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Nanotechnology for thermal comfort and energy efficiency in educational buildings with a simulation and measurement approach in BSh climate

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Educational buildings have a large share and impact on urban development. While research shows a significant portion of non-industrial energy consumption in these buildings, obtaining optimal thermal comfort in educational buildings remains one of the main concerns in achieving the grounds to promote students' best performance and efficiency. Extensive research has been done in this field, however, this research presents a new approach to the diverse use of nanotechnology techniques which improve its properties and components in the buildings, aiming to reduce energy consumption and increase thermal comfort. In this paper, thermal comfort and energy consumption are evaluated in a 12-class elementary school located in Shiraz City. Aeropan and nano-Phase change materials (nano-PCMs) is used in the window glass and walls of the studied case. This evaluation presents the simulation and experimental analysis of thermal comfort (PMV) and energy consumption of three classroom alignments in the school building including the Linear-shape (LS), the Integrated Linear-shape (ILS), and the U-shaped (US) alignment. The simulation was performed using EnergyPlus 9.6 software, while the experimental data was collected using TESTO 425 device. The result of this research shows that after applying nano-PCM and Aeropan techniques in window glass and walls, the US alignment has the highest reduction in energy consumption (monthly average of 11.80%) compared to LS and ILS alignments. This alignment includes an energy consumption reduction of 12.03% in the coldest, and, 11.66% in the hottest day of the year in addition to increasing the monthly average thermal comfort of school by the use of nanomaterials.

Keywords Educational buildings, Thermal comfort (PMV), Energy consumption, Nanotechnology, Phase change materials (PCMs)

Thermal comfort is a psychological and physical state that expresses the satisfaction of the individual from the thermal environment[1]. The two main components that determine the level of thermal comfort are the predicted mean vote (PMV) and the percentage of dissatisfied people (PPD)[2]. Currently, there are two types of thermal comfort standards in research: predicted mean vote (PMV/PPD) and adaptive comfort model (ACM)[3]. Thermal comfort is affected by various physical variables including metabolism (met) rate[4], clothing (clo) Insulation[5], indoor dry temperature (°C)[6], mean radiant temperature (°C)[7], relative humidity (%)[8], and Air Speed (Wind) (m/s)[9]. Psychological variables, including individual expectations[10], mood state[11], and past experiences[12], as well as physiological variables such as age[13], gender[13], body size[14], weight[14], and health conditions]15[, should be considered. The optimal amount of thermal comfort has been determined by the ASHRAE 55 and ISO 7730 standards due to Fanger formula calculation. This amount varies across different building occupancy. Energy consumption can be reduced up to optimal level of PMV/PPD in a building, this can be achieved by passive or active techniques. Energy consumption has been one of the most significant environmental and economic challenges of the present era. Therefore, a balance between energy consumption and thermal comfort (PMV/

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PPD) is essential to be established in the design and operation of buildings[16]. Energy consumption is a term that refers to the amount of energy used by a system, such as a building, a device, or a process[17]. Energy consumption is an essential indicator of the environmental, economic, and social performance of buildings, as it directly affects the energy costs and the thermal comfort of the occupants[18,19]. Building energy consumption can be reduced by applying appropriate strategies in two phases of design and construction. In the design phase, optimal patterns can be used to reduce energy consumption and in the construction phase, different materials, and techniques can be used to achieve this goal[20]. Nanotechnology, as an influential factor on thermal comfort and energy consumption in buildings, is a science that refers to the study of objects, properties, and behaviors in a nanoscale[21]. Considering the challenges and limitations of nanotechnology in general, such as cost, access, safety and regulations, the use of nanotechnology in building construction is affected by various factors, including climate (temperature, humidity, and wind), air quality (freshness, thermal comfort, and particles), energy consumption and placement of nanomaterials in building components[22,23]. Nanotechnology can also be combined with other materials to improve performance and efficiency. Phase change materials (PCMs) are another concept that is related to the topic of this research are of great importance because they can store a large amount of energy in a small part[24]. Thermal energy can be stored in PCMs as latent heat (liquid-vapor phase change) or melting heat (solid-liquid phase change), which today the latter is used more than the former[25]. Nanostructured PCM materials are composite materials that have made remarkable progress with the help of nanotechnology. Many positive examples have appeared in the recent years, and among the results, one can mention the improvement in thermal conductivity and stability[26]. This paper presents a new and innovative method of simultaneous application of several nanotechnology techniques in buildings to increase thermal comfort and reduce energy consumption in Shiraz city with semi-arid climate. This study aims to achieve optimal thermal comfort (PMV) and reduce energy consumption by using nano-PCM techniques in window glass and Aeropan in walls. Simulation and experimental analyses were conducted for three arrangements of classes in the studied case, with orientation of 30˚ in southeast (SE) direction. The analyses were presented for the coldest day of the year (January 12), the hottest (July 29), and the monthly average. These; analyses were presented for the coldest day of the year (January 12), the hottest (July 29), and the monthly average. The new combination of nano-PCM materials can improve the energy consumption and thermal comfort of building occupants and make positive changes in the building knowledge and technology.

Literature review

Thermal comfort and energy consumption in educational buildings are two critical factors that affect the health, welfare, and performance of students. Thermal comfort means creating suitable temperature, and humidity conditions in the school environment that prevents students from feeling discomfort, fatigue, and inattention[27]. Energy consumption means the energy required to meet the needs of heating, cooling, lighting, and ventilation in the school, which reduces operational costs and greenhouse gas emissions[28]. Therefore, designing and operating educational buildings concerning these essential two factors can help improve the quality of education, increase productivity, and reduce environmental pollution[29]. The topic of this research includes various concepts and aspects such as thermal comfort, energy consumption, nanotechnology, nano-PCMs, and educational buildings.

One of the important lines of this research is thermal comfort. Thermal comfort studies have started decades ago, but since 1930, a scientific and engineering approach has been adopted to investigate this issue in buildings with different uses such as; residential[37–39], office[40–42] and educational[43–47].

There are two methods for evaluating thermal comfort: the predicted mean vote (PMV/PPD) model and the adaptive (ACM) model. The PMV model was introduced by Fanger in the late 1960s, is based on the thermal balance model, measuring six internal environmental variables[2]. Fanger (1970) has given relation between PMV with PPD(Percent of People Dissatisfed) by, which says even if the PMV is zero 5% of the people feel dissatisfied, When the PMV is in the range of ± 0.5, and then PPD is less than 10%[15].

The adaptive model is a relatively new model that determines the acceptable temperature range for buildings that use mixed mode air conditioning (natural ventilation (NV) or air conditioning (AC)) based on the outdoor temperature[48]. Current thermal comfort standards such as ISO 7730[49], EN 15,251[50], and ASHRAE Standard 55[1], based on the PMV/PPD and adaptive thermal comfort models, determine the design values for the operative temperature and the comfort equations[48]. Additionally, thermal comfort and energy consumption in Iran have been studied in various types of built environment such as residential buildings, hospitals, office buildings, markets, gardens, sidewalks, urban spaces, and educational spaces[6,32,51].

Second line of this research is nanotechnology and its applications in architecture. Nanotechnology applications in architecture can be divided into two main groups: design[52,53] and building materials[21,22,54]. Nanotechnology can provide various benefits such as improving performance, durability, and beauty of building materials in architecture[54]. Nano-PCMs are one of the new applications of nanotechnology in building materials. They are known as the phase changed materials that have particle sizes less than 100 nanometers. These materials can be embedded in building materials as microcapsules and thus, increase the thermal storage capacity while reducing energy consumption of buildings[55]. So far, many studies have been published on the role of nanotechnology in educational buildings[33,56,57], but what has received less attention is the impact of nanotechnology and its role on thermal comfort and energy consumption in educational buildings and especially, the elementary schools.

Studies presented in Table 1 indicate shows that sufficient research has not yet been done in terms of nanomaterial performance on energy consumption and thermal comfort in educational buildings. In most studies, the effect of nanotechnology is only investigated on the energy consumption of the building, avoiding the thermal comfort. This is while reducing energy consumption is directly related to providing the desired and permissible thermal comfort for the user. Also, the nanotechnology used in previous studies only investigates one of the building components. And, only a limited number of studies have used more than one simulation and experimental method to achieve high accuracy in their results. It is also important to note that most of the studies

Author (Year)	Research method	Technique	Remarks and findings
Abdin et al. (2018) [30]	Simulation (Design builder) And Experimental method	Nanoparticles incorporated in glass	Reduction of energy consumption by 20% by using Low-E glass
Al-Marri et al. (2021) [31]	Simulation (Revit)	Nanoporous based on palm kernel used in the wall	Reduction of energy consumption by 6% and greenhouse gas emissions (such as CO2) by 6%
Rangel et al. (2022) [32]	Experimental method (KD2 Pro and Decagon Devices)	PCM used in the roof	Reduction of the internal temperature and cooling load by 2.5 °C and 6.85%. Improving thermal comfort by 50 min
Aliakbari et al. (2022) [33]	Simulation Rhino 3D,) Grasshopper, Ladybug, Honeybee)	Nano insulation (silica nanoparticles) used in windows	Reduction of energy consumption in the cities of Bandar Abbas, Yazd, Mashhad, Rasht and Tabriz by 2.23%, 7.61%, 5.45%, 5.68% and 6.25% respectively.
Ibrahim et al. (2022) [34]	Simulation Design Builder 6.1))	Nanotechnology used in glass	Reduction of energy consumption for cooling in educational buildings by 34.74%
Yang et al. (2023) [35]	numerical simulation	Nano-PCM (Al2O3-paraffin CuO-paraffin) Used in glass	Energy consumption reduction of 2552 kJ/d, compared to PCM without nano applied in glass
Bargozin et al. (2023) [36]	Simulation	Liquid thermal insulation containing nanoporous silica aerogels	Reduction of energy consumption by 21 – 45% with the use of 0.5 mm thermal insulation
De Masi et al. (2023) [37]	Simulation (EnergyPlus) And Experimental method	Aerogel-based cool ceiling	Reduction of the maximum temperature on the hottest day of the year, 25% and 28% for ceramic coating and airgel, respectively.

