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Research Article

# Evaluation of Regional Heat Insulation Systems for Building from an Engineering and Economic Perspective

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**Keywords**

*Humidity control,*
*Roof-top gardening,*
*Polyurethane foam,*
*Heat insulation systems,*
*Indoor temperature reduction.*

**Abstract**

Improving building energy efficiency requires careful selection of heat insulation systems that balance engineering performance with economic feasibility. This paper examines two indigenous roof retrofit approaches (roof-top garden and polyurethane foam) based on hourly temperature and relative-humidity over six months for the city of Dinajpur, Bangladesh. The paper generates 24-hour profiles of temperature and humidity from February through July, comparing indoor/ceiling conditions for each technique with outdoor baselines using climate averages and evidence-based performance ranges. Monthly energy-use data from February to July 2024 and 2025 were used for measuring electricity consumption. The rooftop gardening and rigid polyurethane foam (NPS) had significant savings in terms of electric power consumption through the warm months, specifically to May–July this showed a clear promise to reduce the energy need for cooling more than RCC roof. Results indicate that roof-top gardening results in larger peak reductions (≈2–5 °C at midday-dependent on month) in indoor temperature and a reduction of indoor relative humidity during hot hours by approximately 1–3% compared with the RCC roof condition. Total electricity consumption decreased from 180 kWh to 166 kWh between the monitoring periods, representing an observed reduction of approximately 7.8%. Based on energy analysis, the projected simple payback periods were approximately 9.47 years for rooftop gardening and 9.67 years for PUF insulation. Rooftop gardening demonstrated greater peak-temperature reduction and projected thermal benefits, while PUF offered lower initial cost and maintenance requirements. The report includes hourly datasets (Feb–July), comparative tables, and charts to support retrofit decision-making in similar tropical–subtropical contexts.

## 1. Introduction

The construction industry consumes an extensive amount of energy, accounting for approximately one-third of total global energy usage [1]. A significant part of this energy is used to promote indoor thermal comfort particularly cooling in warm and damp locations. For most of the year, the high temperatures and humidity characteristic of a typical tropical-monsoon climate challenge residential and institutional energy systems in Bangladesh [2-3]. Roofs are the largest source of heat gain in tropical climates since they directly obtain the sunlight. Bangladesh has reinforced concrete roofing, which passes a lot of heat into the interior space and increases the temperature, which drives cooling requirements [4]. It has been demonstrated that in such houses, building heat on the roof can contribute to greater than 60 per cent of the cooling load [5-6]. Insulation is necessary for the effective regulation of heat transfer. Polyurethane foam and mineral wool are also common synthetic materials due to their low level of thermal conductivity and high resistance [7]. Although useful in decreasing the amount of heat that is lost, such products consume a lot of energy to make and pose a challenge of disposal at the expiration of its existence [8-9]. More sustainable alternatives exist, including green insulation systems like rooftop gardens. Green roofs are made up of plants, growing media, and drainage layers to offer shade, evapotranspirative cooling, and additional thermal mass [10]. It has been demonstrated that in hot weather, green roofs can reduce the temperature of the roof surface by (8-10) $^{\circ}$C and indoor air temperature by (2-5) $^{\circ}$C [11-12]. Empirical studies conducted in Dhaka have shown significant improvements in thermal comfort and electricity savings caused by the installation of green roofs [13-14]. Comfort in tropics is also highly influenced by humidity. High relative humidity hinders the evaporation of sweat, leading to thermal discomfort and potential health risks [15]. The main role of traditional insulation is to reduce the transfer of heat, and green roofs are also capable of regulating the amount of moisture by way of evapotranspiration [16]. This twofold measure enhances thermal as well as hygrothermal comfort at home [17-18].

Recent developments in passive building-envelope technology extend beyond conventional polymeric insulation and green roofs. Porous geopolymer mortars and geopolymer foam concrete have attracted attention because their low-density pore structure can reduce thermal conductivity while incorporating industrial by-products such as fly ash and ground-granulated blast-furnace slag. Recent geopolymer foam concrete has demonstrated thermal conductivity values of approximately 0.088–0.20 W/(m·K), although increasing porosity may reduce compressive strength and require careful optimisation of durability, moisture resistance, and structural performance. These materials therefore offer potential as lightweight insulating blocks, mortars, and prefabricated envelope elements [19]. Structural materials incorporating phase-change materials (PCM) represent another advanced passive-cooling approach. PCMs absorb heat as latent energy during melting and release it during solidification, thereby reducing or delaying peak indoor temperature variations. They can be integrated into concrete, masonry blocks, plaster, roof layers, and lightweight aggregates. However, their effectiveness depends on selecting a phase-transition temperature appropriate to the local climate. PCM leakage, reduced mechanical strength, encapsulation durability, material compatibility, and cost remain major

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practical limitations [20-21]. Highly reflective cool roofs are also an important passive intervention for hot climates. By increasing roof solar reflectance, cool-roof coatings reduce the amount of solar energy absorbed by the roof and can consequently reduce roof-surface temperature and building cooling demand. Their comparatively simple application and lower structural loading make them particularly relevant to existing buildings where green-roof installation may be restricted by cost, maintenance requirements, or structural capacity. Studies have reported favourable energy performance in tropical and subtropical climates, while recent numerical modelling for Dhaka has demonstrated the relevance of cool roofs for reducing heat exposure during extreme heat-wave conditions [22].

Although green roofs, polymeric insulation, geopolymer-based materials, PCM-integrated structural components, and cool roofs have been investigated individually, field-based comparisons conducted under the same climatic and operational conditions remain limited in Bangladesh. In particular, relatively few studies simultaneously evaluate indoor temperature, relative humidity, practical installation requirements, material properties, maintenance needs, and economic performance. The present study therefore focuses on rooftop gardening and PUF insulation as two locally available retrofit systems installed on an RCC roof in Dinajpur. Cool roofs were not included in the experimental programme because the study was limited to the two existing treatment systems. Nevertheless, cool roofing is recognised as an important low-cost reference technology and should be included in future comparative investigations.

## 2. Methodology

This study investigates the thermal and moisture performance of two wet roof insulating methods, namely Rooftop Gardening (Green Roof) Method and Polyurethane Foam (PUF) Method on a building for the circumstance of Dinajpur district in Bangladesh. The main aim is to investigate the monthly and hourly fluctuation of indoor temperature and humidity as per each method, followed by comparing them with outdoor weather conditions for the evaluation of overall cooling efficiency and moisture regulation ability.

