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RESEARCH ARTICLE

Enhancing thermal properties of eco-bricks through integration of post-consumer plastic waste: a sustainable construction approach

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Abstract

The rapid increase in plastic waste generation from industrial activities poses significant environmental impacts due to non-biodegradable nature of plastics. This research investigates the ability of utilizing post-consumer polyethylene terephthalate (PCPET) waste as a partial replacement for sand in sustainable construction materials. In specific, the research concentrates on enhancing thermal properties of eco-brick by exploiting low thermal conductivity. Thereby this research aims to improve sustainability of alternative building materials, evaluated through Life Cycle Assessment (LCA) and thermal comfort analysis. LCA calculations for eco-brick production utilized data from the Ecoinvent 3.9.1 database, with lifecycle modeling executed in OpenLCA software. The results highlight that eco-bricks with 1:2 ratio of washed polyethylene terephthalate (PET) exhibit the lowest environmental impact across categories namely global warming potential, ozone depletion and acidification. Remarkably, this 1:2 ratio of material composition (33.3% waste PET and 66.6% M-sand) yields a remarkable 126.67% reduction, and recycled brick aggregates show an impressive 182.22% reduction in carbon emissions compared to construction brick benchmarks. Conventional clay bricks achieve only a 68.89% reduction. For thermal comfort analysis, the eco-brick is tested using building design data under 4 ventilation options and 5 climate zones. In the view of sustainability of construction material, the produced eco-brick performs better than clay brick, fly ash brick, autoclaved aerated concrete (AAC) block, porotherm brick and gypsum block. The average difference between energy consumption considering each climatic zone and orientation is 42.47 kwh, for ventilation option 1, 48.45 kwh, for ventilation option 2, 42.42 kwh, for ventilation option 3 and 53.89 kwh, for ventilation option 4. This indicates that incorporating recycled plastics into building materials significantly improves the thermal properties.

Keywords Life cycle assessment · Plastic waste · Eco-bricks · Thermal comfort · Ventilation options · Climate zones · Thermal property

1 Introduction

1.1 Background

Brick is an important construction material used around the world, acting as the foundation of masonry. Over time, there has been a significant increase in its production, mostly because to the growing needs for infrastructure and housing in developing countries [1]. India, China, and Spain are the leading brick-producing nations, with yearly output rates exceeding 240 billion bricks [25]. Bricks made of clay have traditionally been widely utilized, but many academics have recently begun producing bricks made of waste materials as an alternative to conventional bricks, as clay is a non-renewable natural resource [2]. India alone generates 9.46 million tonnes of plastic waste per year, with 43% originating from disposable plastics, largely used for packaging, and 40% from neglected plastic waste. Despite the nation has begun attempts to eliminate disposable plastics by 2022, the accumulation of several million metric tons of solid waste, which still creates an imminent risk to the ecosystem and demonstrates no signs of decomposing for thousands of years, remains a significant challenge for the entire nation [3]. The generation of waste plastic has detrimental effects on environment and connected to air quality. Because of the

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rapid rate of generation, it was decided to explore and analyze the viability of employing waste plastic as an alternative to conventional bricks. In response to the prevailing trend towards eco-friendly construction materials, the production of masonry and other construction components increasingly relies on utilizing various waste materials as raw inputs [4]. They will assist with environmental sustainability while also maintaining material needs and regulations. As a result, several attempts have been made to include waste into the brick manufacturing process, and their physical and mechanical properties have been studied.

1.2 Life cycle assessment (LCA) in construction material

In this context, the usage of LCA becomes invaluable it provides an opportunity to look at the environmental impact of construction materials across the lifecycle. LCA looks at the environmental burdens at different stages of the lifecycle, such as raw material extraction, transportation, manufacturing, construction, disposal, and utilization. This approach offers a systematic and holistic for evaluating the environmental analysis of materials, enabling the identification of chances for enhancement. LCA studies quantify effects on carbon emissions, consumption of energy, water use, waste generation, air pollution, as well as ecosystem depletion [5]. First, LCA quantifies the environmental effect of building materials, enabling targeted improvement strategies. Secondly, LCA facilitates informed decision-making by quantifying effects including energy consumption, waste generation, emissions, and resource depletion. Thirdly LCA encourages the adoption of eco-friendly practices in the building sector. Numerous studies have investigated bricks made from waste plastic mixtures, with some researchers also analyzing the environmental effect of conventional bricks.

1.3 Role of thermal conductivity in constriction materials

The usage of appropriate building materials is an effective approach to minimizing the utilization of energy in structures. The use of low-embodied energy materials and effective construction techniques can reduce dependency on traditional sources of energy. The importance of choosing low thermal conductivity building materials plays a critical role in preventing excessive heat transfer between indoors and outdoors while assuring comfort for inhabitants [6]. The installation of adequate thermal insulation in construction envelopes has the potential to significantly decrease electricity usage for both heating and cooling, addressing environmental degradation and lowering CO2 emissions. Furthermore, low thermal conductivity bricks appear as a long-term address for green construction efforts. Such bricks are made using methods such as expanding air pockets and using high thermal insulation materials, hence promoting environmental conservation and energy-efficient building practices. Several attempts to utilize plastic as a replacement material in the construction sector have previously been conducted for bricks. The study found that adding plastic waste into brick manufacture produced bricks with low water absorption, high compressive strength, an even surface, and durability [26]. It also underlined the economic and practical advantages of making bricks out of plastic waste. Additionally, studies in the literature indicate that employing plastic garbage in bricks production can lead to light weight bricks with enhanced thermal characteristics [27]. The experimental investigation on the usage of plastic garbage in brick manufacturing highlights importance of reducing thermal conductivity for enhanced insulation capability [7]. Specifically, a lower thermal conductivity value of PET waste, the lower the heat conductivity of the material [27]. This discovery indicates a significant enhancement in thermal properties of building things when using recycled plastics. The improved thermal properties attributed to PET waste can be attributed to its low thermal conductivity, as evidenced by the obtained value. Another study found that when the quantity of waste in the sample mixture increased, the thermal conductivity decreased [8]. By adding plastic to the mixture, the percentage of pores increases, which improves the porosity of the material. This increase in pore size is directly correlated with a decrease in thermal conductivity.

1.4 LCA-the cradle-to-gate approach

Therefore, this study employed the LCA method to appraise environmental effects linked to bricks crafted from post-consumer PET waste [9]. The assessment involved defining and quantifying the energy and materials utilized, as well as evaluating the environmental garbage produced to assess possible environmental effects. Additionally, to conducted a comparative analysis with conventional bricks such as clay brick, fly ash brick, autoclaved aerated concrete (AAC) block, porotherm brick, and gypsum block [10]. The comprehensive evaluation of the performance of bricks incorporating plastic waste and the comparative analysis allow for a thorough consideration of environmental impacts and energy consumption. This, in turn, can offer novel insights into the synergy of the recycled plastic garbage material. The assessment followed the 'Cradle to Gate' variant, encompassing raw material extraction, transport, manufacturing, and concluding with the end-of-life stage [11, 12] "Cradle to Gate" is a LCA variant that considers the environmental effect of a material from the time of conception or extraction of raw materials ("cradle") until the end of its point at factory gate ("gate"). This approach encompasses the entire production process, including resource extraction, manufacturing, transportation, and other relevant stages up to the point when the product leaves the manufacturing facility followed by end-of-life stage. The goal is to offer a thorough understanding of the environmental footprint connected to the production of a particular item [13].

1.5 LCA of eco-bricks

This study's primary goal is to measure the amount the eco bricks made with waste plastic and m-sand. Basically, the LCA of the eco bricks associated with the different stages like extraction and processing of waste plastics, mixing and molding it with m-sand, transportation, the usage, end life as well as recycling. The system boundary is considered as 'Cradle to Gate' with modules C1-C4 and D [14–16]. The production process encompasses raw material extraction, transportation, manufacturing, and ultimately, the end-of-life phase. This study adheres to LCA standards, specifically the international guidelines ISO 14040:2006 [17, 18] and ISO 14044:2006 [19] for LCA methodologies, along with the European standard EN-15804:2011 (https://nexus.openlca.org/database/EN15804add-on) for evaluating the environmental performance of buildings.