Table 1. Background of research.

done in this field are focused on buildings with non-educational uses. Educational buildings play a crucial role in shaping the learning environment for students and educators. As energy consumption continues to rise globally, optimizing building performance becomes essential. New possibilities are opened up by recent advancements in nanotechnology. However, despite growing interest, there remains a gap in research concerning the impact of nanomaterials on both energy consumption and thermal comfort in educational buildings. The uncharted territory of nanotechnology's effects within educational facilities is highlighted by Table 1. Most studies have narrowly examined the effect of nanotechnology on energy consumption, neglecting the critical aspect of thermal comfort. This gap is bridged by this research, which simultaneously evaluates both parameters, recognizing that energy reduction must align with occupant thermal comfort. Unlike previous studies that often focus on isolated building components, a holistic approach is taken in this study by considering the entire building envelope. Through the analysis of the combined effects of Aeropan (used in walls) and nano-PCM (applied to windows), a more comprehensive understanding of nanomaterial performance is provided. Methodological rigor is also ensured by employing two complementary methods: EnergyPlus software simulations and experimental measurements using the TESTO 425 device. The importance of understanding nanomaterial behavior in educational settings for informed decision-making and sustainable design is emphasized by this study, which specifically targets an elementary school in semi-arid climate. In summary, this research contributes to the existing body of knowledge by investigating nanomaterials' impact on energy consumption and thermal comfort in educational buildings, employing a multidisciplinary approach and focusing on real-world applications to enhance building performance and create healthier indoor environments for economic.

Material and method

In order to reduce energy consumption and increase thermal comfort by using nanomaterials such as Aeropan in the wall and nano-PCM in the windows of the educational building, the research method of this paper is divided into two parts which is presented as follows.

A. Material

This research was conducted in the city of Shiraz, located in the Central-South region of Iran, West Asia. Shiraz is the capital of Fars province, one of the largest cities of Iran with hot-dry summers and cool winters. Based on the Koppen-Geiger classification, it has a BSh climate[58], also known as a semi-arid (BS) and hot (h) climate[59]. The case study of this research is an elementary school located in the recently developed northwest of the city, surrounded by gardens Fig. 1. Initially, a class module with a length and width of 8 m × 6 m, a height of 3.5 m, and window dimensions of 3 m × 2 m, was designed for this school based on the standard 1 ASHRAE and publication 697[60] (Table 2). The order of which the classes are aligned next to each other is shown in Fig. 2, including Linear-shape (LS), Integrated Linear-shape (ILS) and, U-shape (US)[64]. Also, the thermophysical properties of building materials used in this research are stated in Table 3.

To improve the thermal performance of the building, different nanotechnology techniques are used in various parts of school. These techniques include the use of nanomaterials in the interior and exterior walls (Tec1), ceiling (Tec2), floor (Tec3), and window (Tec4)[25]. This study simulates the four above mentioned techniques in a primary module of one classroom (Fig. 2). Then, the monthly energy consumption in January is analyzed

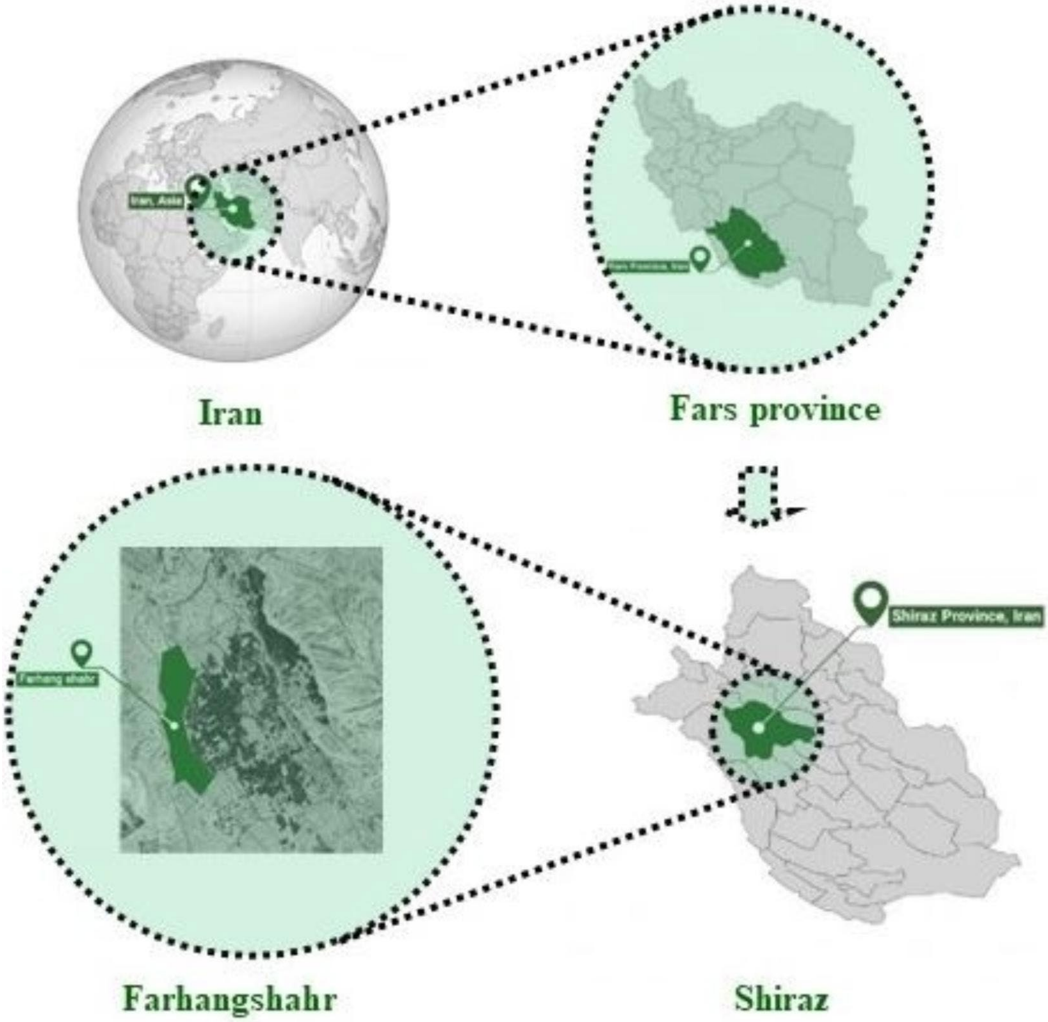

Fig. 1. Location of the studied case. The maps used in Fig. 1 were obtained from Google Maps and then processed by the authors using Adobe Photoshop 2023 v24.7.4.1251[61].

		References
Length (m)	8	Publication 697,ASHRAE
Width (m)	6	Publication 697,ASHRAE
Height (m)	3.50	Publication 697,ASHRAE
Window length (m)	3	ASHRAE
Window width (m)	2	ASHRAE
OKB (m)	1.12	Publication 697
Door Height (m)	2.10	Publication 697
Door width (m)	1	Publication 697
OKB Door window (m)	1.30	Publication 697
Suggested class light intensity (lux)	350	Publication 697
Suggested corridor and staircase light intensity (lux)	150	Publication 697

Table 2. Dimensions and specifications of the building.

and compared in two different conditions including with and without using the nano techniques. Table 4 shows that using nanomaterials in the school reduces energy consumption mostly in the exterior walls (by 9.39%) and windows (12.15%), followed by the ceiling (4.40%) and the floor (1.64%). This reduction in energy consumption can also increase the thermal comfort of building users. Based on the achieved result, this research investigates

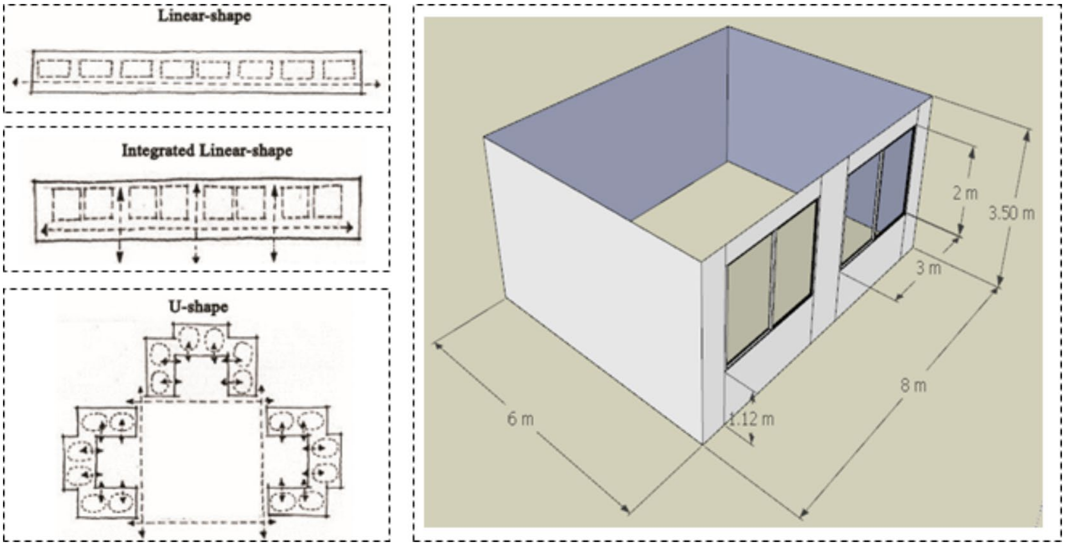

Fig. 2. Class module and their three arrangement modes.