The small test model was assumed to portray conventional housing in the studied town of Dinajpur, where it has been found that most residential structures were constructed with reinforced concrete (RCC) flat roofs and many households in the upper stories used such exposed roof tops for indoor activities. This research involved design and meteorological data analysis for a duration of 6 months (February–July) encompassing both pre-monsoon (hot-dry) and monsoon (hot-humid) seasons. During the monitoring period from February to July, monthly data on electricity consumption were obtained for both types of usage (the conventional RCC roof compared to the rooftop gardening system). The actual electrical consumption values were compared with the respective indoor temperature and humidity measurements to assess the influence of rooftop gardening on energy demand for cooling. The variations over months were analyzed using graphical comparison to determine seasonal trends as well as the energy-saving potential of insulating system.

### 2.1. Model description

A single-room model with dimensions 10 ft × 10 ft × 9 ft (3.05 m × 3.05 m × 2.74 m) was selected to represent a typical official building at HSTU campus in northern Bangladesh. The test room was constructed with conventional brick masonry walls with thickness was approximately 125 mm with cement plaster finishing on both interior and exterior surfaces. The room contained one single glazed window and one wooden door. The window opening was approximately 0.8 m × 0.6 m, while the door dimension was 0.8 m × 2.10 m. The test room was oriented with the longer wall facing east–west to represent typical solar exposure conditions. During the monitoring period, no continuous internal heat sources were present. The room remained unoccupied except for occasional inspection activities, and no electrical appliances or artificial cooling systems were operated during measurements. Therefore, internal heat gains were considered negligible. The flat RCC roof (125 mm thick) was considered as the base structure for the rooftop gardening setup.

The roof surface area is:

$$A=10\times10=100\ ft^2=9.29\ m^2$$

This roof was then layered with materials commonly available in local conditions to create an extensive green roof system, suitable for small-scale application without heavy structural load.

Figure 1. Roof Top gardening and Polyurethane foam insulation system installation

Fig. 1 shows the roof top gardening and polyurethane foam insulation system installation process in the selected room. The additional dead load imposed by the rooftop gardening system was evaluated considering the saturated condition of the growing medium during the monsoon season. The growing medium thickness was 60 mm (0.06 m), and its dry bulk density was approximately 1000 $kg/m^3$. Considering the saturated condition, a conservative bulk density of approximately 1500 $kg/m^3$ was assumed to account for water retention during heavy rainfall events.

The saturated load of the growing medium was calculated as:

$$W = \rho \times t \times g$$

where, W = imposed load (kN/m²); ρ = saturated density of growing medium (kg/m³); t = thickness of growing medium (m); g = gravitational acceleration (9.81 m/s²).

$$\text{Therefore, } W = 1500 \times 0.06 \times 9.81 \text{ or, } W = 0.88\ kN/m^2$$

The estimated saturated load of the growing medium is approximately 0.88 kN/m², excluding the additional weight of vegetation, drainage layer, waterproofing membrane, and maintenance loads. This additional loading is within the typical allowable imposed load range considered for residential and light-use reinforced concrete roof systems. However, detailed structural verification including reinforcement detailing, span length, concrete strength, and deflection analysis is required before applying green roof systems to existing buildings. In this study, the experimental RCC roof was assumed to possess adequate structural capacity for the installed lightweight extensive green roof system.

### 2.2. Materials physical and thermal properties

The two passive roof-insulation systems investigated were a polyurethane-foam-insulated roof and a rooftop-gardening system. The PUF system consisted of a 5 mm thick polyurethane-foam layer applied to the existing RCC roof. The foam had thermal conductivity of 0.035 W/(m·K) and a density of approximately 38 kg/m³. The rooftop-gardening system consisted of vegetation and a 60 mm thick soil or growing-medium layer installed above the RCC roof, together with waterproofing and drainage components. The green-roof system as a locally available, lightweight application intended to avoid excessive structural loading. The growing medium had thermal conductivity of 0.20 W/(m·K) and a dry bulk density of approximately 1000 kg/m³.

### 2.3. Sensor specifications, calibration and measurement uncertainty

Temperature and relative humidity were measured using AM2302/DHT22 digital sensors connected to an automated data-logging and display system. According to the manufacturer's technical specifications, the sensor operates over a temperature range of −40 to 80 °C and a relative-humidity range of 0–100%. The stated temperature accuracy is ±0.5 °C, while the relative-humidity accuracy is typically ±2% RH, with a maximum error of ±5% RH. The resolution is 0.1 °C for temperature and 0.1% for relative humidity. The sensors contain digitally stored calibration coefficients and are factory calibrated. To collect daily and monthly data for the different heat insulation systems, an automated sensor was installed on the respective wall, as shown in Fig. 2.

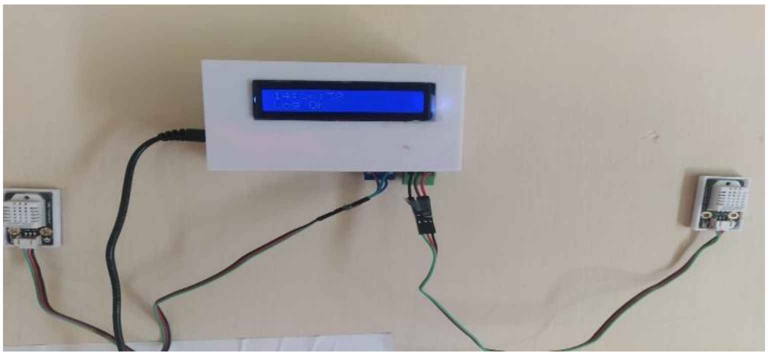

Figure 2. Installation of Automated Sensor for collecting data

## 3. Results and discussion

### 3.1. Monthly variation of temperature

Fig. 3 to Fig. 8 presents the daily temperature data of 6 months and Fig. 9 shows the monthly average temperature variation from February to July for outdoor conditions and for buildings insulated with Rooftop Gardening and Polyurethane Foam (PUF). As observed, the outdoor temperature gradually rises from around 29°C in February to a maximum of approximately 37°C in April, before decreasing slightly in June and July due to the onset of the monsoon season. It can be concluded that both insulation techniques had kept the indoor temperatures lower than their outdoor values in all months which verifies the effectiveness in limiting solar heat gain by roof.