1.6 Assumptions and limitations

LCA is an effective methodology for assessing the environmental footprint of a material or a system over its lifecycle. However, like any methodology, it comes with certain assumptions and limitations are as follows, LCA relies on the presupposition that the raw materials used in eco bricks are sustainably sourced, devoid of significant environmental impacts linked to extraction or transportation. The precision of this presumption is critical for ensuring an unbiased assessment. Firstly, it is contingent on the expectation that manufacturing processes involved in brick production are executed efficiently and align with best practices. Any deviations from these practices can markedly influence the overall environmental footprint. Subsequently, LCA operates under the premise of a standard and consistent use phase for eco bricks. However, this may not fully account for variations in maintenance, durability, or user behavior, factors that could significantly impact the actual environmental consequences during this phase. Also, LCA bases its findings on assumptions regarding recycling/disposal methods. The accuracy of these assumptions relies on the waste management infrastructure and practices prevalent in the region where the bricks are employed. Finally, LCA relies on a typical transportation model for intermediate products, raw materials, and final plastic-induced bricks. Nonetheless, actual transportation distances and modes can vary, influencing the overall carbon footprint associated with the evaluation of life cycle.

1.7 Research contribution

The research contributions are discussed as follows:

- Evaluating the environmental impact of eco-bricks that are produced using the mixture of PCPET waste materials with different material composition ratios through LCA.
- Analyzing the thermal comfort of eco-bricks in comparison with conventional bricks such as clay brick, fly ash brick, AAC block, porotherm brick and gypsum block under four diverse ventilation options and five climate zones.
- Demonstrating the results of mix design, specifically the mix ratio 1:2 consistently exhibited the least impact on the global warming potential (GWP), ozone depletion, acidification, and other relevant groups.
- Verifying the sustainability of eco-brick through thermal comfort analysis for distinct ventilation conditions and climatic zones. The result indicates that eco-brick offers better sustainable construction in terms of energy consumption than other conventional bricks.

The remaining of this research paper are organized by, Sect. 2 presents materials and methods, used for the production of eco-bricks from PCPET wastes. Section 3 discusses the experimental results executed to investigate the sustainability of eco-brick in terms of LCA and thermal comfort analysis. Finally, Sect. 4 concludes the paper with summary of research contribution.

2 Materials and methods

This research work focuses on two main objectives: (i) LCA for assessing the environmental effects associated with bricks made from PET waste and (ii) thermal comfort analysis for energy-saving building design.

2.1 Functional unit (FU)

The FU under consideration consists of various forms of plastics, as informed by prior Life LCA evaluations. The designated functional unit for this study takes the form of a brick block measuring 230 × 110 × 90 mm^3. Table 1 presents the optimal composition ratios for all systems, with a particle size range of 7 mm–9 mm and a 29-day curing period. The experiment performed on the design bricks indicates the

Table 1 Details of mix design

Scenario	Design type	Eco-brick Type	Ratio	Material Composition Percentage (%)		Compressive strength (MPa)
				Waste PET	M-sand	
1	M1	W	2:1	66.6	33.3	14.72
2	M2	UW	2:1	66.6	33.3	13.81
3	M3	W	1:1	50	50	12.56
4	M4	UW	1:1	50	50	11.98
5	M5	W	1:2	33.3	66.6	10.47
6	M6	UW	1:2	33.3	66.6	9.83
7	M7	R-PET	1:2	33.3	66.6	7.23

Table 2 M-Sand- physical properties

Physical properties	Fineness Modulus	Moisture Content (%)	Water absorption (%)	Specific Gravity	Loose Bulk Density (Kg/m^3)	Compacted Bulk Density (Kg/m^3)
M-sand	2.85	0.4	1.15	2.5	1689.50	1769.10

highest compressive strength attained among all systems is 14.72 MPa, while the lowest is 7.23 MPa. This underscores the observation that the mixture of m-sand and PET particles yields greater strength compared to conventional bricks. The identified functional unit for this study is an eco-brick with a weight of 1 kg.

Plastic and M-sand are blended in different proportions—1:1, 1:2, and 2:1—to produce bricks with varying levels of each material. At the same time, bricks from each mix ratio are broken down to create recycled brick aggregates, which are then mixed with M-sand in three distinct ratios. The resulting samples are subjected to strength property testing. The composition of all design mixes is outlined in Table 1, with the following abbreviations: W for Washed, UW for Unwashed, and R-PET for Recycled PET.

To improve result comparability over diverse masonry systems and construction materials, the functional unit is redefined. The initial FU is reputed as 1 m^2 of wall with standard thickness 0.22 m. This unit provides consistent comparison with different wall systems, involving steel frame + drywall, concrete walls, wood frame, and other alternate materials generally utilized in construction industry. Additionally, we have used 1 kg of brick as supplementary FU to offer values into material specific evaluation, specifically for researchers concentrating on weight based comparisons. This guarantees that emission information are normalized to as consistent unit as functional performance which enables straight comparison over diverse wall systems and materials, such as steel frame + drywall, concrete walls and wood frame.

Table 3 M-Sand-chemical properties

Chemical Properties	M-sand
Alumina	12.5
Iron Oxide	4.65
Magnesium Oxide	2.5
Calcium Oxide	3.5
Iron Oxide	4.35
Loss on Ignition	2.5

2.2 Material preparation

2.2.1 M-Sand

M-Sand, an environmentally friendly alternative to natural river sand, is becoming increasingly popular in construction. It utilizes crusher dust, which accounts for 25% of coarse aggregates from stone crushers, as a substitute for clay soil in brick making. This solution helps address waste disposal challenges and contributes to the conservation of natural resources. In India, the adoption of M-Sand has rapidly increased, replacing river sand with high-quality, well-graded, and cubical sand produced by modern crushers. This shift, which has taken place over the past 4–5 years, has led to notable improvements and benefits. The innovative use of crusher dust, typically viewed as waste, as a full replacement for sand in brick masonry offers several advantages. An experimental study removes micro fines from the crusher dust, ranging from 4.75 mm to 75 µm, in accordance with the Indian standard IS 383–1970. These fines are repurposed, demonstrating M-Sand's potential for construction applications, as detailed in Tables 2 and 3, which outline its chemical and physical properties [20, 21].

2.2.2 Recycled PET aggregates

The aim of this research is to investigate the recyclability of common water bottles, particularly those made from post-consumer PET waste (PCPET). This waste can be categorized into washed and unwashed types. Initially, the collected PCPET bottles were shredded into smaller pieces. The washed PCPET fragments then underwent a thorough cleaning process, which involved hot washing with detergent to remove labels, adhesives, and other contaminants. After being thoroughly cleaned and dried, the fragments were processed using industrial machinery, resulting in PCPET flakes with a maximum size of 7 mm and a density of 464 kg/m^3. In contrast, the unwashed PCPET flakes, which were not as thoroughly cleaned, may still contain some impurities [22]. The binder used in the process is a polymer-based material, such as epoxy resin. The physical properties of the PCPET used in this study are detailed in Table 4.

Table 4 Physical properties of PET

Physical properties	Values
Coefficient of thermal expansion	7 × 10–3/ºC
Long term service temperature	115—170ºC
Melting point	260 °C
Specific gravity	1.3 – 1.4
Water absorption	0.07 – 0.10
Density	1380 kg/m^3
Elastic modulus	3100 MPa

2.2.3 Manufacturing process of eco-bricks

The procedure commences by thoroughly mixing m-sand and plastic in various ratios- 1:1, 1:2, and 2:1, with the aim of generating bricks with various compositions. The ultimate goal is to determine the most optimal combination that produces the desired results. At the same time, discarded brick pieces (RA) are collected from each mixture and blended in three different ratios with m-sand for subsequent strength evaluations. In the creation of M1 to M6 design mixes, plastic flakes are melted in a sealed container at temperatures spanning from 180 to 190 °C for 30–45 min. In order to ensure environmental protection, this process is conducted

Fig. 1 Brick samples

in a controlled environment. The resulting samples are showcased in Fig. 1.

After being melted, M-sand is added as filler and mixed manually to achieve uniform distribution. The mixture of filler and molten plastic is meticulously blended to shorten the overall mixing time. As the plastic melts, it forms a deep connection with the filler particles, creating perfect mixture for making bricks. This mixture is carefully poured into sturdy steel molds, measuring 14.5 × 8.5 × 3 cm, and compacted with pressure to ensure complete filling. Afterward, the molds are left to cool in the open air. To ensure easy extraction and prevent damage to the brick edges, the inner walls of the molds are oiled before removal. Following a curing period of 2 to 3 h under room conditions, the specimens are demolded and left to set before undergoing testing. On the other hand, when it comes to design mix M_7, the bricks produced are carefully demolished and melted using temperatures between 190 and 210 °C for 40–50 min. Afterward, M-sand is incorporated as filler and the molding process is carried out following the same steps used for the 1:2 design mix ratio.