Material	References	Thickness(mm)	U-value (W/m2.k)	References
Exterior wall	Brick	100	8.759	33
	Cement block	110	9.596	33
	Aeropan as internal insulation	10	0.749	62
	Gypsum board	10	8.421	33
	The overall thickness		**230**	
Interior wall	Gypsum board	10	8.421	33
	Brick	100	8.759	33
	Aeropan as external insulation	10	0.749	62
	Gypsum board	10	8.421	33
	The overall thickness		**130**	
Window	glass	4	Table 6	63
	TiO_2-paraffin	12		
	glass	4		
	Aluminium profile	2	-	-
Door	Timber	35	-	64
	Metal handle	20	-	
	glass	6	5.7	63
	Steel hinge	3	-	
Ceiling	concrete	200	5.216	33
	Ceiling air space resistance	180	5.555	33
	Acoustic tile	20	3.141	33
	Gypsum board	20	8.421	33
	The overall thickness		**384**	
Floor	Lightweight concrete	50	5.216	
	floor material	50	3.31	
	The overall thickness		**100**	

Table 3. Thermo-physical properties of the building materials. Significant values are in bold.

the simultaneous performance of two nanomaterials in the school's window glass and walls, in addition to discovering how thermal comfort could be increased while reducing the energy consumption by using these nanomaterials.

Aeropan panel is a novel thermal insulator made by nanotechnology and aerogel material. This panel, due to having very low thermal conductivity (0.015 W/mK), needs less thickness (Table 5). With a thickness of only 10 mm, it provides a similar performance to expand polystyrene panel with a thickness of 25 mm. The

Nano technique	Tec1	Tec2	Tec3	Tec4
Without nano	188.117			
With nano	170.442	179.833	185.016	165.258
difference	17.675	8.284	3.101	22.859

Table 4. Total energy consumption (kWh) without and with nano coating in January.

Technical data	Value	Unit	Test method
Format	1,400 × 720	mm	-
Thickness	10	mm	-
Thermal conductivity at 10 c	0.015	W/ mK	EN12667
Resistance to steam diffusion	5	-	EN12086
Temperature of use limitations	-200 + 200	C	-
Resistance to compression (for 10% deformation)	80	kPa	EN826
Specific heat	100	J/kgK	ASTM E 1269
Nominal density	230 ± 20%	kg/ m^3	-
Reaction to fire classification	C S1 DD	-	EN 13501-1
Long term water absorption by partial immersion	Wp ≤ 0.01	kg/ m^2	EN 1609
Color	Gray/White	-	-

Table 5. Aeropan technical specifications[50].

Material	Glass	TiO_2-Paraffin
Density, kg/m3	2500	850
Specific heat capacity, J/(kg.K)	840	2230
Thermal conductivity, W/(m.K)	0.96	0.36 (solid)
Viscosity, Pa.s	-	0.031
Absorption coefficient, m − 1	19	431.1 (solid) 1060.2 (liquid)
Refractive index	1.5	2.6 (solid) 3.2 (liquid)
Melting temperature, ˚C	-	27–29
Latent heat, kJ/kg	-	205

Table 6. The thermophysical characteristics of both glass and nano-PCM[51].

Technique	Interior or Exterior	Material	Place of use	Simulation information	Reference
Aeropan	Interior and exterior	Nano aerogel panel with 10 mm thickness	Interior and exterior wall	U-value (0.749)	[62]
Nano-PCM	Interior and exterior	TiO_2-Paraffin	Glass	Table 6	[63]

Table 7. Nano and Nano-PCM technique.

aerogel-based insulating panel guarantees a longer useful life than traditional insulators in addition to reducing thickness, installation cost and, time[62].

In this research, a nano-phase changed material (nano-PCM) consisting of TiO_2 nanoparticles added to paraffin was used to fill the space between two window glasses. The size of the nanoparticles is 20 nm, and their volume is 0.005%. Table 6 shows the thermophysical characteristics of both glass and nano-PCM. When sunlight shines on the outer surface of the glass, some of it is reflected, and some passes through. The glass with nano-PCM inside takes in the remaining energy and therefore, heat transfer happens on both sides of the window by convection and radiation. The heat that the glass receives is usually moved to the inside and outside of the window by conduction, convection and radiation. In general, the heat absorbed by the heat transfer mechanisms of conduction, convection, and radiation is transferred to the inside and outside of the window[63].

The innovation of this research lies in the simultaneous use of two nanomaterials, the nano-PCM and the Aeropan in the window glass of the school, which are used to improve thermal comfort and reduce energy consumption (Table 7).

B. Method

This paper aims to investigate the performance of two nanomaterials in improving thermal comfort and reducing energy consumption in an educational building. These nanomaterials are the nano-PCM in window glasses and the Aeropan in walls. For this purpose, a mix of simulation and experimental methods was used. In the school building design section, the module and alignment of the classes were presented. Then, the thermal comfort and energy consumption of these alignments were analyzed and compared in two different conditions including with usual building materials (Table 3), and, with the same materials enriched by the nano-PCM window and the Aeropan wall coatings.

As shown in Fig. 3, this paper investigates four keywords of thermal comfort, energy consumption, nano technology and educational building design in its first step. Shiraz city was selected as the research context and its climatic parameters were studied. The case study is a 12-class elementary school with a 30° southeast orientation. Standard dimensions for the class module were selected and used[1,60]. Then, three different arrangements for the classes, including Linear-shape (LS), Integrated Linear-shape (ILS), and U-shape (US), were modeled by SketchUp 2015 software. To evaluate the thermal comfort and energy consumption in these arrangements, EnergyPlus 9.6 software was used. Also, the performance of nano-PCM window and Aeropan

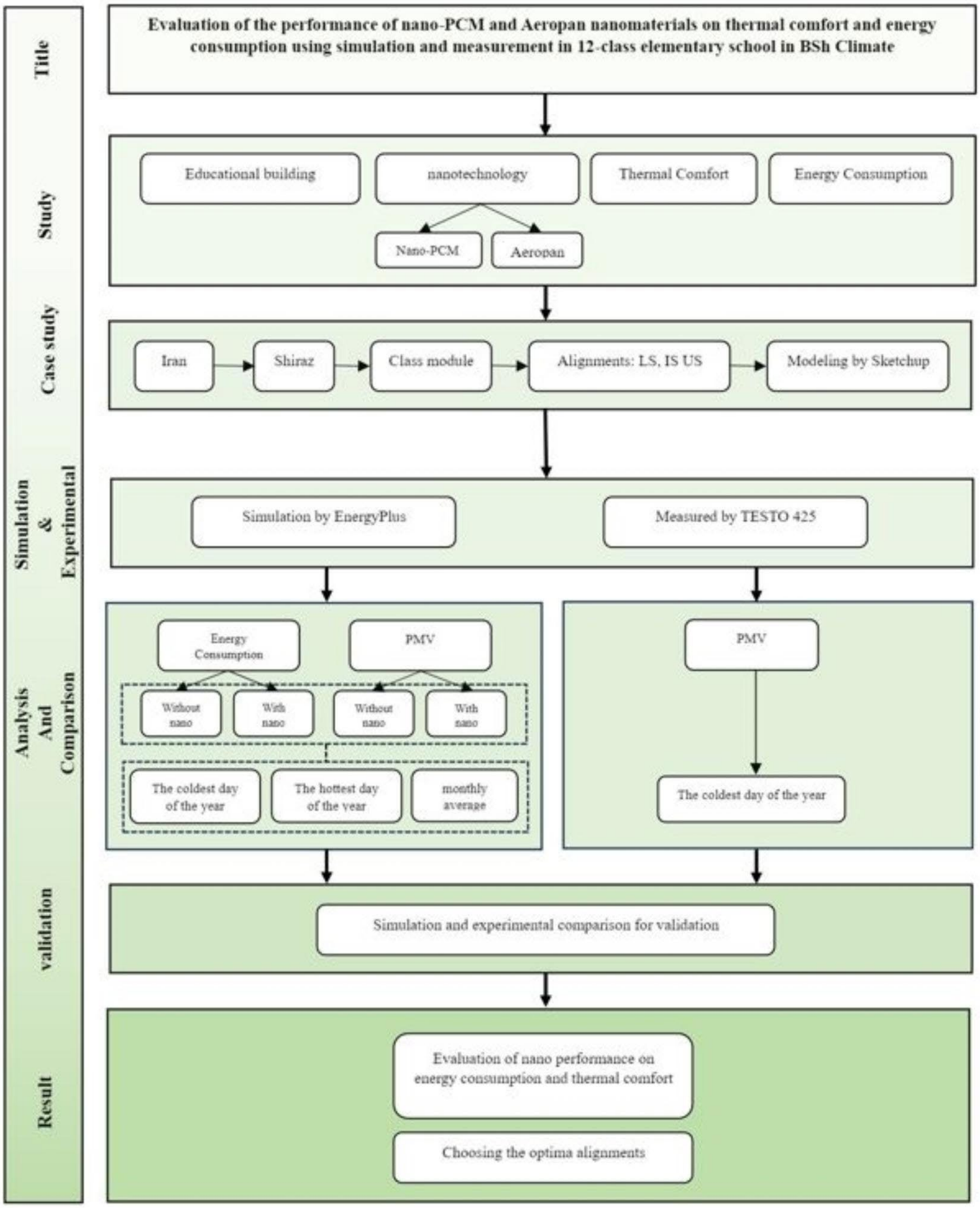

Fig. 3. Flowchart of different part of this article.

