compete with existing insulation products.

3.7. Formatting of Mathematical Components

This section presents the application of Fourier’s Law of Heat Conduction to evaluate the thermal behavior of the recycled plastic insulation materials. The formula quantifies the rate of heat transfer through each material based on its thermal conductivity, surface area, temperature difference, and thickness. By computing the Q for PET, HDPE, and PP, the study interprets how effectively each material resists heat flow under identical thermal conditions. Lower values of Q indicate better insulation performance, as less heat is transmitted through the material.

Fundamental heat conduction include the following:

Q= Heat transfer rate (Q) (W)

K= thermal conductivity of the material

A= Cross-sectional area normal to heat flow (m²)

T₁- T₂= temperature difference across the material °C

D= thickness of the material (0.10)

T₁= 55°C (Typical roof temperature between 11:00am – 3:00PM)

Proposition 1. If a material has a lower thermal conductivity k, then its surface temperature under equal heat exposure will also be lower.

$$T_1 - T_2 = \Delta T$$

Taking this into consideration, table 11 shows temperature difference and thermal resistance of CPI materials.



Table 11. Temperature difference and thermal resistance of CPI materials.

Material	(T ₂) (°C)	(ΔT = 55 - T ₂)
PET	39.7	15.3°C
HDPE	36.1	18.9°C
PP	34.8	20.2°C

At the same time, Fourier’s Law of Heat Conduction provides a quantitative method to evaluate how much heat is transmitted through a material. The formula is expressed as:

$$Q = \frac{k A(T_1 - T_2)}{d}$$

Using this formula, the Q for each recycled plastic material was calculated to assess its insulation effectiveness. A lower Q value indicates that less heat passes through the material, demonstrating better insulation performance.

$$Q_{PET} = \frac{0.24(0.10)(15.3)}{0.01}$$

$$Q_{PET} = \frac{0.3672}{0.01} = 36.72 W$$

$$Q_{HDPE} = \frac{0.50(0.10)(18.9)}{0.01}$$

$$Q_{HDPE} = \frac{0.945}{0.01} = 94.5 W$$

$$Q_{PP} = \frac{0.22(0.10)(20.2)}{0.01}$$

$$Q_{PP} = \frac{0.4444}{0.01} = 44.44 W$$

From the equation above, $Q \propto k$. Reducing k decreases the heat flow through the material. Given identical environmental exposure, a lower heat flow results in cooler surface temperatures. This was confirmed experimentally: PP (lowest k) exhibited the lowest temperature (34.8°C), followed by HDPE and PET.

Table 12 presents the computed Q for recycled PET, HDPE, and PP materials using Fourier’s Law of Heat Conduction. The Q indicates how much energy passes through the material under a given temperature difference, with lower values representing better insulation performance.

Table 12. Heat transfer rates and insulation performance of CPI materials.

Material	Heat transfer (Q) (W)	Meaning
PET	36.72 W	Lower heat transfer due to lower ΔT (but weaker insulation because PET gets hottest)
HDPE	94.5 W	Highest heat transfer less efficient insulation
PP	44.44 W	Low heat transfer + lowest surface temperature best insulation performance

PET shows a Q of 36.72 W. Although this is relatively low, PET’s higher surface temperature observed in testing suggests that it absorbs more heat, resulting in slightly less



effective insulation compared to PP. This indicates that while PET slows down heat transfer to some extent, its thermal behavior under peak conditions is less favorable. HDPE exhibits the highest Q at 94.5 W, indicating that it allows more heat to pass through. This corresponds with its higher internal temperature in the prototype testing, reflecting less efficient insulation performance. And PP has a heat transfer rate of 44.44 W, which is low, and it also maintains the lowest surface temperature among the three materials. This combination demonstrates that PP provides the most effective insulation, minimizing heat flow while keeping the interior cooler.

4. Discussion

The findings of this study demonstrate the strong potential of recycled plastics particularly PP and HDPE as sustainable ceiling insulation materials, consistent with recent academic research on plastic-based building insulation. Across all experimental phases, PP consistently outperformed HDPE and PET in terms of thermal efficiency, melting stability, and environmental durability. The lowest recorded surface temperature for PP (34.8°C) indicates its superior resistance to heat transfer, a characteristic that aligns with the findings of Huang et al. (2023), who reported lower thermal conductivity values for PP-based insulation materials compared to conventional alternatives. Similar studies conducted in tropical and subtropical climates have emphasized the suitability of PP for reducing indoor heat gain due to its low thermal diffusivity and moisture resistance (Kim et al., 2023; Jung et al., 2023).

The durability results of this study further reinforce the reliability of recycled plastics for long-term building applications. After nine months of natural environmental exposure including prolonged sunlight, rainfall, and fluctuating humidity PET, HDPE, and PP exhibited no observable discoloration, deformation, or structural degradation. These findings are consistent with prior long-term exposure studies that reported high ultraviolet and moisture resistance in recycled polyolefin materials (Rikhter et al., 2022; Karali et al., 2024). In contrast, conventional insulation materials such as fiberglass and foam boards have been documented to experience moisture absorption, microbial growth, and mechanical degradation under similar conditions (Zhao et al., 2024). The absence of mold growth and pest infestation observed in this study also supports earlier research indicating that plastic-based insulators are biologically inert and well-suited for humid tropical environments (Vásárhelyi, 2023).