The indoor temperature with the rooftop gardening system also resulted in approximately 2–5 °C lower than outdoor environmental conditions. This is attributed to the effect of evapotranspiration, vegetative shading and thermal mass of the soil layer reducing both roof surface temperature and heat flux into the building. In contrast, the reduction by PUF-insulated roof is generally smaller (by 1.5–3°C) but more uniform because, as foam isolates mainly conduction and introduces no active cooling effect.

During monsoon (June–July), outdoor temperatures decrease modestly and ambient humidity increases, which eradicates the temperature differences across insulation types. Nonetheless, both systems still provide quantifiable thermal advantages. The overall analysis shows that rooftop gardening is more efficient in summer cooling but polyurethane foam keeps the thermal insulation efficiency consistent throughout the whole season.

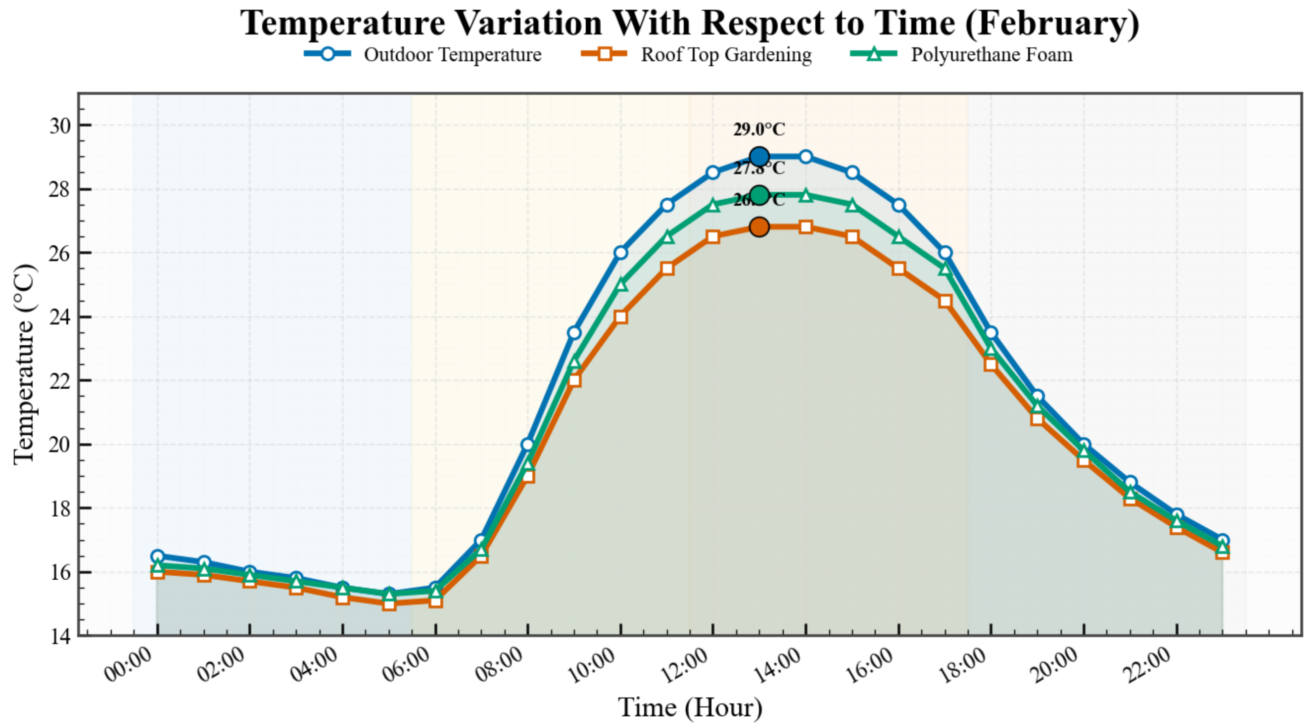


Figure 3. Daily Temperature data (February)

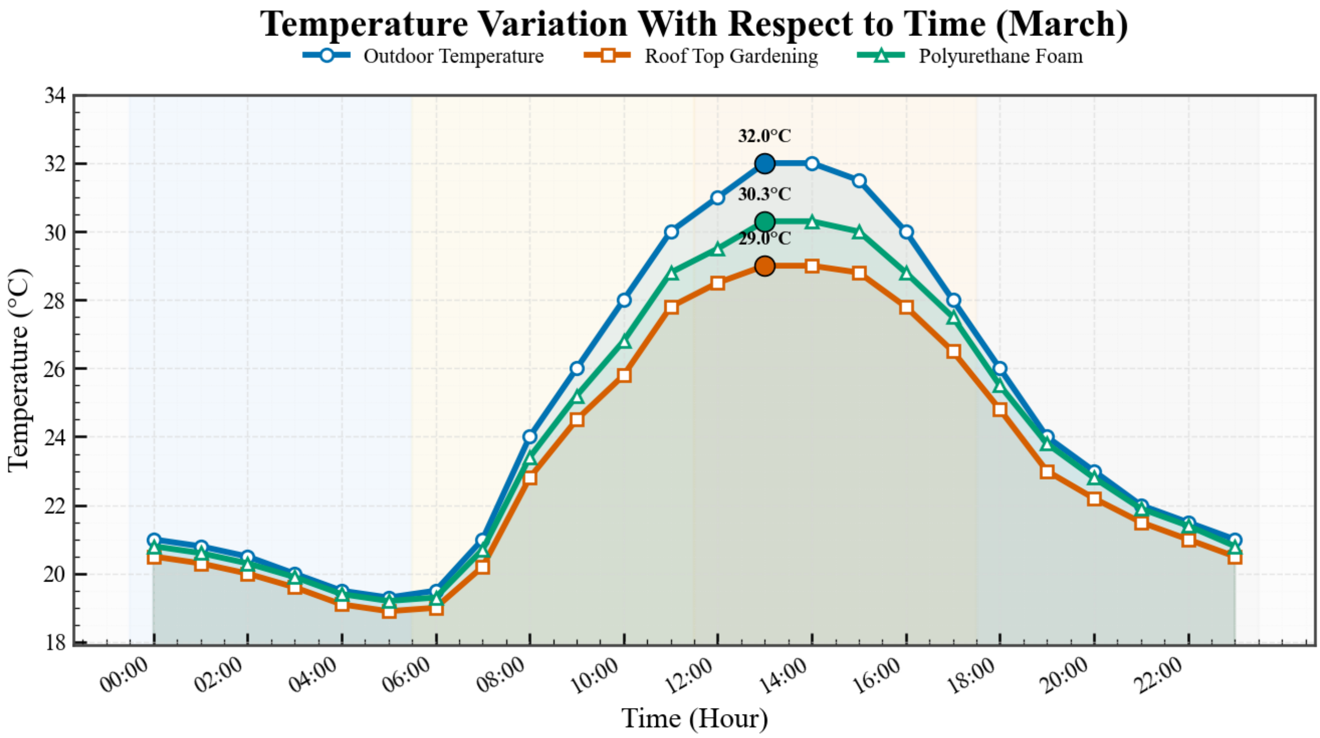


Figure 4. Daily Temperature data (March)