Time (hour)	Experimental PMV	Simulation PMV	Difference
8	-1.295	-1.272	0.018
9	-1.285	-1.271	0.014

Table 8. Simulation and experimental PMV without nano-coating on the coldest day of the year (12 January).

Fig. 4. The TESTO 425 device is used to measure thermal comfort parameters.

wall nanomaterials on these parameters was investigated. For this purpose, each section of the class alignments was considered a thermal zone. The data on the weather of the Shiraz city, the thermal features of the building materials, the heating and cooling systems, the lighting level, and the activity and clothing of the people were specified in the software. Then, the output data for three different times of the year, including the coldest day (January 12), the hottest day (July 29), and the monthly average on the 15 of each month in the time interval of 8-am to 15-pm were calculated. As stated by Barzegar and Heidari 2014 in[65], Shiraz city, with semi-Arid climate, needs extreme cooling from July to August, and extreme heating from January to February. If we could obtain thermal comfort in the city's most challenging climatic condition which includes the coldest and the hottest days of the year, we would be able to claim the optimal thermal comfort could be obtained in the rest of the days of the year when we need extreme cooling and heating. Therefore, this paper analysis January 12th as the coldest, and July 29th as the hottest day of the year. These data were compared in each of the three alignments, LS, ILS, and US, in two types of materials (Table 3).

Environmental parameters such as temperature, radiant temperature, relative humidity, and wind were measured by the TESTO 425 device for the reliability of the research on the coldest day of the year (January 12) at 8 and 9 am (Table 8). This; device was placed at a height of 80 centimeters from the ground level (Fig. 4) in a school classroom similar to the simulated one. Accordingly; the measured values of temperature, relative humidity, and wind speed were respectively 16.6 °C, 24.3%, and 0.03 m/s at 8 am. and 17.1 °C, 21.3%, and 0.05 m/s at 9 am. The clothing rate (0.8 clo) and activity (1.4 met) were determined based on the observations made by the students. Then; the measured characteristics were entered into the CBE website[66], and the PMV value was calculated based on the Fanger formula. Finally; the results of the measurement and simulation were compared, and the accuracy and validity of the simulation data were extracted. Considering that there is a very slight difference between the simulated and experimental PMV values, the validity of the simulation data was confirmed (Table 5).

Validation

To validate the present article, PMV and energy consumption were first calculated using the EnergyPlus software. EnergyPlus is a reliable tool that computes the thermal loads of buildings using the heat balance method. PMV, based on the Fanger formula, has been calculated in the EnergyPlus software. This method considers all the heat balances on the external and internal surfaces, and the transient heat conduction through the building[67]. This software has a high accuracy and its average deviation for monthly average energy consumption is 3.2% and for indoor air temperature is 0.8 °C[68]. Then, the results obtained from the simulation were evaluated and validated with the experimental data measured by the TESTO 425 device. The accuracy and precision of the simulation and experimental data were compared and the reliability was presented.

Results

The results of this research are presented in two sections: thermal comfort (PMV) and energy consumption on the coldest day and the hottest of the year, and, the monthly average.

- Calculation of thermal comfort (PMV) of three alignments LS, ILS, and US with and without nanomaterial coating on the coldest and the hottest day of the year, and, the monthly average.

Coldest day of the year

The amount of thermal comfort (PMV) on the coldest day of the year (January 12), from 8am to 15pm, was simulated for three alignments: LS, ILS, and US, using two types of materials: the materials in Table 3 and the same materials with nano-PCM window and Aeropan wall coating (Fig. 5; Table 9). The result shows that the PMV increases over time in all of the three alignments. The minimum and maximum values of PMV for each

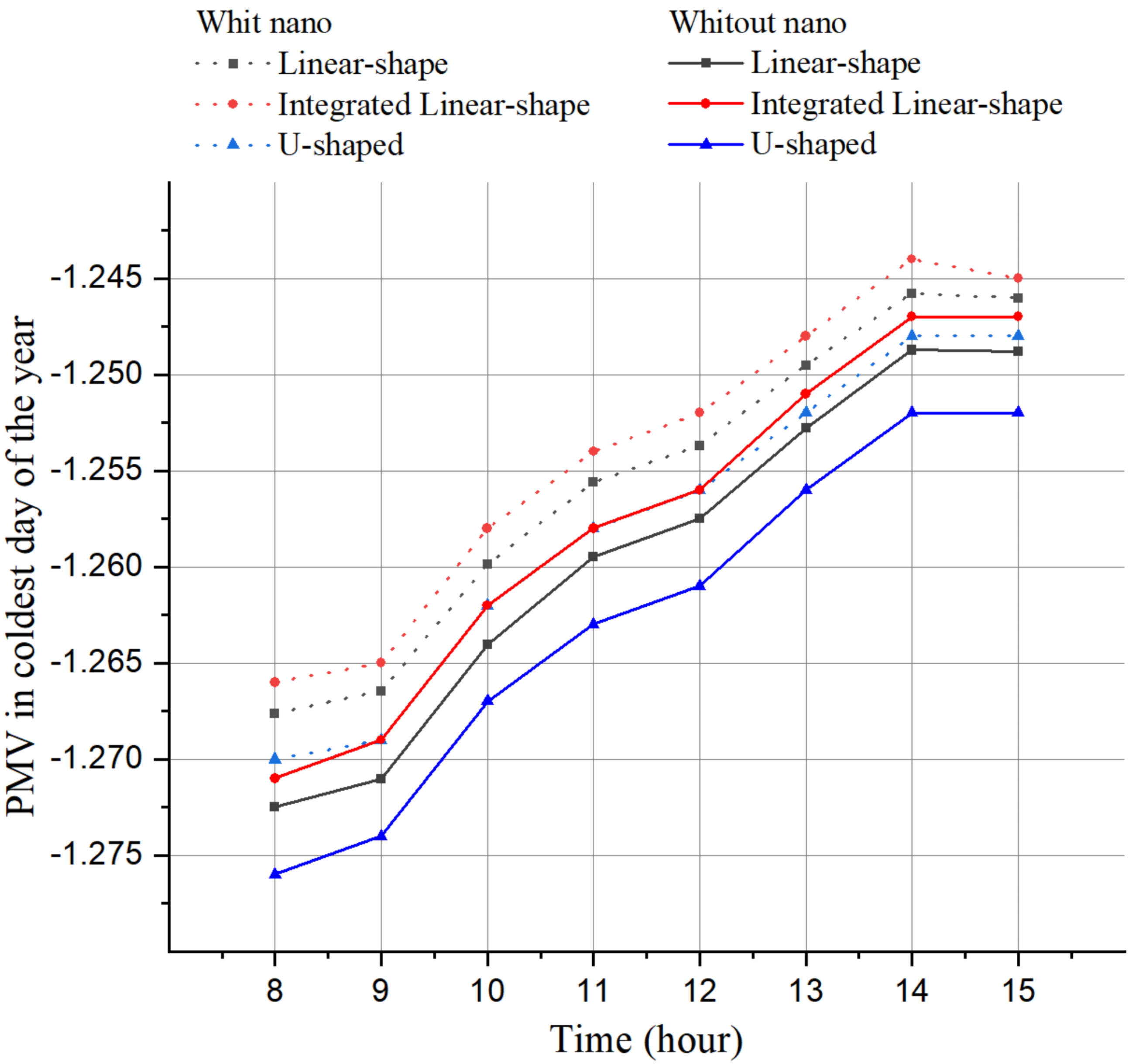

Fig. 5. PMV without and with nano-coating on the coldest day of the year.

Time (hour)		8	9	10	11	12	13	14	15
Linear-shape	Without nano-coating	-1.272	-1.271	-1.264	-1.260	-1.257	-1.253	-1.249	-1.249
	With nano-coating	-1.268	-1.266	-1.260	-1.256	-1.254	-1.250	-1.246	-1.246
	difference	0.004	0.005	0.004	0.004	0.004	0.003	0.003	0.003
Integrated Linear-shape	Without nano-coating	-1.271	-1.269	-1.262	-1.258	-1.256	-1.251	-1.247	-1.247
	With nano-coating	-1.266	-1.265	-1.258	-1.254	-1.252	-1.248	-1.244	-1.245
	difference	0.005	0.004	0.005	0.004	0.004	0.003	0.003	0.002
U-shape	Without nano-coating	-1.276	-1.276	-1.267	-1.263	-1.261	-1.256	-1.252	-1.252
	With nano-coating	-1.270	-1.269	-1.262	-1.258	-1.256	-1.252	-1.248	-1.248
	difference	0.006	0.005	0.005	0.006	0.005	0.004	0.004	0.004

Table 9. PMV without and with nano-coating on the coldest day of the year.