2.3 Thermal comfort analysis

The mechanical properties of the produced bricks are then tested, with the highest compressive strength achieved being 14.41 MPa with a mixture ratio of 1:2 (PET waste: M-sand). The enhanced strength is due to the higher content of M-sand, which boosts compressive strength, possibly supported by the plastic particles functioning as binders among the filler materials. Subsequently, eco-brick samples with a 1:2 ratio that exhibit superior mechanical properties are chosen for additional thermal insulation testing.

2.3.1 Thermal properties

Thermal conductivity k is a fundamental property of a material that defines the capability of heat conduction. It refer to the rate of heat transfer through a unit thickness if a material when there is a 1 ˚C temperature differential across it. The unit of measurement for thermal conductivity is W/m k.

Conductance is represented by C, which is its capacity to promote heat flow. The amount of heat that a material conducts at a given thickness when there is a 1 ˚C temperature differential over it is known as its conductance. W/m^2 K is the unit of measurement. Conductance is estimated utilizing the material thermal conductivity (k) if the thickness of the material is known.

In reality, a wall or roof assembly is typically made up of several different types of products. For instance, a brick wall granite cladding on the inside, plaster on the outside, or plaster on both exterior and interior. In these situations, it is necessary to compute the assembly's total conductance is known as the *U-factor* which is the total heat transfer coefficient of heat transfer. W/m^2 K is the unit of measurement. As a result, the U-value is the total conductance of all the assembly materials.

$$U = C_1 + C_2 + C_3 + \dots + C_n \tag{1}$$

Thus $U = \sum C$ where C_1,C_2,C_3 and C_n are each layer's conductance of the assembly. An excellent envelope design will use materials with a lower U-factor. This paper evaluates the conductivity or k-value of the materials and U-Values of wall assemblies to assess the building performance, to arrive at an accurate result, for comparing the performance of thermal each material. The selected materials' thermal conductivity is tabulated in Table 5. The k-values directly measured utilizing Guarded Hot plate Method, verifying with ASTM C177 standard.

Thermal resistance, also known as R, is a material's ability to withstand heat flow. It guages material's insulating efficiency. As thickness of the material increases, so does its resistance. When materials are utilized in series, add thermal resistances so that a similar area conducts lower heat for a certain temperature difference. The individual resistance of every product is determined to compute the assembly R-value. This resistance total is then added together to get the final R-value is determined using the expression below.

$$R_t = R_{si} + R_1 + R_2 + \dots + R_n + R_{se} \tag{2}$$

Here, R_t = the overall assembly's thermal resistance; R_{si} = thermal resistance's Inner surface, R_{se} = thermal resistance's outer surface; R_1, R_2 and R_n are the thermal resistance of the assembly's individual layers. The reciprocal of the R-value is the U-factor.

$$U = 1\Big/\sum R \tag{3}$$

2.3.2 Thermal comfort and energy efficiency evaluation

This research has evaluated the thermal properties of eco-bricks with respect to energy efficiency and potential thermal comfort for user. The analysis is detailed below:

(i) Building layout and ventilation strategies

A standard building layout covering a floor area of 100 m^2 and volume of 300 m^3 was modelled for this research. The

Table 5 k-Value of materials

Materials	k-value
Clay brick	0.72
Fly ash brick	0.54
AAC block	0.14
Porotherm brick	0.60
Gypsum block	0.30
Eco brick	0.21

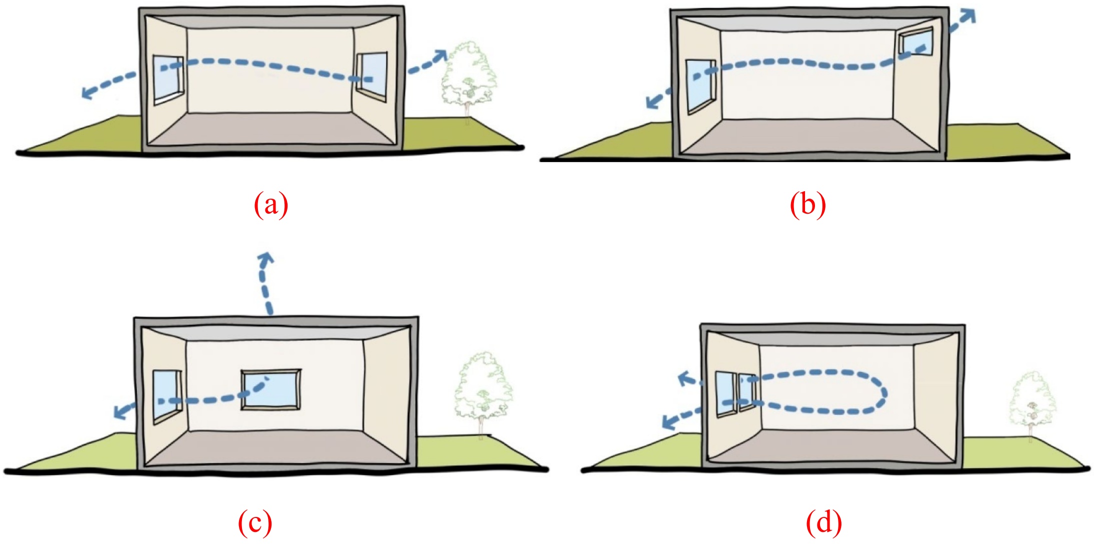

Fig. 2 Ventilation options: (**a**) 1, (**b**) 2, (**c**) 3 and (**d**) 4

walls are built utilizing diverse brick types, including eco-bricks with a thickness of 0.22 m. The simulation was executed at 4 ventilation strategies (shown in Fig. 2): (i) windows on parallel walls of equal dimension, (ii) windows off parallel walls of differing heights, (iii) windows on adjacent walls and (iv) windows on the same wall.

The dimensions of modelled windows are 5 m × 12 m × 0.6 m, with adjusted sill heights and orientations to imitate real-world scenario. In one of the wall, the door made of dimension 1 m × 2.1 m is included. Some of the factors such as roof assembly, glazing specification (U-value = 5.8 and SHGC = 0.81) and service loads are kept constant for all scenarios.

(ii) Climate zones

India has a wide range of climates, which, which is roughly divided into 5 areas with unique climates. The simulation was performed across 5 different climate zones as defined by the Indian climate classification system:

(i) Hot and dry—Summer (– 20 ℃ to 45 ℃); winter (– 0^0C to 25 ℃)
(ii) Warm and humid—Summer (– 25 ℃ to 35 ℃); winter (20 ℃–30 ℃)
(iii) Composite—Summer (– 27 ℃ to 43 ℃); winter (– 4 ℃ to 25 ℃)
(iv) Temperate—Summer (– 17 ℃ to 24 ℃); winter (– 16 ℃ to 23 ℃)
(v) Cold—Summer (– 4 ℃ to 24 ℃); winter (- (– 14) ℃ to 8 ℃)

The significant climatic variation between these zones determines the specific thermal comfort needs of buildings in each zone.

(iii) Simulation tool

DesignBuilder (https://www.altensis.com/en/services/designbuilder-software/) is a software tool that is based on EnergyPlus, designed to simplify the process of construction simulation. It is primarily utilized for carbon, energy, lighting, and comfort measurement and control. It integrates quick 3D construction modeling with dynamic energy simulations with a user-friendly interface.

EnergyPlus: The US Department of Energy's designed EnergyPlus is the most thorough energy simulation program to simulate the energy flow of a building's heating, ventilation, and air conditioning systems. BLAST has been continually improving its features and capabilities and is based on the most popular DOE-2 features and abilities.

3 Results and discussion

3.1 Eco-brick sustainability assessment results for LCA

Table 6 shows the data inventory for every scenario looked at in this study. The information relates to the manufacture of 1 kg eco-brick; which is chosen as the unit of operation of the LCA phase. Table 6 also shows the most significant emissions from every system as derived from a study of LCA of the above-mentioned 7 scenarios.