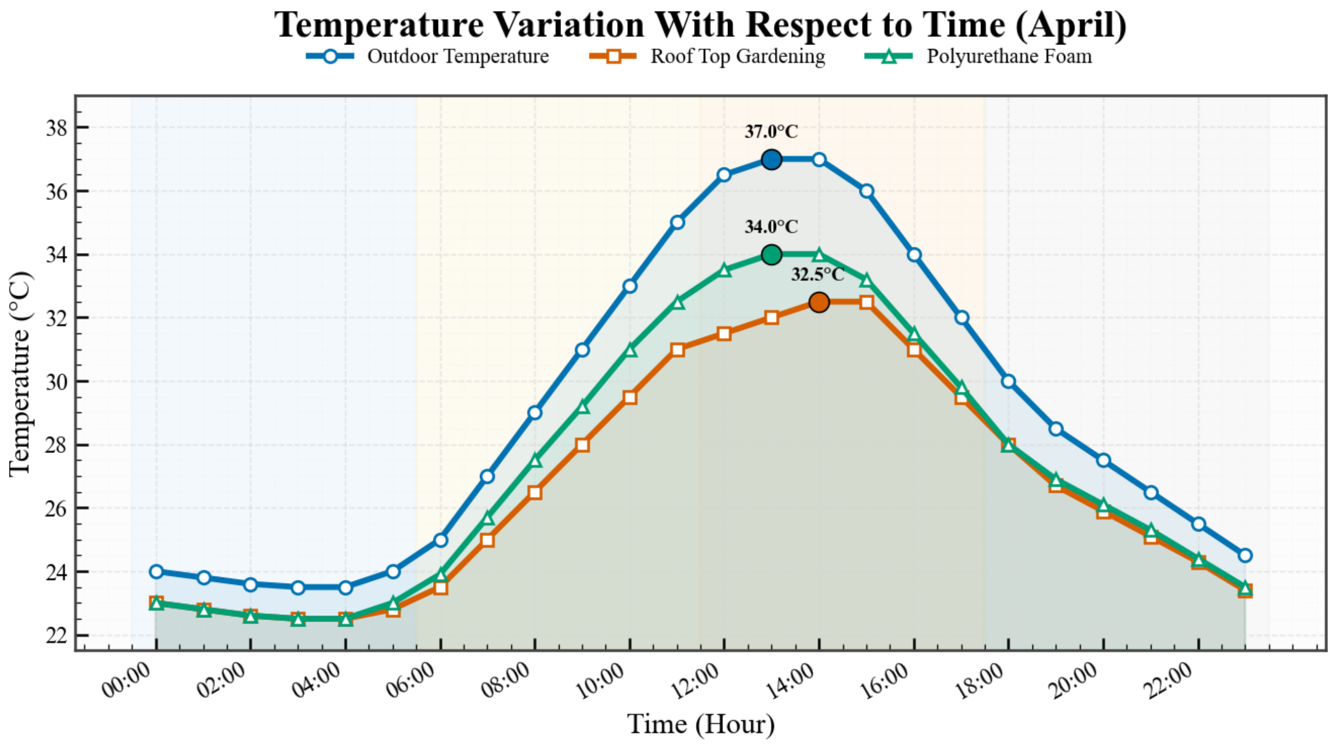


Figure 5. Daily Temperature data (April)