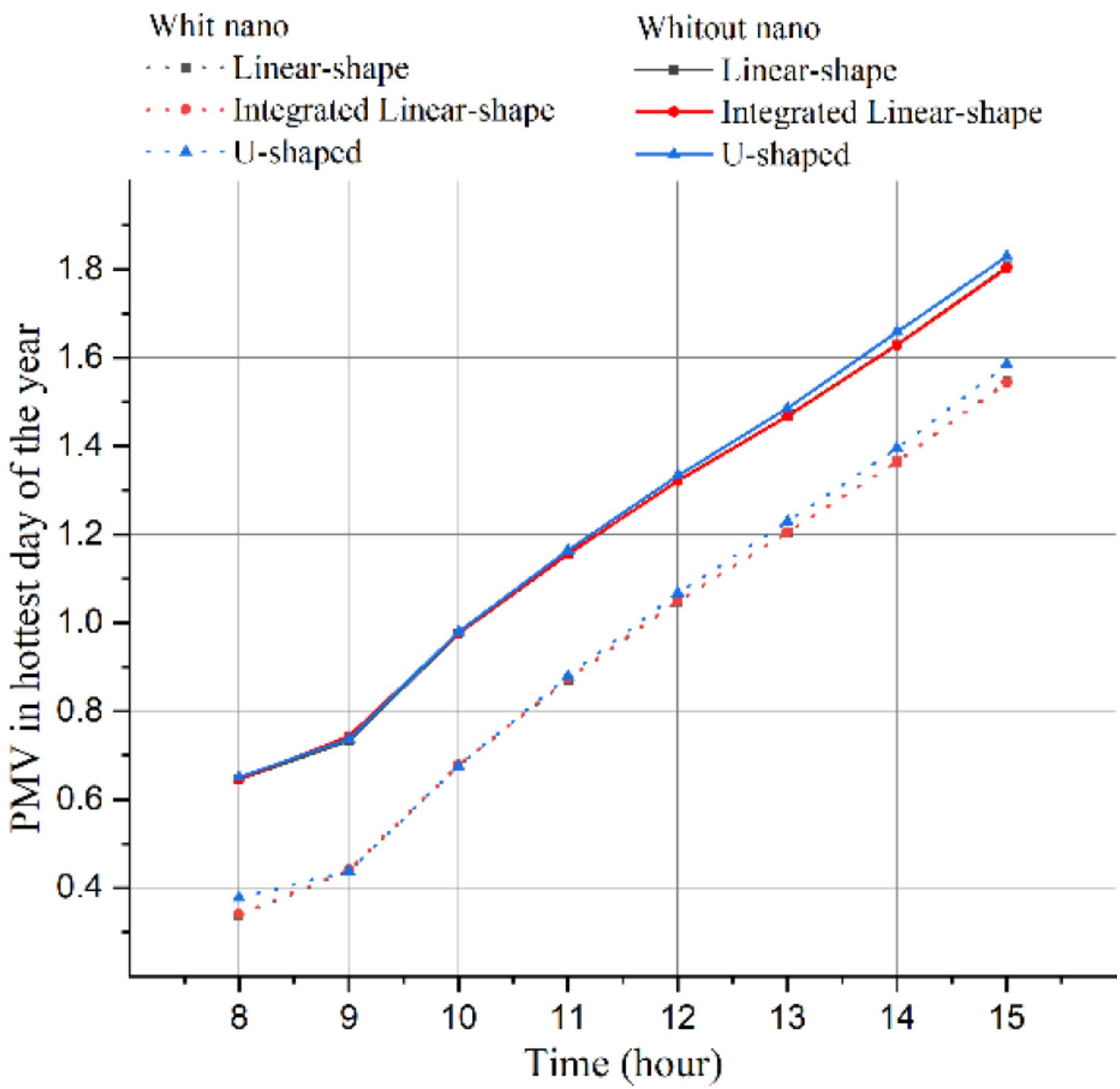

Fig. 6. PMV without and with nano-coating on hottest day of the year.

of the three diagrams are respectively at 8 am and 2 pm. Generally, all three alignments have undesirable cold PMV when using nanomaterials.The ILS, LS, and US alignments led to more desirable PMV levels respectively before the utilization of nanomaterials. After incorporating nanomaterials, this order was maintained, indicating the excellent performance of the nanomaterials. For instance, the ILS alignment at 8:00 AM led to the lowest PMV value of -1.271. Following the application of nanomaterials, this value decreased to -1.266, which is lower than other alignments, both with and without nanomaterials. Without exception, the PMV improved after using nanomaterials, bringing it closer to the desired thermal comfort conditions.

Hottest day of the year

The amount of thermal comfort (PMV) on the hottest day of the year (July 29), from 8am to 15pm was simulated for three alignments: LS, ILS, and US, using two types of materials: the materials in Table 3 and the same materials with nano-PCM window and Aeropan wall coating (Fig. 6; Table 10). The results shows that the PMV in each of the three alignments was within the thermal comfort range ($0.645 \leq PMV \leq 0.980$) only from 8am to 10am. The US alignment without nanomaterials had the highest PMV value of 1.829 at 15pm, indicating undesirable hot PMV. However, using nanomaterials enhanced the PMV values in the three alignments. The performance order of all three alignments remained unchanged before and after the utilization of nanomaterials. This indicates the excellent coordination of the nanomaterials and their very good performance. The PMV values at 11am for the LS, ILS, and US alignments decreased respectively by 0.285, 0.283, and 0.285, and remained within the thermal comfort range until 12pm. The LS alignment with nanomaterials had the most desirable thermal comfort conditions with a PMV value of 0.338 at 8 am.

Monthly average

The average monthly thermal comfort (PMV) from 8am to 15pm was simulated for three alignments: LS, ILS, and US, using two types of materials: the materials in Table 3 and the same materials with nano-PCM window and Aeropan wall coating (Fig. 7; Table 11). The result shows that the PMV in the three alignments was within the thermal comfort range in April and May for the LS, and ILS, and in April, May and September for the US alignment. In other months, all arrangements were out of the thermal comfort range and showed undesirable cold or hot PMV. However, using nanomaterials enhanced the PMV values in the three alignments in August and September, and brought them within the thermal comfort range. This enhancement in the PMV values for the LS, ILS, and US was respectively 0.126 and 0.097, 0.125 for August and 0.102, and 0.147 and 0.127 for September.

Calculation of energy consumption of three alignments, LS, ILS, and US, with and without nanomaterial coating on the coldest and the hottest day of the year, and the monthly average. In this study, we employed identical modules with consistent dimensions and areas, varying only in the alignment of their indoor spaces. As a result of this uniformity in module areas, comparing energy consumption becomes straightforward using the unit of kilowatt-hours (kWh), obviating the need for kilowatt-hours per square meter (kWh/m²). Therefore, in this article, we express energy consumption in watt-hours (Wh) for both the coldest and hottest days of the year. Additionally, we considered the average monthly energy consumption in kilowatt-hours (kWh).

Coldest day of the year

The energy consumption on the coldest day of the year (January 12), from 8am to 15pm, was simulated for three alignments: LS, ILS, and US, using two types of materials: the materials in Table 3 and the same materials with nano-PCM window and Aeropan wall coating (Fig. 8; Table 12). The result shows that the energy consumption in the three alignments decreased over time towards noon and afternoon. Before the utilization of nanomaterials, the LS, ILS, and US alignments had the lowest energy consumption level respectively. After incorporating nanomaterials, this order was maintained, indicating the excellent coordination of the nanomaterials and their very good performance. The highest energy consumption of 3074Wh was observed at 8am for the US alignment without nanomaterials. The lowest energy consumption of 1708Wh was observed at 15pm for the LS alignment with nanomaterials. However, using nanomaterials decreased the energy consumption in the three alignments at 8am, including LS alignment with 242Wh, the ILS alignment with 324Wh, and the US alignment with 370Wh.

Time (hour)		8	9	10	11	12	13	14	15
Linear-shape	Without nano-coating	0.645	0.733	0.975	1.155	1.325	1.468	1.629	1.805
	With nano-coating	0.338	0.438	0.676	0.871	1.048	1.205	1.365	1.546
	difference	0.307	0.295	0.299	0.284	0.273	0.263	0.265	0.259
Integrated Linear-shape	Without nano-coating	0.645	0.734	0.976	1.156	1.321	1.467	1.628	1.803
	With nano-coating	0.340	0.441	0.679	0.873	1.050	1.205	1.364	1.543
	difference	0.305	0.293	0.297	0.283	0.271	0.262	0.264	0.260
U-shape	Without nano-coating	0.651	0.737	0.980	1.164	1.333	1.486	1.658	1.829
	With nano-coating	0.337	0.438	0.676	0.879	1.067	1.229	1.395	1.565
	difference	0.314	0.299	0.304	0.285	0.266	0.257	0.263	0.264

Table 10. PMV without and with nano-coating on the hottest day of the year.