3.1.1 Variations in the different scenarios

In scenario 1, with the compressive strength of 9.87 MPa, the experiment involved the transformation of 2:1 proportion of washed PET and m-sand through melting and molding,

Table 6 Comparative study of all scenarios- Data inventory of impact categories through all life cycle stages

Impact Categories	Unit	Scenario 1 (M1)	Scenario 2 (M2)	Scenario 3 (M3)	Scenario (M4)	Scenario 5 (M5)	Scenario 6 (M6)	Scenario 7 (M7)
Acidification	mol H + eq	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Climate Change	kg CO2 eq	0.38	0.38	0.36	0.36	0.34	0.34	0.34
Ecotoxicity	CTUe	3.37997	3.37997	3.5957	3.62372	3.86467	3.86467	3.86467
Eutrophication, freshwater	kg P eq	1.55798E-05	1.55798E-05	1.71338E-05	1.72548E-05	1.89177E-05	1.89177E-05	1.89177E-05
Eutrophication, marine	kg N eq	0.001899267	0.001899267	0.001509267	0.001529267	0.001169267	0.001169267	0.001169267
Eutrophication, terrestrial	mol N eq	0.00452	0.00452	0.00458	0.00459	0.00466	0.00466	0.00466
Human toxicity, cancer	CTUh	8.79349E-11	8.79349E-11	9.27127E-11	9.32391E-11	9.84905E-11	9.84905E-11	9.84905E-11
Human toxicity, non-cancer	CTUh	1.27567E-09	1.27567E-09	1.31911E-09	1.32637E-09	1.37634E-09	1.37634E-09	1.37634E-09
Ionizing radiation	kBq U-235 eq	0.19764	0.19764	0.19834	0.19894	0.2002	0.2002	0.2002
Land use	Pt	0.63562	0.63562	0.65193	0.65896	0.6816	0.6816	0.6816
Ozone depletion	kg CFC11 eq	2.51315E-08	2.51315E-08	2.52569E-08	2.53331E-08	2.5527E-08	2.5527E-08	2.5527E-08
Particulate matter	disease inc	2.35779E-08	2.35779E-08	2.40358E-08	2.40988E-08	2.46135E-08	2.46135E-08	2.46135E-08
Photochemical ozone formation	kg NMVOC eq	0.001260888	0.001260888	0.001270888	0.001280888	0.001290888	0.001290888	0.001290888
Resource use, fossils	MJ	1.61066	1.61066	1.6169	1.62224	1.63329	1.63329	1.63329
Resource use, minerals and metals	kg Sb eq	1.95047E-07	1.95047E-07	2.03604E-07	2.04407E-07	2.13687E-07	2.13687E-07	2.13687E-07
Water use	m^3depriv	0.03126	0.03126	0.04096	0.0416	0.05189	0.05189	0.05189

followed by a curing phase lasting 28 days. The resulting samples displayed a significant decrease of − 20.86% in terms of GWP. Additionally, use of depletion of abiotic elements and fossil fuel resources are decreased by 0% and − 302% respectively. These findings demonstrate the positive environmental impact of this process. However, there was a slight increase of 2% in water usage. Encouragingly, the indicators for Land use, Eco toxicity, and human toxic and nontoxic radiations showed no adverse effects, with all results at 0%. In the second scenario, we maintain the same ratio of raw materials, but this time we use unwashed PET with impurities. This mixture, combined with one part of M-sand, is then melted and molded, and left to cure for 28 days. These samples achieved a compressive strength of 4.64 MPa.The resulting GWP is slightly higher at − 22.22% compared to Scenario 1, likely due to the presence of impurities. However, the water usage impact is significantly reduced to 1.79%.

In scenarios 3 and 4, which involve a composition of one part plastic and one part M-sand, washed PET and unwashed PET are employed, respectively. Notably, both scenarios exhibit the lowest GWP, registering at − 11.59% and − 17.59%, respectively, following a curing period of 28 days. This favorable outcome is attributed to the use of reduced quantities of plastic particles, suggesting a correlation between plastic content reduction and a decrease in GWP. However, there is an increase in water usage potential for both scenarios, with a rise of 3.95% and 2.86%, respectively. This may be linked to the reduction in PET content affecting the internal structure of the bricks, leading to a less smooth composition. In both scenarios, positive results are observed across various impact divisions namely eutrophication, human toxicity, ozone depletion, and land use. In scenario 3, acidification records a decrease of − 0.27%, while in scenario 4, it results in a slightly lower decrease of − 0.28%. This nuanced difference underscores the subtle variations in environmental outcomes between the two scenarios. Through a thorough investigation of three distinct scenarios labeled as 5, 6, and 7 with maximum compression of 8.95 MPa, 14.75 MPa and 7.01 MPa correspondingly, all utilizing a 1:2 design mix ratio, a detailed analysis was carried out by introducing novel components into the mixture. This involved including a variety of plastics, such as washed and unwashed PET, as well as recycled aggregate made from re-melted bricks from the two initial scenarios and combined with M-sand(Recycled aggregate) at same ratio. Thus, the composition consisted of one part plastic and two parts M-sand. Scenarios 5 and 6 demonstrated an impressive decrease in GWP, recording values of – 11.59% and – 12.95%, respectively. This remarkable reduction in the overall impact of global warming set these scenarios apart as highly superior compared to other variations.

On the other hand, scenario 7 showed a deviation from this trend by displaying a GWP of – 37.17%. This distinct result could potentially be explained by the higher proportion of M-sand, the filler material, in comparison to plastic, resulting in a significant decrease in the overall global warming impact. Upon further investigation, it was discovered that scenarios 5, 6, and 7 had acidification potential values of – 0.27%, – 0.28%, and – 39%, respectively. Interestingly, scenario 5 also showed a substantial decrease of 10.67% in water usage. This can be attributed to the higher amount of M-sand used and the reduction in plastic matter, which ultimately improved plasticity of brick structure. Furthermore, even key impact categories like resource elements, fossil fuels, land use, and human toxicity showed minimal impact of 0% in all scenarios examined.

3.1.2 Comparative LCA of eco-brick with the other bricks

This study continues by comparing the LCA results of Eco bricks to those of traditional bricks on the market. Through this comparative analysis, valuable insights are gained, providing a better perceptive of eco-brick potential and aiding in their commercialization. The manufacturers' Environmental Product Declarations (EPDs) for Clay Brick (CB), Fly ash Brick (FAB), AAC Block (AAC), Porotherm Bricks (PB), and Gypsum Blocks (GB), which document the person's health and environment, affects each product. These EPDs follow ISO standards and provide a product's effect on the person's health and environment. "The EPD is a crucial tool for assessing a product's impact on the environment and human health, meeting the high standards of ISO 14025 and following the rigorous LCA methodology [23].

The LCA analysis, outlined in Table 7, provides a comparative perspective on the GWP across various types of bricks, including eco-bricks. Clay bricks exhibit a GWP of 0.14 kg CO_2eq, while fly ash bricks and AAC blocks register 0.12 kg CO_2eq and 0.29 kg CO_2eq, respectively. Porotherm bricks and gypsum blocks show GWP values of 0.19 kg CO_2eq and 0.24 kg CO_2eq, correspondingly. Of particular note, fly ash bricks emerge as the most impactful in terms of eutrophication and eco-toxicity potential, with values reaching 319% and 850%, respectively. Ecobricks with a 1:2 ratio, incorporating washed PET, exhibit an impressive reduction of 126.67%, while unwashed PET shows a decrease of 128.89%. The use of recycled aggregates results in an even more substantial decrease of 182.22%. These values are benchmarked against the standard carbon emission value of 0.45 kg CO_2eq for bricks in construction [24], as illustrated in Fig. 3.

Table 7 Comparative study of all scenarios with conventional bricks- Data inventory of impact categories through all life cycle stages

Impact categories	Unit	M1	M2	M3	M4	M5	M6	M7	CB	FAB	AAC	PB	GB
Acidification	mol H + eq	0	0	0	0	0	0	0	0	0.02	0	0	0
Climate change / GWP	kg CO_2eq	– 0.21	– 0.22	– 0.12	– 0.18	– 0.12	– 0.13	– 0.37	0.14	0.12	0.29	0.19	0.24
Ecotoxicity	CTUe	– 2.81	– 3.02	– 1.91	– 2.57	– 1.91	– 2.12	– 4.14	0.21	8.50	NA	0.62	NA
Eutrophication	Kg PO4 eq	0	0	0	0	0	0	0	0	3.19	0	0	0
Human toxicity, cancer	CTUh	0	0	0	0	0	0	0	0	2.13	NA	0	NA
Human toxicity, non-cancer	CTUh	0	0	0	0	0	0	0	0	10.30	NA	0	NA
Ionizing radiation	kBq U-235 eq	– 0.01	– 0.01	– 0.01	– 0.01	– 0.01	– 0.01	– 0.02	0.32	NA	NA	0	NA
Land use	Pt	– 0.32	– 0.32	– 0.11	– 0.22	– 0.11	– 0.11	– 0.28	0.05	NA	NA	NA	NA
Ozone depletion	kg CFC11 eq	0	0	0	0	0	0	0	0	8.09	0	0	0
Particulate matter	disease inc	0	0	0	0	0	0	0	0	NA	NA	0	NA
Photochemical ozone formation	kg NMVOC eq	0	0	0	0	0	0	0	0	NA	0	0	0
Resource use, fossils	MJ	– 3.02	– 3.09	– 2.88	– 3.02	– 2.88	– 2.95	– 4.25	0.96	0.06	2.11	0	4.47
Resource use, minerals and metals	kg Sb eq	0	0	0	0	0	0	0	0	NA	0	1.99	0
Water use	m^3depriv	0.02	0.02	0.04	0.03	0.04	0.04	0.03	0.01	0.04	0	0	0.02