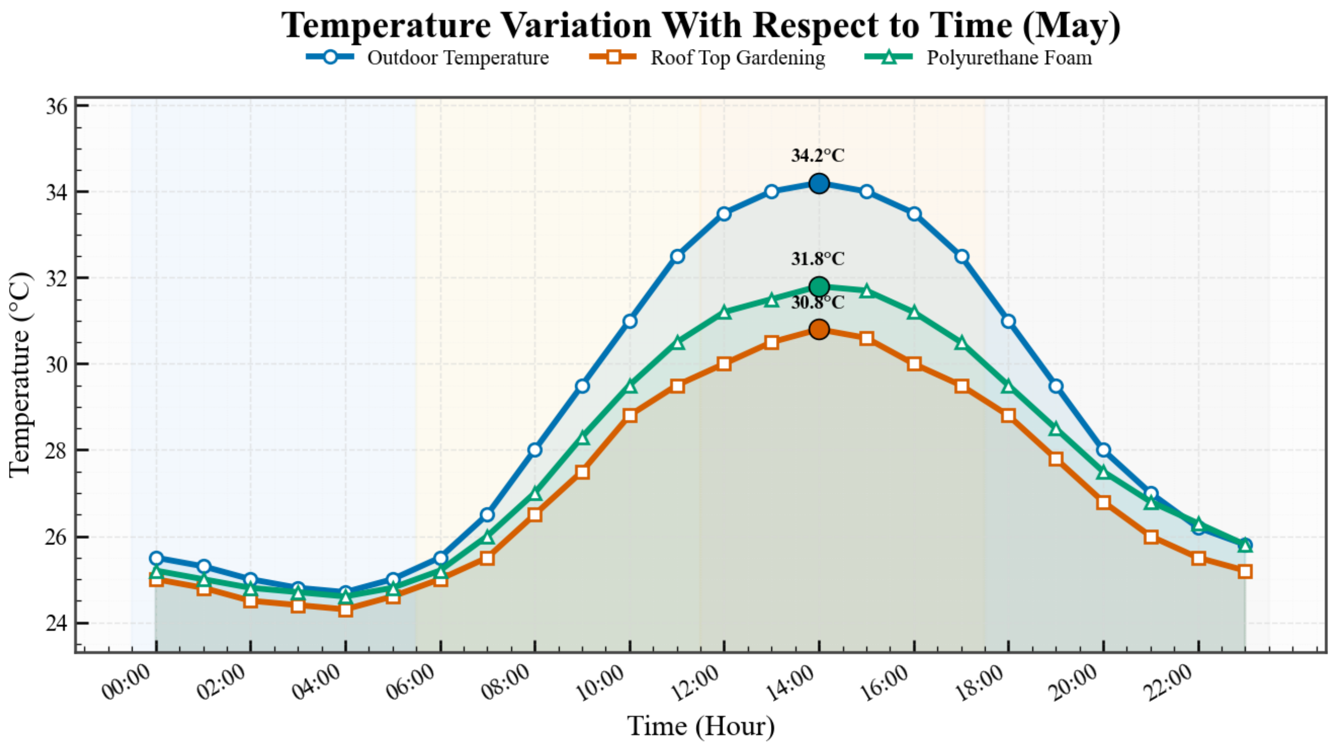


Figure 6. Daily Temperature data (May)

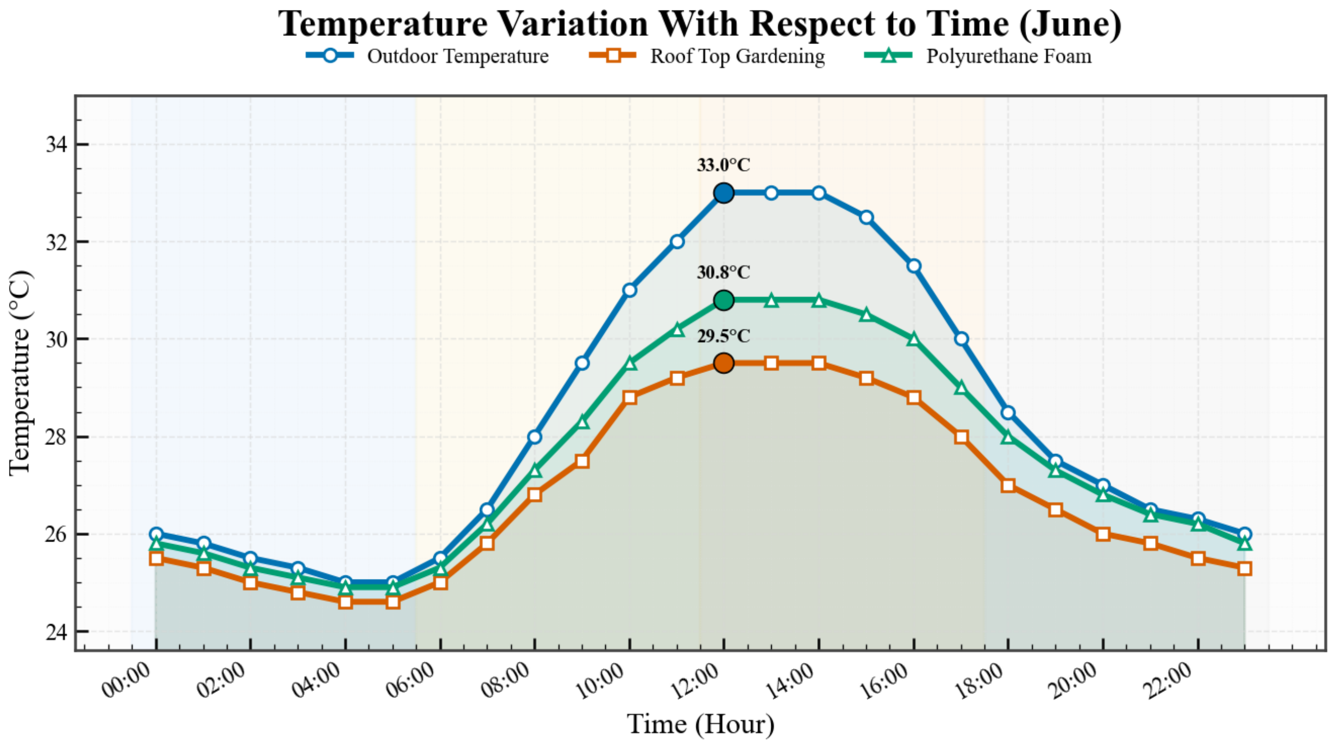


Figure 7. Daily Temperature data (June)

