sustainability

Review

A Review on Trombe Wall Technology Feasibility and Applications

Aleksejs Prozuments [1,2,*], Anatolijs Borodinecs [1,2,*], Guna Bebre [1] and Diana Bajare [3]

[1] Department of Heat Engineering and Technology, Faculty of Civil Engineering, Riga Technical University, LV-1048 Riga, Latvia
[2] WWL Houses Ltd., LV-3016 Kalnciems, Latvia
[3] Department of Building Materials and Products, Faculty of Civil Engineering, Riga Technical University, LV-1048 Riga, Latvia
* Correspondence: aleksejs.prozuments@rtu.lv (A.P.); anatolijs.borodinecs@rtu.lv (A.B.)

Abstract: The current global energy challenges require strategies to increase energy-independence across regions and individual countries in order to facilitate and foster the utilization of passive energy sources. As such, solar energy utilization for covering and offsetting building heating loads is a sustainable way to reduce energy consumption (electricity, gas etc.) for space heating. Trombe wall technology is a passive building solar heating system that can be modified and applied to mild and cold regions. This work presents a review of Trombe wall system's feasibility and applications across different climatic regions. Trombe wall systems are applicable as a secondary space heating source in mid-sunshine and cold regions. However, a number of design and structural aspects must be thoroughly considered, including the incorporation of PCMs, and the integration of PV/BIPV elements and other performance-improving aspects to enhance the system's thermal performance and output. The findings of this work can be used in potential future assessments of the Trombe wall system's technology in different climatic regions.

Keywords: Trombe wall; energy efficiency; passive energy systems; solar thermal energy; passive heating

Citation: Prozuments, A.; Borodinecs, A.; Bebre, G.; Bajare, D. A Review on Trombe Wall Technology Feasibility and Applications. *Sustainability* **2023**, *15*, 3914. https://doi.org/10.3390/su15053914

Academic Editors: Alireza Afshari, Jinhan Mo and Matthew Johnson

Received: 18 January 2023
Revised: 16 February 2023
Accepted: 17 February 2023
Published: 21 February 2023

1. Introduction

As the price of active and fossil energy sources continues to rise, Trombe wall technology, as a means for passive carbon-free energy generation and storage, is becoming increasingly appealing. Depending on the external climate and the desired level of indoor comfort, the Trombe wall may be combined with an alternative heating system [1]. Consequently, the Trombe wall is typically used as a supplementary system in medium-temperature and cold regions to save building heating energy during the cold period of the year [2].

The Trombe wall is a passive solar thermal energy storage unit that is utilized to offset building heating loads in an innovative and environmentally friendly way in order to reduce building energy consumption (electricity, gas, etc.) for space heating [3,4].

This approach has been employed to store solar thermal energy since early days of human civilization. However, it was French scientist Felix Trombe who developed and patented Trombe wall concept in 1973.

However, when using passive solar energy for space heating, the unsteady patterns and fluctuations in incident solar radiation must be addressed. The greatest amounts of heat radiation are available in the summer when premises require cooling rather than heating. In order to reduce the cooling load, it is necessary to limit the area of west-facing windows because the highest solar radiation occurs during the day [5]. Moreover, a heat-resistant building accumulates the solar radiation received in the first half of the day in its structural elements and by creating natural or artificial shading elements [6–8].

Trombe wall technology has been applied more widely in Southern European and Mediterranean regions in newly constructed buildings and building retrofits as part of passive solar energy utilization technique considering architectural preferences and economic feasibility [9].

Although Trombe walls are a traditional passive solar heating system for buildings, they can be used to cool buildings in the summer by changing the position of vents to produce a stacking effect and, thus, divert the room air out [10]. However, there are other, more efficient passive cooling solutions; therefore, cooling is not the primary focus of Trombe wall systems. Hence, within the framework of this review, the focus is solely on Trombe wall applications for space heating purposes.

2. Methodology

The aim of this study was to conduct a literature review on Trombe wall technology, and its applications and performance-improving modifications. While some of the literature sources contain unique and valuable findings to foster the understanding of and knowledge on the subject of the application of the Trombe wall technology (and its variety of performance-enhancing modifications), other sources focused on the numerical modelling and mathematical representation of a physical (or other) behavior in Trombe wall systems on the basis of relevant hypotheses and simplifying assumptions.