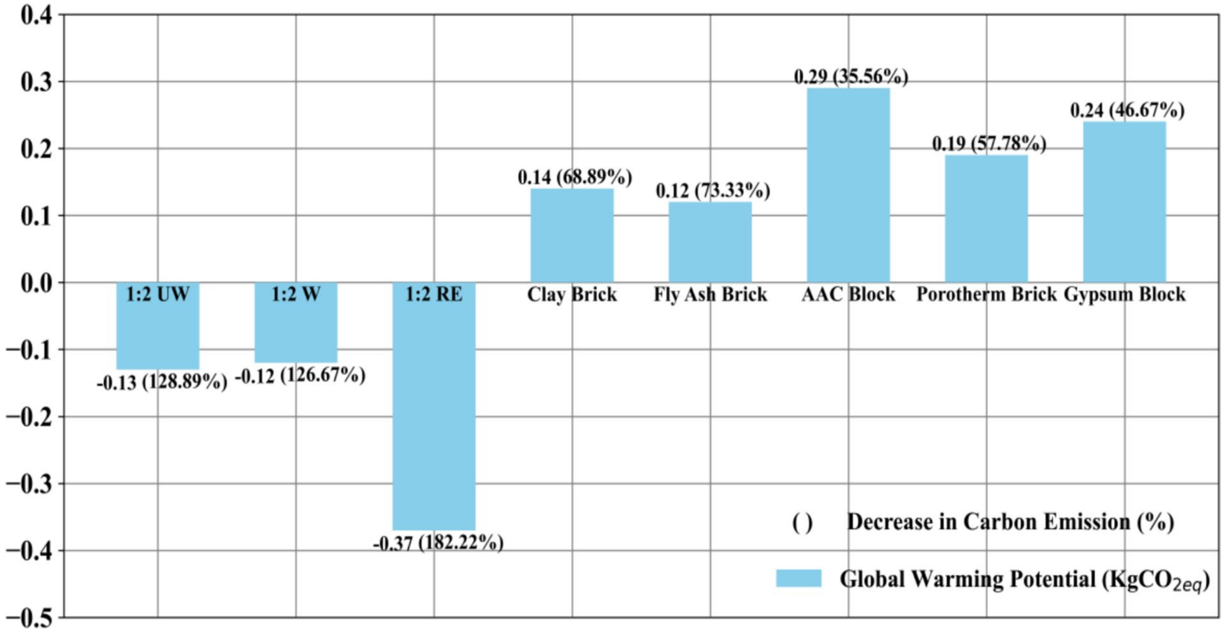

Fig. 3 Comparative analysis on GWP and decrease in carbon emission of different bricks

Table 8 CO_2 emission for 1m^2 of wall

Brick type	Mass per $m^2$of wall (kg)	CO_2 emissions (kg CO_2eq per kg)
M1	396	71.28
M5	420	58.80
Concrete	520	145.60
Steel frame + Drywall	480	130.20

This representation accentuates that Eco-bricks achieve the highest reduction in carbon emissions, with AAC blocks exhibiting the least reduction at 35.56%. The calculation of the percentage reduction in carbon emissions is given in Eq. (4), improving comprehension of environmental benefits affiliated with adopting eco-friendly brick alternatives.

$$\begin{aligned} &\mathit{Decrease\ in\ carbon\ emission} \\ &\quad = ((\mathit{Benchmark} - \mathit{GWP}) / \mathit{Benchmark}) \\ &\quad \times 100\% \end{aligned} \tag{4}$$

Here, the reduction percentages are derived from GWP results obtained utilizing OpenLCA software.

Table 8 displays the result of CO_2 emission for 1 m^2 of wall. The adoption of 1 m^2 of wall as primary FU offers a consistent and normalized framework for comparing the environmental impacts of eco-bricks with other masonry systems. This emphasizes the environmental benefits of eco-bricks, specifically those with washed PET compositions. From the finding of table, it is clear that M1 type brick achieved significantly lower CO_2 emission per square meter compared to typical systems.

3.2 Thermal comfort evaluation results

In order to arrive at a comprehensive result, 4 commonly used ventilation options; 5 different climate zones, with summer and winter mean temperatures have been considered and modelled in software of DesignBuilder.

3.2.1 Comparative analysis of k-value

The Comparative Analysis is based on the commonly used ventilation options such as (a) windows of the same dimensions placed on parallel walls, (b) windows of different heights placed on parallel walls, (c) windows on adjacent walls and (d) windows on same wall. The results are determined for climatic zones arbitrarily for each ventilation option.

Simple box building of area 100 m^2 and volume 300 m^3, with glazing specifications of U-Value 5.8, SHGC 0.81 was modelled in DesignBuilder software, and the simulations were run for all 6 brick types in 5 climate zones at summer and winter temperatures and with 8 Orientation options. The energy consumption values in kWh were determined.

A. Windows of same dimensions placed on parallel walls

Windows of dimensions 5 m × 1.2 m were placed at the center of the walls, and a door of dimension 1 m × 2.1 m was

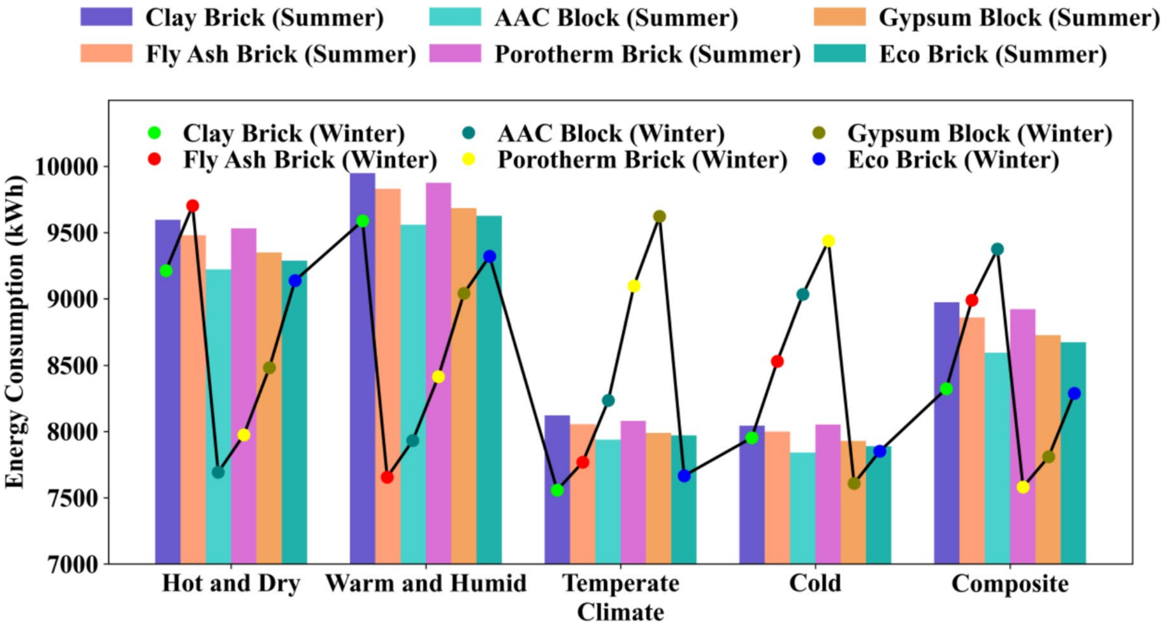

Fig. 4 Energy Consumption results for season orientation 90◦ for ventilation option 1

placed at one of the adjacent walls. The roof assembly, window specifications, and service loads remained constant; the only variable in the building fabric is the opaque wall construction. Figure 4 displays the energy consumption results for season orientation 90◦ for ventilation option 1.

B. Windows of different heights placed on parallel walls

The window of dimension 5 m × 1.2 m was placed at the center of one wall, and another window of dimension 5 m × 0.6 m was placed at the center of opposite wall. The sill height of the former window is 0.9 m and later window is 2.3 m. A door of dimension 1 m × 2.1 m was placed at one of the adjacent walls. The roof assembly, window specifications, service loads remained constant, the only variable in the building fabric is the opaque wall construction. Figures 5 show that Eco bricks perform better than all other types of bricks.