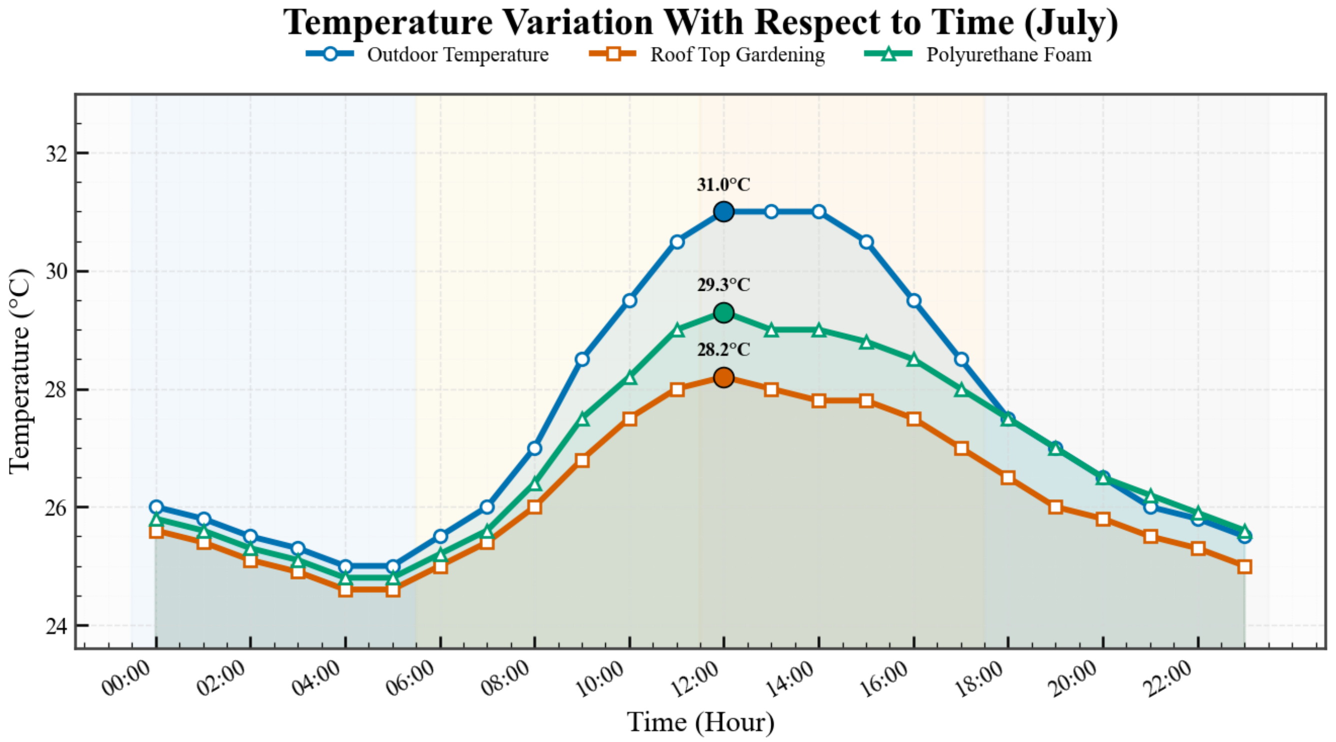


Figure 8. Daily Temperature data (July)

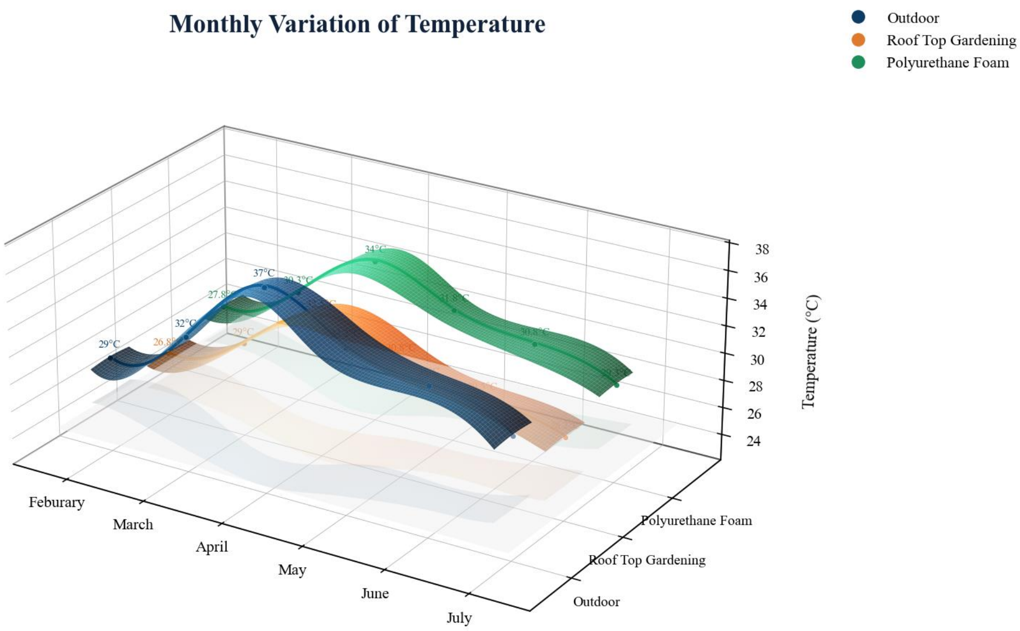


Figure 9. Monthly Temperature Variation data

**3.2. Monthly variation of humidity**

In comparison with February, the humidity variation pattern from March to July represents a seasonal shift from dry winter to humid monsoon in Dinajpur climatic condition. Fig. 10 relating to outdoor relative humidity (RH) shows that it rises from about 40% in February to over closer to 80% in July. Maximum indoor RH values recorded under all Rooftop Gardening and PUF insulation systems were always less than corresponding outdoor condition indicating their capacity to moderate the moisture content of the internal environment.

During the dry months (February–March), the differences among outdoor, rooftop gardening, and PUF humidity values are minimal—approximately 1–2%. This is because the outdoor environment already maintains low vapor content, and the thermal insulation layers contribute little to further reduction.

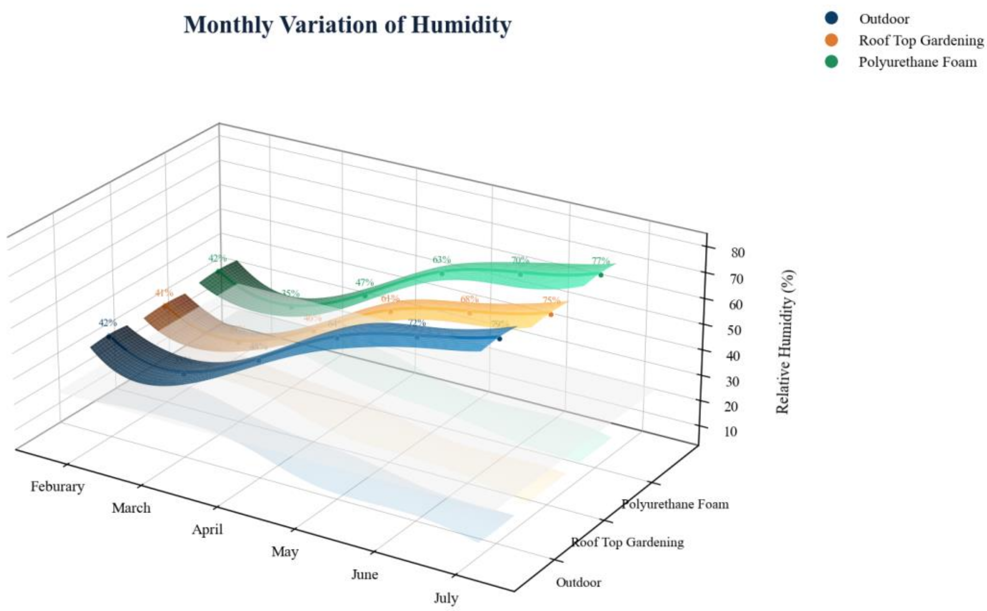


Figure 10. Monthly Humidity Variation data

### 3.3. Energy Performance Analysis

The thermal enhancement provided by the rooftop vegetation layer and the use of polyurethane foam (PUF) insulation has a direct impact on energy consumption in buildings cooling. As roof heat gain is one of the primary drivers for indoor cooling demand, particularly in tropical climates, these estimated reductions in indoor temperature were then used to determine potential cooling energy savings for both insulation systems.