User acceptability results further corroborate the technical findings, with PP achieving the highest weighted score (87.2%) among respondents. This outcome aligns with recent studies emphasizing that material adoption in sustainable construction depends not only on performance but also on perceived durability, environmental benefits, and ease of installation (Ramos, 2023; United Nations, n.a.). Similar surveys conducted among homeowners and construction professionals have shown a growing preference for recycled materials when performance parity with traditional products is demonstrated (Jung et al., 2023; Kim et al., 2024). The convergence of experimental performance data and user perception in this study strengthens the argument that recycled plastic ceiling insulators satisfy both technical requirements and market expectations.

Despite these promising outcomes, several limitations were identified that are consistent with challenges reported in existing literature. Fabrication trials revealed uneven melting behavior in PET, variability in heat distribution, and operational inefficiencies associated with charcoal-based heating systems. Comparable issues have been documented in small-scale plastic recycling and molding studies, where non-industrial heating methods resulted in inconsistent material properties (Rikhter et al., 2022; Zhao et al., 2024). These findings highlight the need for standardized industrial-grade molding and controlled heating systems to improve production consistency, scalability, and material uniformity. Additionally, while the nine-month outdoor exposure period provided valuable insights, previous studies recommend longer-term evaluations spanning two to five years to comprehensively assess aging, thermal fatigue, and mechanical stability (Karali et al., 2024; Vásárhelyi, 2023).

Future research should therefore focus on enhancing PET performance through composite additives or fiber reinforcement, as suggested by Jung et al. (2023), as well as conducting full-scale residential installation trials to validate laboratory findings under real occupancy conditions. Comparative energy consumption analyses between recycled plastic ceiling insulators and commercially available insulation materials are also recommended to quantify potential energy savings and carbon emission reductions, as emphasized in recent



climate-focused building studies (Safieddine et al., 2025). By addressing these research gaps, future work can further strengthen the role of recycled plastic insulation in advancing sustainable, climate-resilient housing solutions.

5. Conclusions

This study concludes that recycled plastics specifically PP and HDPE are viable, durable, and efficient alternatives for ceiling insulation applications. PP exhibited the highest thermal performance, greatest resistance to weathering, and strongest user acceptability, making it the most competitive material among the three tested plastics. HDPE also demonstrated moderate to high performance, while PET showed limitations in both melting consistency and thermal behavior.

This study evaluated the recycled plastic materials PP, HDPE, and PET as ceiling insulation alternatives, with the objectives of assessing their thermal performance, durability under environmental exposure, and user acceptability. The results demonstrate that recycled plastics, particularly PP and HDPE, are viable, durable, and energy-efficient materials for ceiling insulation applications. Among the materials tested, PP consistently exhibited the highest thermal efficiency, lowest surface temperature, superior melting stability, and strongest resistance to weathering, thereby fulfilling the primary objective of identifying an optimal recycled plastic material for insulation use. HDPE also demonstrated moderate to high performance across all criteria, while PET showed limitations related to melting consistency and thermal behavior, indicating its comparatively lower suitability in the current form.

In relation to durability and environmental resistance, the study confirmed that all tested recycled plastic materials maintained structural integrity throughout nine months of outdoor exposure. The absence of visible degradation, mold formation, and pest infestation highlights the ability of recycled plastics to withstand environmental stressors commonly encountered in tropical climates. These findings support the second research objective by demonstrating the long-term reliability of CPI under real environmental conditions. Furthermore, user acceptability assessments revealed strong willingness to adopt CPI, particularly those made from PP, reflecting positive perceptions of performance, durability, and environmental benefits. This outcome satisfies the third research objective and indicates potential market readiness within the construction sector.

Despite these promising results, several limitations should be acknowledged. The fabrication process relied on small-scale, non-industrial equipment, which resulted in uneven melting and heat distribution, particularly for PET. Additionally, the outdoor exposure period was limited to nine months and did not capture long-term aging effects. These limitations suggest that the results should be interpreted within the scope of the experimental setup.

The findings of this study have important implications for sustainable construction and plastic waste management by demonstrating a practical pathway for recycling plastic waste into functional building materials. Future research should focus on optimizing fabrication techniques using industrial-grade equipment, evaluating long-term performance through multi-year field installations, and conducting comparative energy consumption analyses against commercial insulation products. Such investigations will further strengthen the applicability of recycled plastic insulation in environmentally responsible building practices.

Funding: This research received no external funding.

Acknowledgements: We acknowledge ourselves for hardwork, patience and dedication we put through in this study.

Conflicts of Interest: The authors declare no conflict of interest.

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