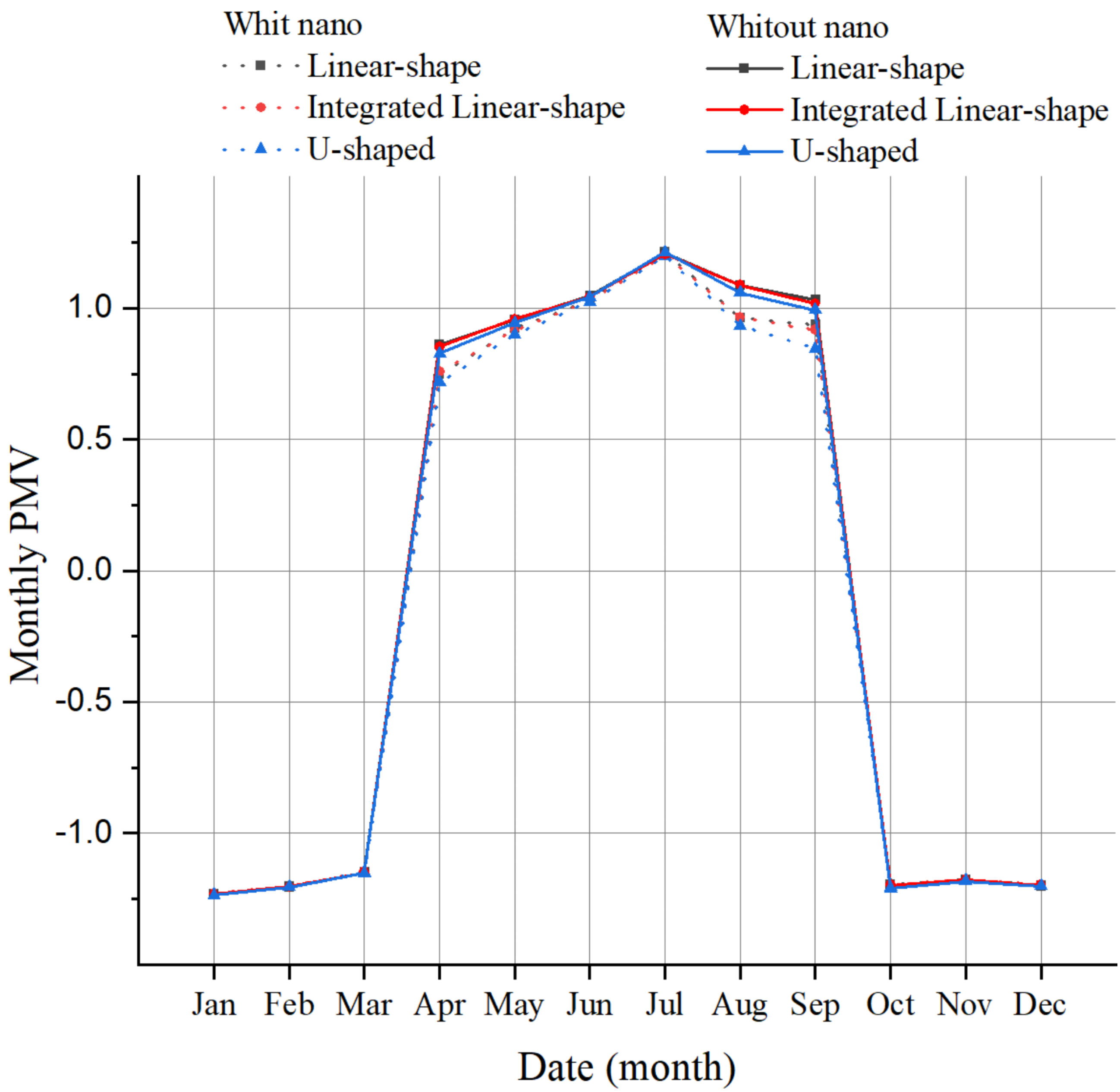

Fig. 7. Monthly PMV without and with nano-coating.

Hottest day of the year

The energy consumption on the hottest day of the year (July 29), from 8am to 15pm, was simulated for three alignments: LS, ILS, and US, using two types of materials: the materials in Table 3 and the same materials with nano-PCM window and Aeropan wall coating (Fig. 9; Table 13). The result shows that the energy consumption in the three alignments increased over time towards noon and afternoon. Before the utilization of nanomaterials, the LS, ILS, and US alignments had the lowest energy consumption level respectively. After incorporating nanomaterials, this order was maintained, indicating the excellent coordination of the nanomaterials and their very good performance. The highest energy consumption of 354 Wh was observed for the US alignment without nanomaterials at 15pm, and the lowest energy consumption of 266Wh was observed for the LS alignment with nanomaterials at 8am. However, using nanomaterials decreased the energy consumption in the three alignments at 15pm when LS alignment became 266Wh, ILS alignment became 315Wh, and US alignment became 354Wh. The findings indicated that the most significant decrease in energy consumption occurred for the US alignment at 3 pm, exactly when the highest energy consumption occurred.

Annual monthly average

The average monthly energy consumption from 8am to 15pm was also simulated for three alignments: LS, ILS, and US, using two types of materials: the materials in Table 3 and the same materials with nano-PCM window and

Months	Without nano	With nano	difference	Without nano	With nano	difference	Without nano	With nano	difference
	Linear-shape			Integrated Linear-shape			U-shape		
January	-1.234	-1.231	0.003	-1.231	-1.229	0.002	-1.236	-1.232	0.004
February	-1.205	-1.202	0.004	-1.204	-1.203	0.001	-1.205	-1.204	0.001
March	-1.152	-1.147	0.006	-1.150	-1.146	0.004	-1.152	-1.148	0.004
April	0.863	0.748	0.115	0.852	0.756	0.096	0.827	0.716	0.111
May	0.955	0.922	0.033	0.958	0.916	0.042	0.943	0.900	0.043
June	1.048	1.032	0.016	1.043	1.028	0.014	1.041	1.023	0.018
July	1.209	1.215	-0.006	1.206	1.202	0.004	1.213	1.199	0.014
August	1.087	0.961	0.126	1.088	0.963	0.125	1.059	0.932	0.127
September	1.033	0.936	0.097	1.018	0.916	0.102	0.993	0.846	0.147
October	-1.205	-1.195	0.010	-1.198	-1.196	0.002	-1.209	-1.204	0.005
November	-1.180	-1.177	0.003	-1.179	-1.175	0.004	-1.183	-1.179	0.004
December	-1.201	-1.199	0.002	-1.198	-1.196	0.002	-1.201	-1.199	0.002

Table 11. Monthly PMV without and with nano-coating.

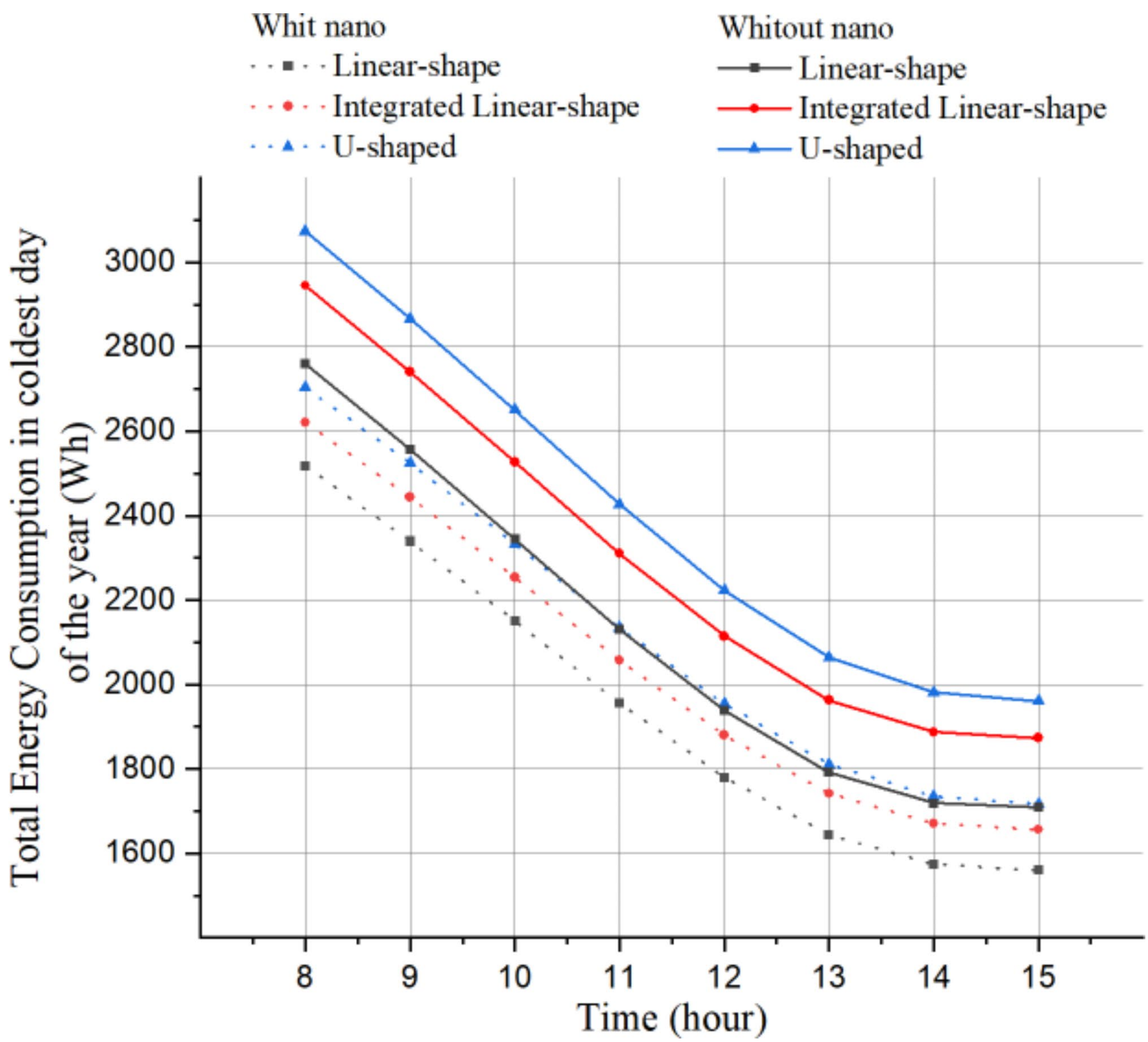

Fig. 8. Total Energy Consumption (Wh) without and with nano-coating on the coldest day of the year.