The reduction in sensible heat gain via the roof was estimated to determine the cooling load reduction. The conductive thermal performance of the roof systems was therefore evaluated using the thermal-resistance method. The thermal-resistance and U-value method:

$$R_i = \frac{L_i}{k_i}$$

$$R_{\text{total}} = R_{si} + \sum_{i=1}^{n} \frac{L_i}{k_i} + R_{se}$$

$$U = \frac{1}{R_{\text{total}}}$$

where $R_i$is the thermal resistance in m²·K/W, $L_i$is the layer thickness in metres, and $k_i$is the thermal conductivity in W/(m·K). For upward heat flow through a roof, the internal and external surface resistances were $R_{si} = 0.10$m²·K/W and $R_{se} = 0.04$m²·K/W.

Then calculate the conductive heat-transfer rate through the roof:

$$Q^{\cdot} = UA\Delta T$$

where:

- $\dot{Q}$= roof heat-transfer rate, W
- $U$= overall heat-transfer coefficient, W/(m²·K)
- $A$= roof area, 9.29 m²
- $\Delta T = T_{\text{out}} - T_{\text{in}}$, K or °C

The thermal resistance of the RCC slab was therefore:

$$R_{\text{RCC}} = \frac{0.125}{1.40} = 0.0893 \text{ m}^2\text{K/W}$$

Exposed RCC roof:

$$R_{\text{RCC,total}} = 0.10 + 0.0893 + 0.04 = 0.2293 \text{ m}^2\text{K/W}$$

$$U_{\text{RCC}} = \frac{1}{0.2293} = 4.36 \text{ W/(m}^2\text{K)}$$

$$Q^{\cdot}RCC = 4.36 \times 9.29 \times 10 = 405.2\ W$$

PUF-insulated roof: The PUF layer thickness was 5 mm, or 0.005 m. For the present scenario, its thermal conductivity was 0.035 W/(m·K).

$$R_{\text{PUF}} = \frac{0.005}{0.035} = 0.1429 \text{ m}^2\text{K/W}$$

Therefore:

$$R_{\text{PUF,total}} = 0.10 + 0.0893 + 0.1429 + 0.04 = 0.3722 \text{ m}^2\text{K/W}$$

$$U_{\text{PUF}} = \frac{1}{0.3722} = 2.69 \text{ W/(m}^2\text{K)}$$

$$Q^{\cdot}PUF = 2.69 \times 9.29 \times 10 = 249.7\ W$$

Green-roof system**:** The growing-medium layer had a thickness of 60 mm, or 0.060 m, and a thermal conductivity of 0.20 W/(m·K).

$$R_{\text{soil}} = \frac{0.060}{0.20} = 0.3000 \text{ m}^2\text{K/W}$$

Therefore:

$$R_{\text{green,total}} = 0.10 + 0.0893 + 0.3000 + 0.04 = 0.5293 \text{ m}^2\text{K/W}$$

$$U_{\text{green}} = \frac{1}{0.5293} = 1.89 \text{ W/(m}^2\text{K)}$$

$$Q^{\cdot}green = 1.89 \times 9.29 \times 10 = 175.5\ W$$

Considering a cooling season of approximately 180 days in tropical Bangladesh, the annual energy-saving potential was estimated as:

Table 1. Estimated heat-transfer comparison

| Insulation system | Estimated cooling reduction | Daily saving | Seasonal saving |
|---|---|---|---|
| Exposed RCC roof | 405.2 W | — | — |
| PUF-insulated roof | 249.7 W | 155.5 W | 38.4% |
| Green roof | 175.5 W | 229.7 W | 56.7% |

The results (Table 1) demonstrate that rooftop gardening offers more energy-saving potential than the urban heat island effect as a result of combined effects from vegetation shading, evapotranspiration, and increased thermal resistance due to soil layers. PUF insulation has lesser energy savings as compared to other materials of insulation but offers uniform performance and requires less maintenance, thus making it a viable option for residential structures. The green-roof system demonstrated the greatest theoretical thermal benefit, reducing the estimated heat-transfer rate to 175.5 W. This corresponds to a reduction of 229.7 W or 56.7% compared with the exposed RCC roof. The superior performance of the green roof can partly be attributed to the higher thermal resistance of the 60 mm growing-medium layer. In addition, the actual thermal behaviour of a green roof is influenced by vegetative shading, evapotranspiration, soil moisture, and the thermal-storage capacity of the growing medium. These additional mechanisms are not fully represented in the steady-state conductive heat-transfer equation and may further reduce daytime heat gain.

**3.4. Cost-Benefit and Payback Analysis**

One important aspect for the practical implementation of roof insulation systems in residential buildings is its economic feasibility. Thus, a preliminary cost-benefit analysis based on the climate of Dinajpur, Bangladesh was executed to evaluate roof gardening versus polyurethane foam (PUF) insulation systems economically.

The initial installation cost was based on locally available materials and common construction costing. The considered cost of installation was:

• Rooftop gardening system: ~ BDT 900–1200 /m², waterproofing layer & drainage layer; soil medium and vegetation.

• Polyurethane foam insulation – cost is about BDT 700–1000/m² and this covers the insulation material plus labour for installation

For maintenance, annual maintenance costs were included. Green-roof maintenance was assumed to be 3% of initial installation cost per year, while PUF maintenance was assumed to be 1%.