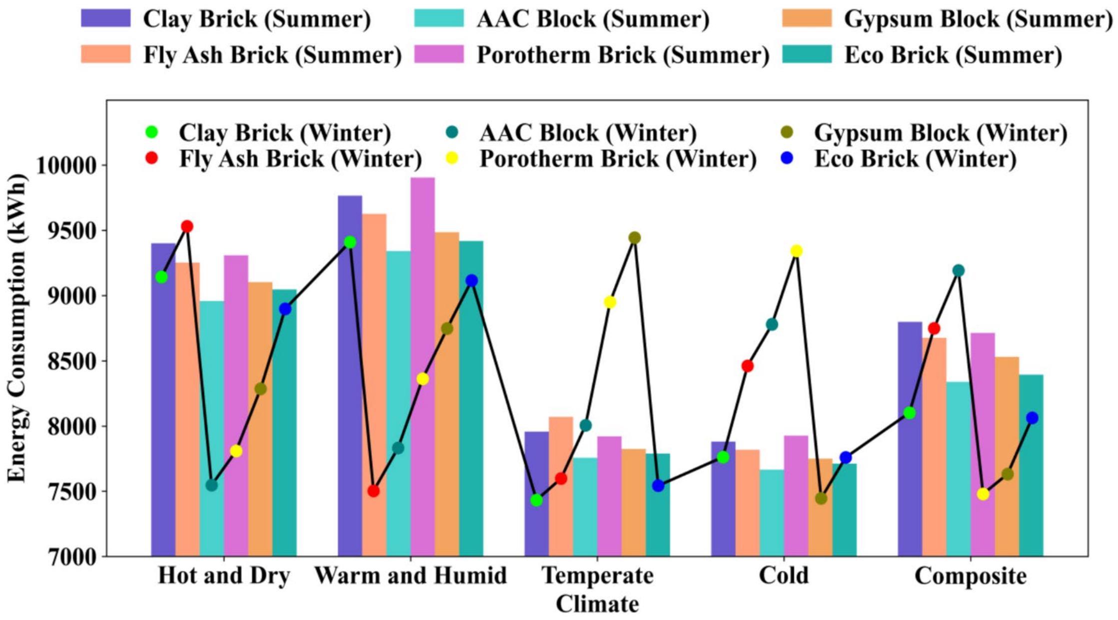

Fig. 5 Energy Consumption results for season orientation 90◦ for ventilation option 2

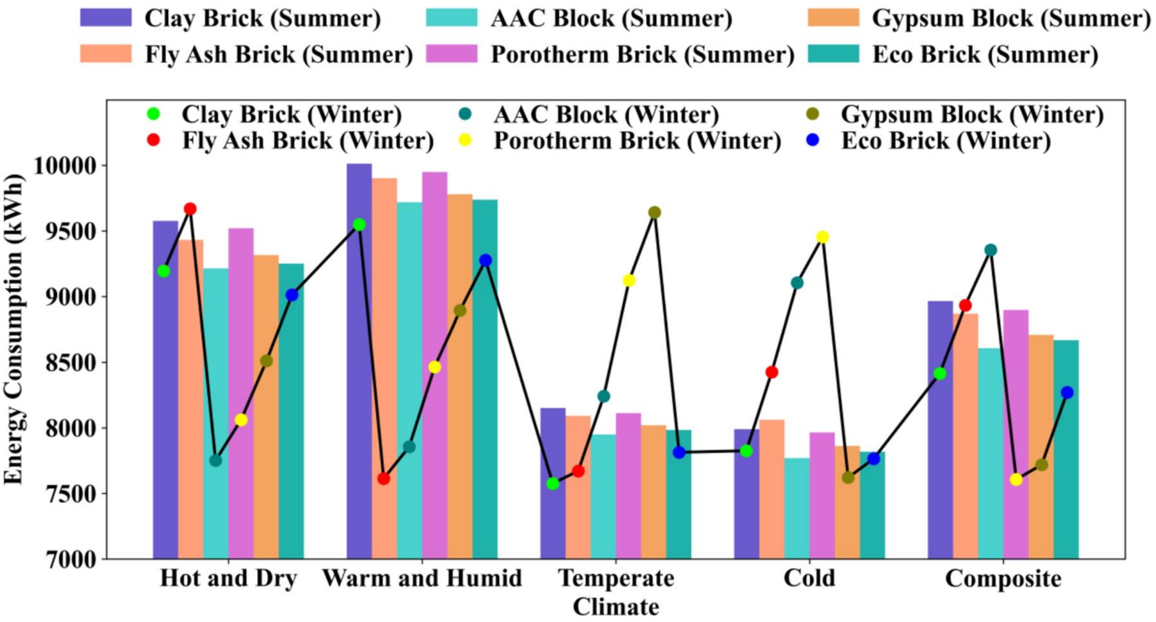

Fig. 6 Energy Consumption results for season orientation 90◦ for ventilation option 3

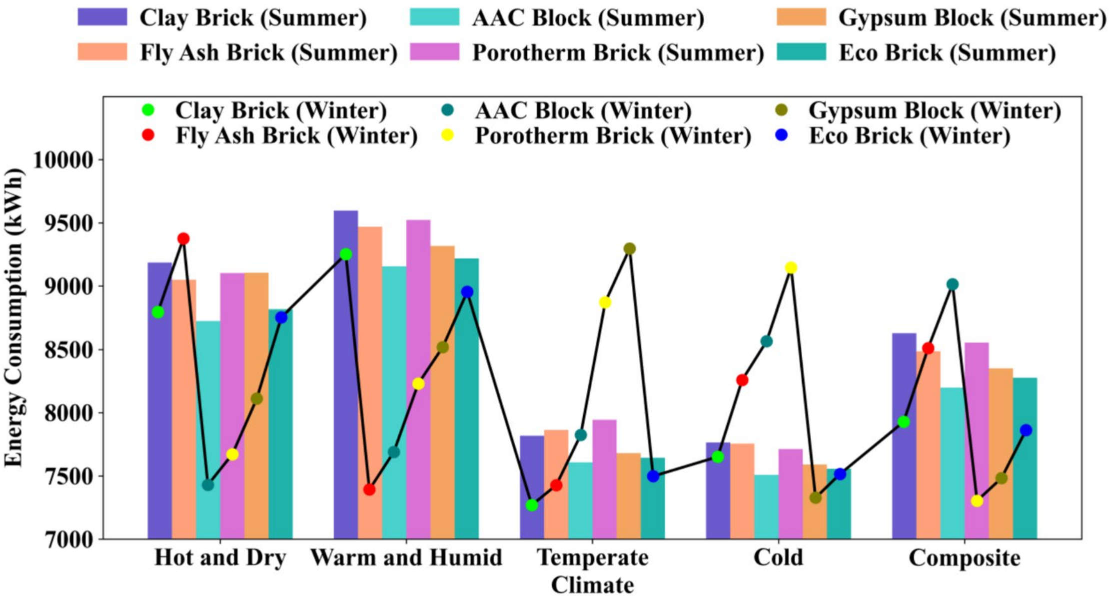

Fig. 7 Energy Consumption for season orientation 90◦ for ventilation option 4

C. Windows on adjacent walls

Windows of dimensions 5 m × 1.2 m were placed at the centre of the walls adjacent to each other, and a door of dimension 1 m × 2.1 m was placed at another adjacent wall. The roof assembly, window specifications, service loads remained constant, the only variable in the building fabric is the opaque wall construction. Figure 6 displays eco-bricks superior performance for ventilation option 3.

D. Windows on same wall

Windows of dimensions 3 m × 1.2 m were placed on the same wall, and a door of dimension 1 m × 2.1 m was placed on one of the adjacent walls. The roof assembly, window specifications, service loads remained constant, the only variable in the building fabric is the opaque wall construction. Figure 7 shows that Eco bricks perform better than all other types of bricks.

3.2.2 Wall assembly U-value calculation

The wall assembly of U-Net is more practical approach, as it considers all the layers of the assembly. Tables 9 and 10 present the U-value of conventional brick walls and eco-brick walls, correspondingly.

Porotherm Bricks are plastered or left without plastering, but the general practice is to leave the Porotherm bricks without plastering. Additionally, the following different construction methods have been analyzed and compared with the commonly used Bricks; (i) Eco Brick wall with Cavity Construction, (ii) Eco Brick wall with Internal Insulation—Expanded Polystyrene and (iii) Eco Brick wall with Internal Insulation—Polyurethane.

3.2.3 ECBC prescriptive requirements—opaque external wall

ECBC recommends the following U-Values for external opaque wall constructions. However, in general practice compliance is achieved either by Prescriptive calculations for the entire Building or by Whole Building energy simulations. Both methods are above and outside the realm of this research. Hence this paper intends to show only the prescriptive calculations for opaque external walls (Tables 11 and 12).