Time (hour)		8	9	10	11	12	13	14	15
Linear-shape	Without nano-coating	2760	2557	2345	2131	1938	1792	1719	1708
	With nano-coating	2518	2339	2151	1956	1780	1644	1574	1560
	difference	242	218	194	175	158	148	145	148
Integrated Linear-shape	Without nano-coating	2945	2740	2527	2310	2114	1963	1887	1873
	With nano-coating	2621	2443	2253	2057	1880	1742	1671	1656
	difference	324	297	274	253	234	221	216	217
U-shape	Without nano-coating	3074	2867	2651	2427	2223	2064	1981	1961
	With nano-coating	2704	2524	2333	2135	1954	1811	1735	1717
	difference	370	343	318	292	269	253	246	244

Table 12. Total energy consumption (Wh) without and with nano-coating on the coldest day of the year.

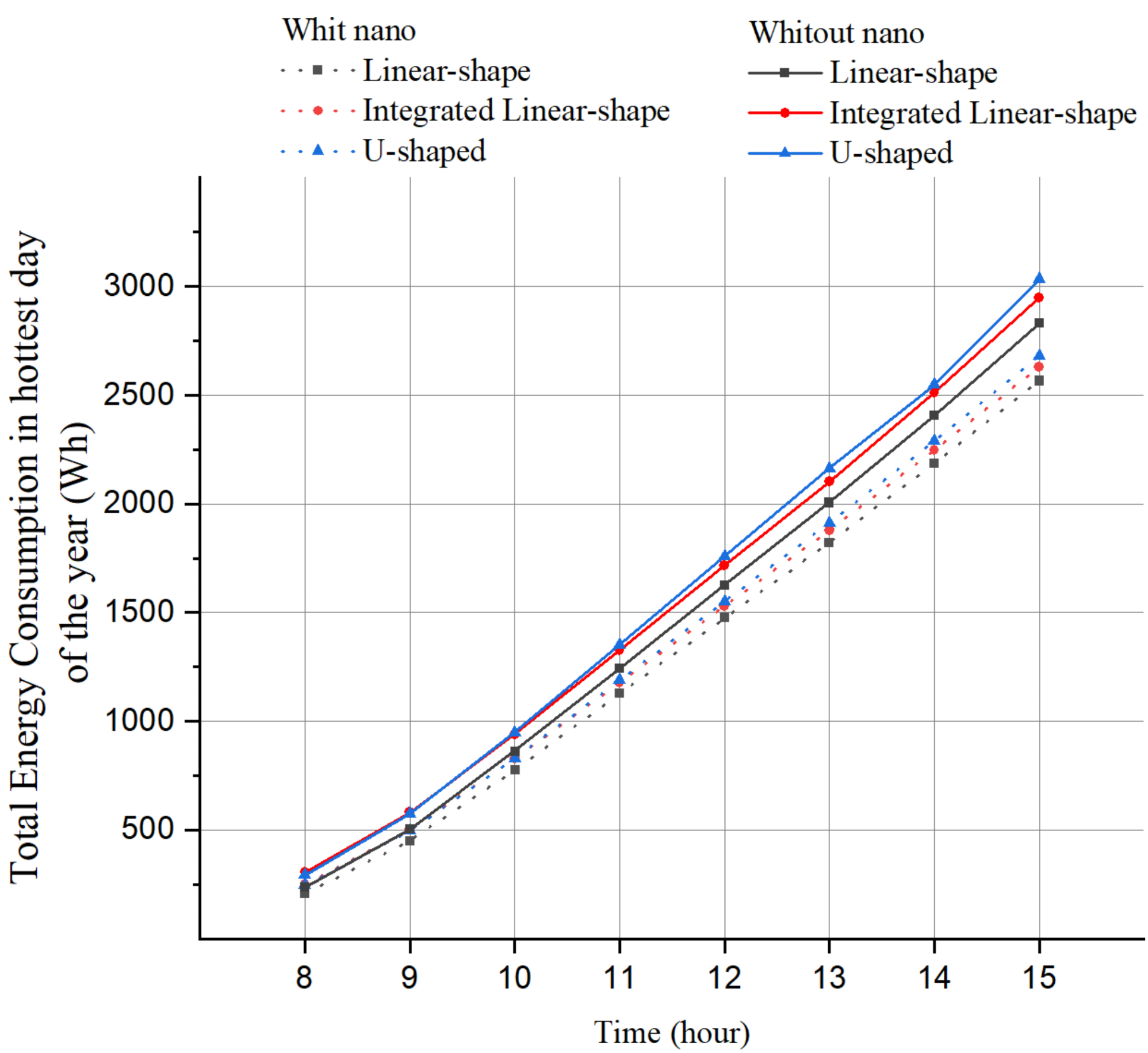

Fig. 9. Total Energy Consumption (Wh) without and with nano-coating on the hottest day of the year.

Time (hour)		8	9	10	11	12	13	14	15
Linear-shape	Without nano-coating	235	505	863	1243	1627	2006	2406	2832
	With nano-coating	206	451	776	1127	1476	1822	2187	2566
	difference	29	54	87	116	151	184	219	266
Integrated Linear-shape	Without nano-coating	305	581	940	1326	1716	2102	2511	2948
	With nano-coating	251	501	828	1177	1529	1879	2247	2630
	difference	54	80	112	149	187	223	264	318
U-shape	Without nano-coating	293	576	948	1353	1761	2163	2548	3036
	With nano-coating	247	497	830	1188	1552	1912	2289	2682
	difference	46	79	118	165	209	251	259	354

Table 13. Total energy consumption (Wh) without and with nano-coating on the hottest day of the year.