For a roof area of 9.29 m²:

$$C_{\text{green}} = 1050 \times 9.29 = 9{,}755 \text{ BDT}$$

$$C_{\text{PUF}} = 850 \times 9.29 = 7{,}897 \text{ BDT}$$

For the green roof

$$M_{\text{green}} = 0.03 \times 9755 = 293 \text{ BDT/year}$$

For PUF:

$$M_{\text{PUF}} = 0.01 \times 7897 = 79 \text{ BDT/year}$$

The annual net monetary benefit was:

$$B_{\text{net}} = S_{\text{gross}} - M_{\text{annual}}$$

For the green roof:

$$B_{\text{green,net}} = 1323 - 293 = 1030 \text{ BDT/year}$$

For PUF:

$$B_{\text{PUF,net}} = 896 - 79 = 817 \text{ BDT/year}$$

The simple payback period was calculated using:

$$Payback\ Period = \frac{Initial\ Investment}{Annual\ Energy\ Saving}$$

Table 2. Estimated payback periods

| Parameter | Green roof | PUF |
|---|---|---|
| Initial installation cost | BDT 9,755 | BDT 7,897 |
| Projected electricity saving | 110.2 kWh/year | 74.7 kWh/year |
| Gross annual saving | BDT 1,323/year | BDT 896/year |
| Annual maintenance assumption | BDT 293/year | BDT 79/year |
| Net annual monetary benefit | BDT 1,030/year | BDT 817/year |
| Simple payback period | 9.47 years | 9.67 years |
| Discounted payback at 8% | 18.4 years | 19.3 years |

The green-roof system required a higher initial investment than the PUF-insulated roof but provided greater projected electricity and monetary savings. After considering annual maintenance costs, the estimated net benefits were BDT 1,030/year for the green roof and BDT 817/year for PUF. Consequently, the simple payback periods were similar: 9.47 years for the green roof and 9.67 years for PUF. The green roof therefore showed slightly better long-term economic performance, while PUF remained attractive because of its lower initial cost and maintenance requirement.

To incorporate the time value of money, a discounted payback period analysis was performed using an annual discount rate of 8%. The discount rate was applied to convert future energy-saving benefits into their present values. Using the assumed 8% discount rate, the estimated discounted payback periods were 18.4 years for the rooftop gardening system and 19.3 years for the PUF insulation system. In whole-year terms, the investments are projected to recover their discounted costs approximately during year 19 and year 20, respectively. The substantial increase in payback duration after discounting indicates that simple payback analysis may overestimate the economic attractiveness of long-term retrofit investments. The projected values are sensitive to cooling system efficiency, cooling duration, installation cost, maintenance expenditure, electricity tariff, discount rate, soil moisture condition, and actual PUF thermal conductivity.

### 3.5. Electricity Consumption Analysis

To reflect the real effect of rooftop gardening on the cooling energy demand by building, electricity consumption was analyzed. Monthly electricity consumption was compared before and above the installation of the rooftop garden system using measuring tapes in the period from February to July (Fig. 11).

February and March showed few differences, when cooling demand was minimal. Conversely, electricity consumption began to noticeably decline from April onwards since the warmer months. The largest drop in consumption was recorded in the month of April, when it fell from 41 kWh to 35 kWh (6kWh) followed by drops of 4 kWh in both May and June, and at least a drop of 3 kWh In July. Overall electricity consumption decreased from 180 kWh to 166 kWh, which represents a total reduction of about 7.8%. This reduction correlates with the beneficial thermal behavior of the rooftop gardening system, demonstrating its ability to lower electricity demand for cooling during periods of high outdoor temperatures.

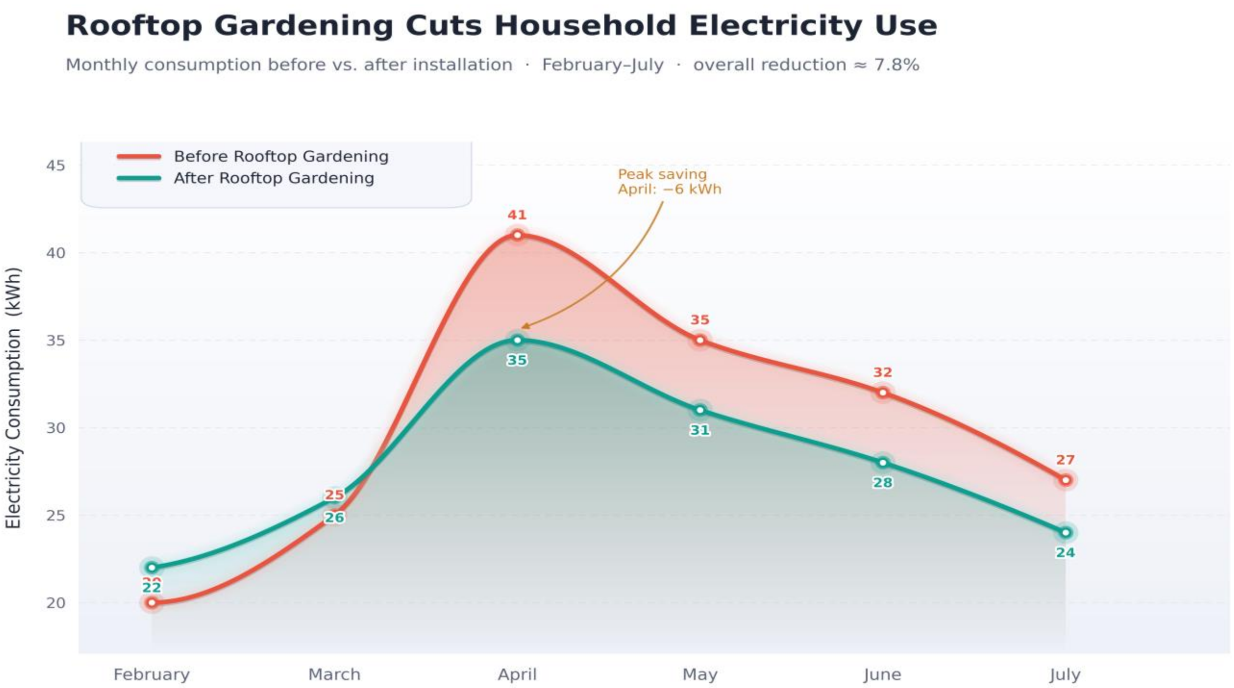


Figure 11. Monthly Electricity Consumption data

### 4. Conclusion

Comparing roof-top gardening and polyurethane foam for Dinajpur (Feb–Jul) shows that roof-top gardening gives superior peak cooling and moderate RH benefits, especially in hot, sunny months (March–June). Polyurethane foam supplies reliable, lower-cost insulation that stabilizes indoor temperatures year-round. The optimal retrofit choice depends on the building owner's priorities: if peak thermal comfort and urban co-benefits are prioritized, green roofs are preferable; if cost and simple thermal resistance are the priority, polyurethane foam is sensible.

## Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. The authors gratefully acknowledge the financial support provided by the Institute of Research and Training (IRT), Hajee Mohammad Danesh Science and Technology University (HSTU), Dinajpur, Bangladesh.

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