3.2.4 Comparative analysis of U-value

The same technique has been utilized for comparative performance of Wall Assembly U-Value calculation.

A. *Windows of same dimensions placed on parallel walls*
B. *Windows of different heights placed on parallel walls*
C. *Windows on adjacent walls*
D. *Windows on same wall*

From the above-presented Figs. 8, 9, 10, 11 , it is evident that AAC Blocks perform a bit better than Eco Bricks, but while considering the entire sustainability perspective of selecting the material, other factors like material composition, carbon emissions, material recyclability, recycled content present in the material and ease of construction, Eco Bricks are a much suitable choice. Moreover, the average difference between the energy consumption values considering all climatic zones, and all orientations is 42.47 kwh, for ventilation option 1, 48.45 kwh, for ventilation option 2, 42.42 kwh, for ventilation option 3 and 53.89 kwh, for ventilation option 4. Considering the environmental benefits that Eco Bricks offer, it would be the better option for Sustainable construction.

Table 9 U-value of brick walls

Brick	Material	Thickness (m)	Conductivity (W/m–K)	*R*-value (m^2K/W)
CB	Outer Plaster	0.01	0.73	0.02
	Clay Brick	0.23	0.72	0.32
	Inner Plaster	0.01	0.73	0.01
	R-value of Assembly			0.35
	U-value of Assembly			2.85
FAB	Outer Plaster	0.01	0.73	0.02
	Fly ash Brick	0.20	0.54	0.37
	Inner Plaster	0.01	0.73	0.01
	R-value of Assembly			0.40
	U- value of Assembly			2.50
AAC	Outer Plaster	0.01	0.73	0.02
	AAC Block	0.20	0.14	1.43
	Inner Plaster	0.01	0.73	0.01
	R-value of Assembly			1.46
	U-value of Assembly			0.70
PB	Porotherm Brick	020	0.60	0.33
	R-value of Assembly			0.33
	U-value of Assembly			3.03
GB	Outer Plaster	0.01	0.73	0.02
	Porotherm Brick	0.25	0.30	0.83
	Inner Plaster	0.01	0.73	0.01
	R-value of Assembly			0.86
	U- value of Assembly			1.16
EB	Outer Plaster	0.01	0.73	0.02
	Eco Brick	0.22	0.21	1.05
	Inner Plaster	0.01	0.73	0.01
	R-value of Assembly			1.09
	U- value of Assembly			0.91

4 Conclusion

This research work contributes to the development of eco-bricks for sustainable building construction. The study's prime motive of this research is to evaluate environmental repercussions of an eco brick manufacturing system incorporating plastic, employing the life cycle performance of cradle-to-gate as well as thermal comfort analysis. To fulfill this objective, seven distinct design mix scenarios were scrutinized. Among these, three scenarios utilized washed PET; three utilized unwashed PET, and the final one involved remelting bricks from the aforementioned scenarios, and subsequently molding them with filler material. The findings of the study indicate that, across almost all scenarios, GWP and acidification emerged as the least impactful contributors among various environmental impact categories. The impact category of water usage exhibited a slight increase in certain scenarios,

Table 10 U-Value of Eco-Brick Wall

Construction methods	Material	Thickness (m)	Conductivity (W/m–K)	*R*-value (m^2K/W)
Eco-brick with cavity construction	Outer Plaster	0.01	0.73	0.02
	Outer Eco Brick Wall	0.22	0.21	1.05
	Air gap	0.10		0.16
	Inner Eco Brick Wall	0.22	0.21	1.04
	Inner Plaster	0.01	0.73	0.01
	R-value of Assembly			1.95
	U-value of Assembly			0.51
Eco-brick wall with Internal Insulation – Expanded Polystyrene	Outer Plaster	0.01	0.73	0.02
	Eco Brick Wall	0.22	0.21	1.05
	EPS	0.10	0.38	2.63
	Inner Plaster	0.01	0.73	0.01
	R-value of Assembly			3.71
	U- value of Assembly			0.27
Eco-brick wall with Internal Insulation – Polyurethane	Outer Plaster	0.01	0.73	0.02
	Polyurethane	0.05	0.02	2.15
	Eco Brick Wall	0.22	0.21	1.05
	Inner Plaster	0.01	0.73	0.01
	R- value of Assembly			3.23
	U- value of Assembly			0.31

Table 11 Opaque assembly maximum U-factor requirements for ECBC compliant buildings

Climate zones	Values
Composite	0.40
Hot and dry	0.40
Warm and humid	0.40
Temperate	0.55
Cold	0.34

contingent upon the type and ratio of PET used. Remarkably, the scenario with a 1:2 ratio outperformed others and even demonstrated superiority over conventional bricks available in the market. This scenario exhibited a significant reduction in carbon emissions and excelled in mechanical strength tests. These results furnish quantifiable data affirming the viability of incorporating alternative waste materials, such as PET, into brick production, offering a sustainable alternative to non-renewable resources. Consequently, PET waste emerges as a viable suggestion for use as an alternative additive in brick production. The importance of choosing low thermal conductivity building materials plays a critical role in preventing excessive heat transfer between indoors and outdoors while assuring comfort for inhabitants. So, the produced eco-bricks are evaluated under different ventilation options and climate zones to determine the thermal conductivity of eco-bricks

Table 12 U-Value improvement calculation for ECBC compliance

Wall assembly	Climate zones			
	U-factor	Composite/ hot and dry/ warm and humid	Temperate	Cold
CB	2.85	− 6.125	− 5.75	− 6.275
FAB	2.50	− 5.25	− 4.875	− 5.4
AAC block wall	0.70	− 0.75	− 0.375	− 0.9
PB	3.03	− 6.575	− 6.2	− 6.725
GB	1.16	− 1.9	− 1.525	− 2.05
Eco brick	0.91	− 1.275	− 0.9	− 1.425
Eco brick wall—cavity construction	0.51	− 0.275	0.1	− 0.425
Eco brick with internal insulation—expanded polystyrene	0.27	0.325	0.7	0.175
Eco brick with internal insulation—polyurethane	0.31	0.225	0.6	0.075