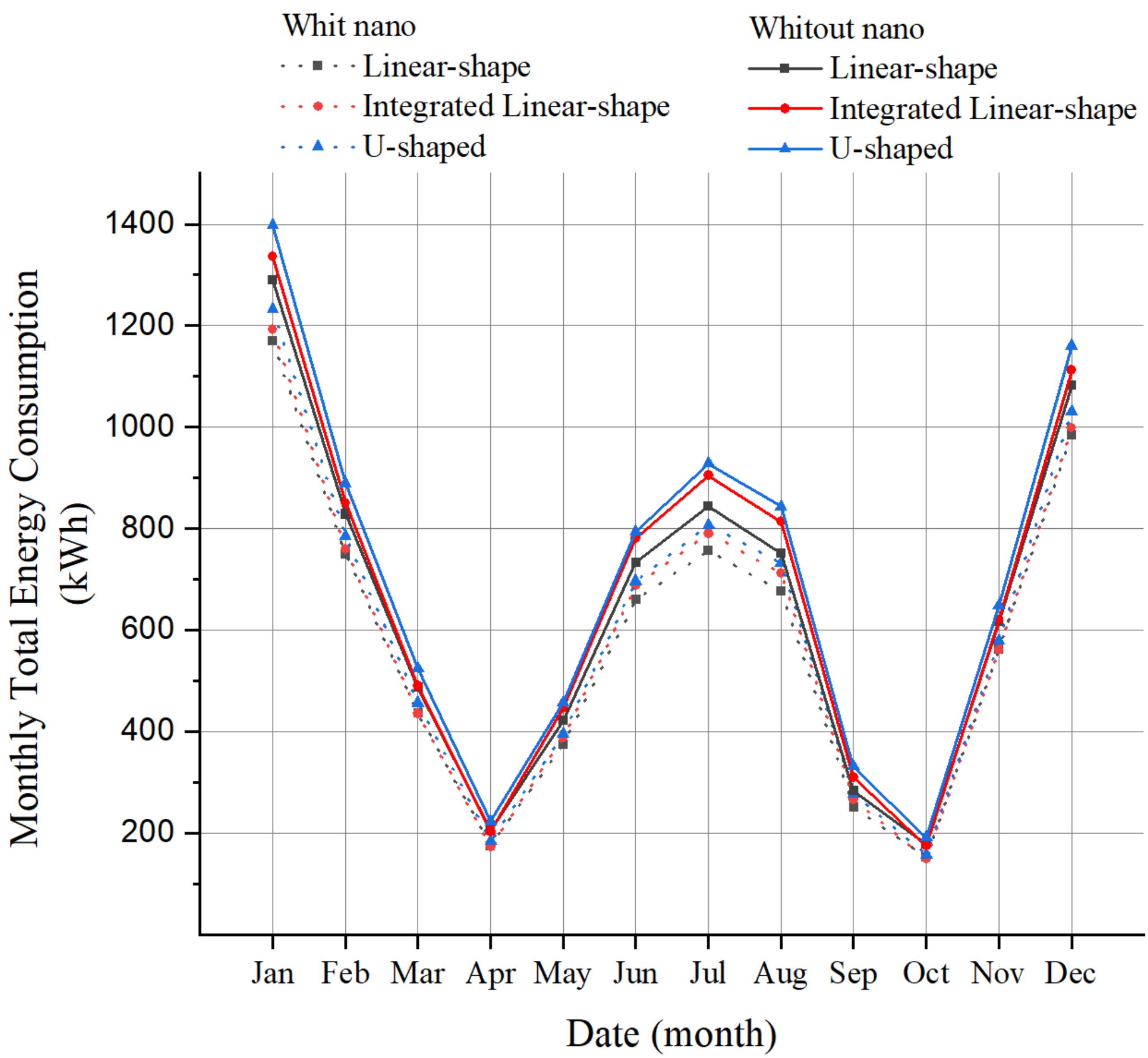

Fig. 10. Monthly Total Energy Consumption (kWh) without and with nano-coating.

Aeropan wall coating (Fig. 10; Table 14). The result shows that the annual energy consumption trend is sinusoidal in different months. The energy consumption decreased from January to April, and from July to October, and increased from April to July, and from October to December. The highest energy consumption was observed in January, and the lowest energy consumption was observed in October for all three alignments. However, using nanomaterials decreased the energy consumption in all three alignments. For example, in January, the energy consumption in the US alignment without nanomaterials was 1397.719kWh, which decreased to 1232.818kWh with nanomaterials. This decrease was also observed in the, LS, and ILS alignments.

Conclusions

This research aimed to investigate the simultaneous effect of two nanomaterials on thermal comfort and energy consumption in a 12-class elementary school in Shiraz with a semi-arid climate. These two nanomaterials are Aeropan used in the walls, and nano-PCM used in the window glass. For this purpose, a mixed method of simulation analysis and experimental was used. The simulation was done using EnergyPlus 9.6 software from 8am to 3pm on the coldest day of the year (January 12), the hottest day of the year (July 29) and the monthly average in three different alignments including LS, ILS, and US. Also, experimental measurements of thermal comfort indicators were performed using the TESTO 425 device on the coldest day of the year (January 12). In order to validate the research, the thermal comfort data obtained from the simulation were compared with the experimental measurement. The results of this research were presented in three sections: the thermal comfort (PMV), the energy consumption, and the optimal alignment of classes.

The thermal comfort (PMV) in three alignments; Linear-shape (LS), Integrated Linear-shape (ILS), and U-shape (US), with and without nanomaterial coating on the coldest and the hottest day of the year, and, the annual monthly average was investigated, and the results reveal:

- on the coldest day of the year, all three alignments were in the undesirable cold thermal comfort conditions without nanomaterials. However, with nanomaterials, the PMV value in the LS, ILS, and US alignments at 8am, which was the most undesirable PMV value at this time, enhanced respectively by 0.31%, 0.39%, and 0.47%, and became closer to the desirable thermal comfort conditions (-0.5).
- on the hottest day of the year, all three alignments were only in the thermal comfort range ($0.645 \leq PMV \leq 0.980$) from 8am to 10am without nanomaterials. However, with nanomaterials, the thermal comfort range in all three alignments expanded from 8am to 12am, and their PMV value enhanced by 2.44 to 2.45%.
- Based on the annual monthly average, the PMV without the use of nanomaterials was in the thermal comfort range ($0.863 \leq PMV \leq 0.993$) in April and May for the LS, and ILS alignments, and in April, May, and September for the US alignment. However, use of the nanomaterials moved August and September into the comfort range of the LS and ILS alignments ($0.748 \leq PMV \leq 0.963$), and August into the comfort range of the US alignment ($0.716 \leq PMV \leq 0.932$).

Also, by examining the energy consumption of three alignments of LS, ILS, and US with and without nanomaterial coating on the coldest and the hottest day of the year, and the annual monthly average, the following results were obtained. It is important to note that the best unit for energy consumption is the unit with the lowest figure.

- on the coldest day of the year, the highest energy consumption of the school without the use of nanomaterials was at 8am in the LS, ILS, and US alignments with 2760Wh, 2945Wh, and 3074Wh respectively. However, with the use of nanomaterials, the energy consumption in the LS, ILS, and US alignments decreased respectively by 8.94%, 11%, and 12.03%.
- on the hottest day of the year, the highest energy consumption of the school without the use of nanomaterials was at 3pm including 2822Wh for the LS, 2948Wh for the ILS, and 3036Wh for the US alignments. However,

	Without nano	With nano	difference	Without nano	With nano	difference	Without nano	With nano	difference
Months	**Linear-shape**			**Integrated Linear-shape**			**U-shape**		
January	1290.488	1169.233	121.255	1335.626	1192.716	142.910	1397.719	1232.818	164.901
February	828.357	749.235	79.121	850.393	759.751	90.643	889.613	784.905	104.707
March	487.005	435.525	51.480	489.672	435.105	54.568	524.507	456.213	68.294
April	204.599	174.781	29.819	202.486	172.895	29.592	222.949	183.811	39.138
May	421.911	374.656	47.255	445.988	388.578	57.411	456.925	394.754	62.171
June	732.107	659.633	72.474	780.518	687.385	93.133	793.821	696.395	97.426
July	843.511	756.140	87.370	904.566	790.555	114.011	928.151	806.824	121.328
August	750.440	676.670	73.770	813.282	712.408	100.875	842.897	731.565	111.331
September	284.024	250.986	33.038	309.872	265.733	44.139	331.039	277.317	53.722
October	177.716	152.424	25.292	174.214	149.487	24.728	191.142	157.112	34.030
November	617.246	561.072	56.173	619.957	560.555	59.403	648.939	578.504	70.435
December	1082.773	984.336	98.437	1112.122	998.759	113.364	1160.999	1030.388	130.612

Table 14. Monthly Total Energy Consumption (kWh) without and with nano-coating.

with the use of nanomaterials, the energy consumption in the LS, ILS, and US alignments decreased respectively by 9.39%, 10.78%, and 11.66%.

- Based on the annual monthly average, the highest energy consumption of the school without the use of nanomaterials was in January with 1290.488kWh for the LS, 1335.626kWh for the ILS, and 1397.719kWh for the US alignment. However, this decreases to 9.39%, 10.699%, and 11.80% respectively with the use of nanomaterials.

The results indicate that the simultaneous use of nano-PCM windows and Aeropan wall nanomaterials leads to a significant reduction in the energy consumption of the school. This reduction is higher in the US alignment compared to the LS, and the ILS alignments by 12.03% in the coldest day of the year, 11.66% in the hottest day of the year, and 11.80% in the annual monthly average. Additionally, using nanomaterials increases the thermal comfort in this alignment more than the other two alignments in all three evaluated timings. Since the difference between the simulation data and experimental measurements is very small (0.01), the credibility of the simulation data has been confirmed. Therefore, the US arrangement, as the optimal arrangement for the simultaneous use of the two mentioned nanomaterials in educational buildings of semi-arid climate is suggested to increase thermal comfort, and reduce energy consumption.

Among the practical implications of this research, we can highlight the provision of design solutions for architects. These solutions enable architects to design in a way that not only reduces energy consumption but also ensures thermal comfort. Additionally, our study introduces the best and most standardized classroom module and alignment for energy reduction. Specifically, in the design of educational buildings in Shiraz, with a semi-arid climate, the U-shape classroom alignment proved to be the most optimal in terms of energy efficiency and thermal comfort. We also introduced nanotechnology and novel materials that are currently less recognized in the Iranian construction industry, especially in Shiraz. These materials have the potential to enhance the quality and efficiency of buildings when incorporated into construction practices.

The limitations of this study include; Due to the fact that the studied building is in the design phase and is not yet built in reality, this study had to face the limit of assessing the validity and reliability of its findings in the actual studied school building. Therefore, the most similar existing school building within the study area was utilized to evaluate the validity and reliability of the study. Additionally, the nanomaterials employed in this research, including nano-PCM and Aeropan, have not yet been utilized in any construction project by the Iranian construction industry in Shiraz. Consequently, this study had no practical opportunity to implement and evaluate its findings in a real-world environment. the future of this research lies in; In the realm of nanomaterials, exploring their applications in thermal comfort and energy efficiency remains a promising avenue for future research. Multifunctional nanocomposites, smart textiles, and energy-efficient building materials are areas ripe for investigation. Additionally, advancements in nanofluids, nanoporous insulation, and thermoelectric materials hold potential for revolutionizing energy management. Integrating nanotechnology into solar energy conversion, HVAC systems, and energy-efficient windows could further enhance sustainability. A holistic approach, including life cycle assessments, ensures responsible utilization of nanomaterials.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Author contributions

M.S. wrote the manuscript with support from R.A., S.T and Z.B. R.A. and S.T supervised the project. Z.B helped supervise the project. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

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