A. Windows of same dimensions placed on parallel walls

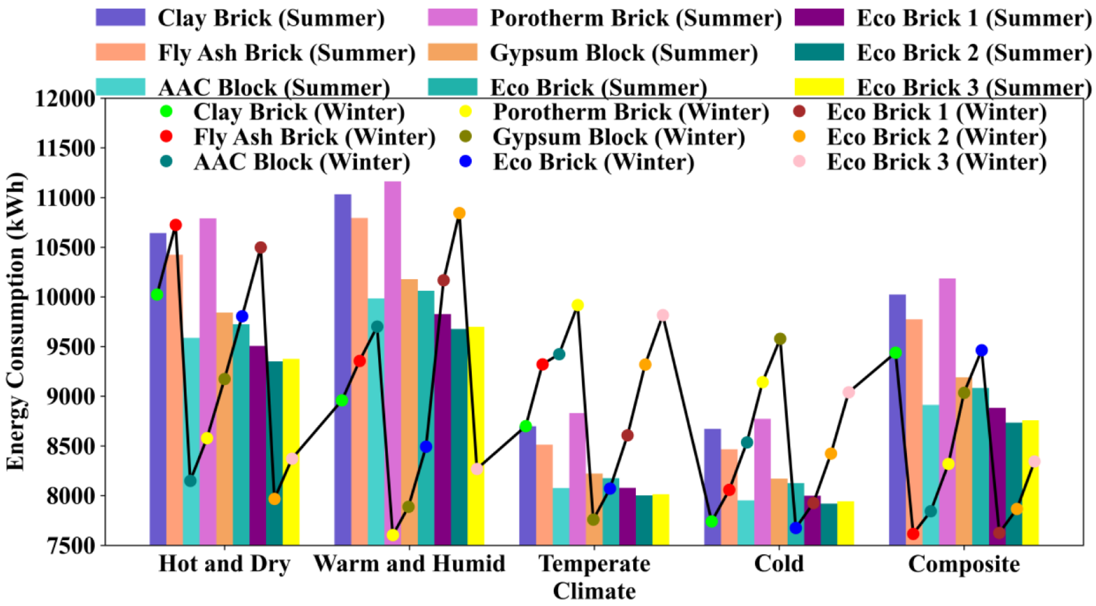

Fig. 8 Energy Consumption for season orientation 90◦ for ventilation option 1

B Windows of different heights placed on parallel walls

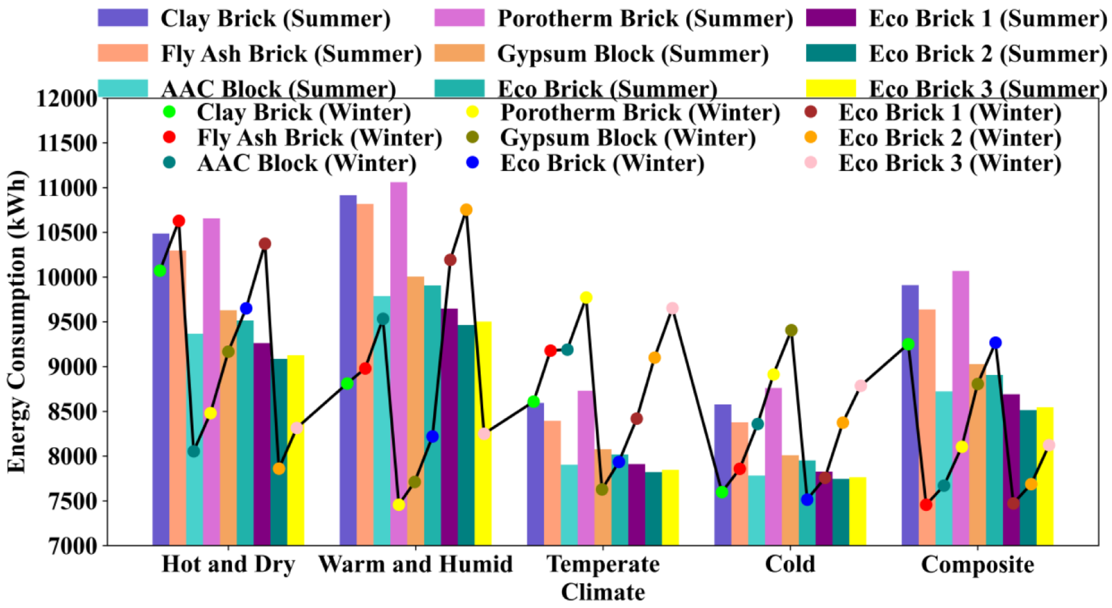

Fig. 9 Energy Consumption for season orientation 90◦ for ventilation option 2

for achieving ensured insulation capability. The experimental investigation comparing different conventional bricks demonstrated that eco-bricks offer better environmental performance for construction, particularly in terms of reduced GWP and improved thermal properties.

It is recognized that evaluation of logical and economic complications involved on scaling up production is very crucial. So, we will take this as part of our future plan, including evaluation of production efficiency, material cost, potential market demand and integration of eco-brick manufacturing with existing construction supply chains. This will provide improved knowledge of economic feasibility and scalability of producing eco-bricks with PCPET on a large scale. For future research endeavors, an economic evaluation

C Windows on adjacent walls

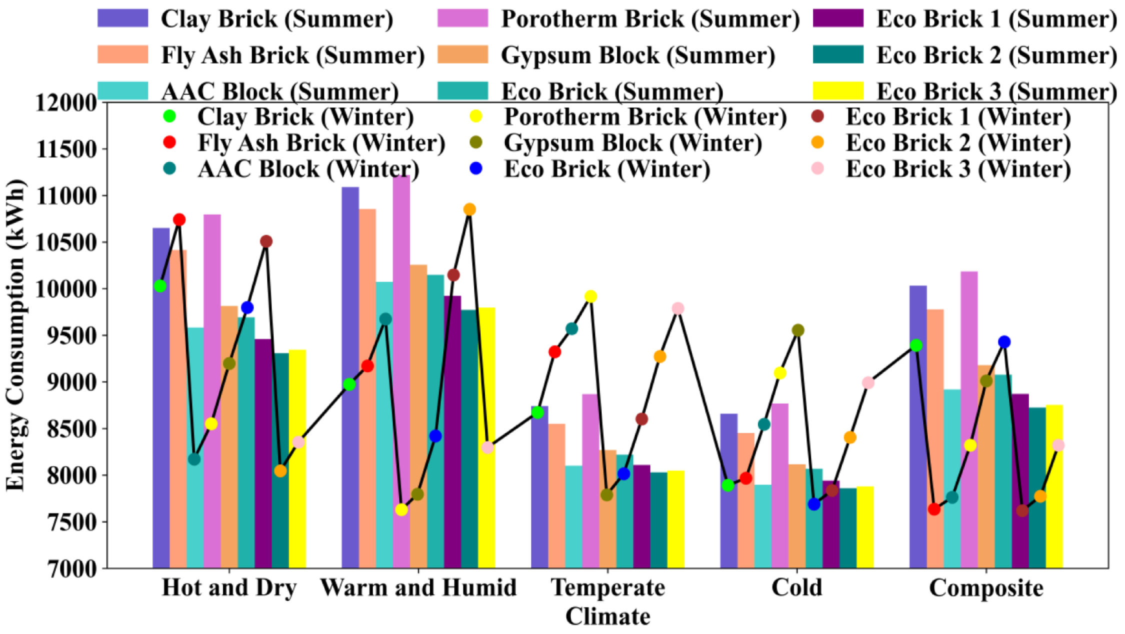

Fig. 10 Energy Consumption for season orientation 90◦ for ventilation option 3

D Windows on same wall

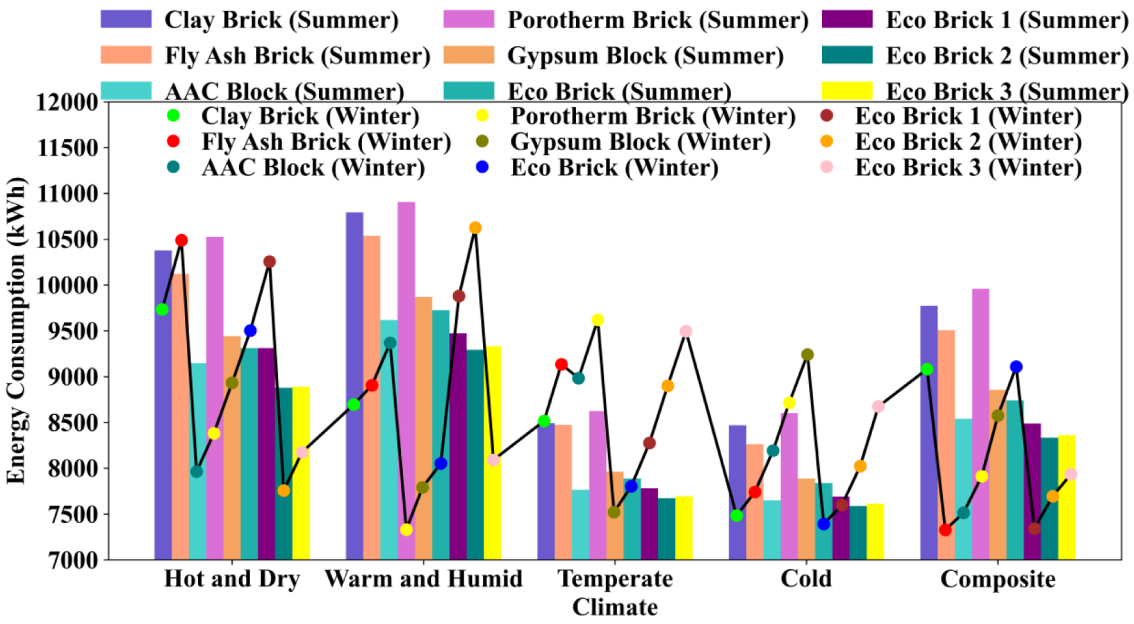

Fig. 11 Energy Consumption for season orientation 90◦ for ventilation option 4

is recommended to gauge the savings impact resulting from PET incorporation in plastic recycling. It is planned to extend the study scope to include broad geographic range which provides comprehensive understanding of thermal and environmental performance of eco-bricks under diverse conditions. Also, to improve reliability and accuracy of LCA, it is intended to integrate localized information from various regions and incorporate dynamic energy modelling under diverse conditions. It is planned to expand the research to cradle-grave view, covering the lifecycle of eco-bricks, including their use phase, upkeep and final disposal or recycling.

Author contributions All authors agreed on the content of the study. VA and LTN collected all the data for analysis. VA agreed on the methodology. VA and LTN completed the analysis based on agreed steps. Results and conclusions are discussed and written together. The author read and approved the final manuscript.

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Data availability The data that support the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of interest The authors declare no competing interests.

Human and animal rights This article does not contain any studies with human or animal subjects performed by any of the authors.

Ethics approval This article does not contain any studies with human participants.

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