Therefore, this study includes the most recent experimental and technological research of renowned scholars in the field of passive solar technology, particularly for indoor space heating purposes.

As such, the review focuses on analyzing the most recent studies in this field, encompassing published scientific articles between 2001 and 2023. The majority of the examined articles were published between 2017 and 2023 (71 out of 96, 74%; Figure 1).

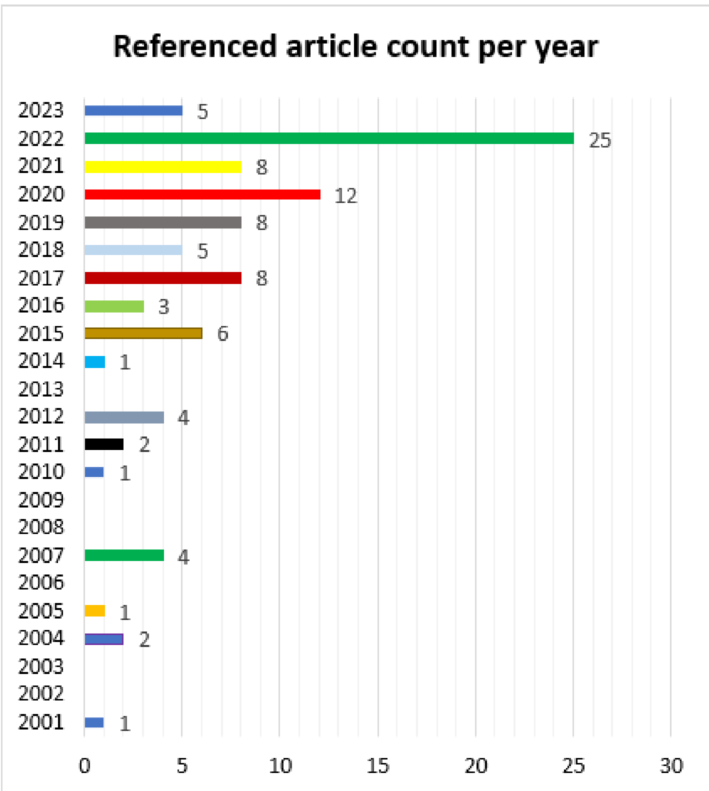

Figure 1. Referenced article count per year (2001–2023).

Another criterion for the reference selection was to encompass research across the wider regional spectrum where relevant studies on the technology were conducted.

None of the particular bibliometric parameters was applied with regard to evaluating authors (publication count, citation count, M-quotient, and the H-, HC-, E-, G-, and I-10 (I-N) indices) or journals (impact factor, eigenfactor, article influence score, SCImago journal rank, source-normalized impact per paper) within the framework of the referenced articles in this review.

3. Overview of Trombe Wall Solutions and Applications

3.1. Traditional Trombe Wall Solution

In recent decades, the Trombe wall technology has gained considerable attention as an effective passive solar building facade system. Its applications are rather simple and cost-effective, and it is suitable in a wide range of geographical regions [6,11].

A typical Trombe wall structure consists of various layers; however, the fundamental components of a structure are a massive thermal wall with transparent and clear outer glazing (usually tempered glass or glass composites [12]) and an air gap inbetween. A typical Trombe wall consists of three main components: glass, air channel, and a thermal storage wall. A thermal wall collects and stores incident solar energy [13,14].

The thermal storage wall is constructed from materials with a high thermal capacity to allow for solar radiation to be stored and accumulated for an extended period of time [15]. This also reduces the system's instant dependance on solar resource and allows for thermal heat transfer operation when the solar resource is not present. In order to achieve greater solar absorption, the wall surface is typically painted dark [16]. The glazing material's function is to transmit solar radiation and produce a greenhouse effect within the air channel. The difference in air density between the warm air channel and the cold room then produces a space heating cycle through the natural buoyancy effect [17]. During the daytime, sunlight passing through the glass is absorbed by the massive thermal wall (which usually features high thermal storage capacity) and is slowly conducted inwards through the massive wall [18]. High-transmission glazing (typically featuring a low U-value, a low shading coefficient, and high visual light transmittance) optimizes solar heat gains for the massive wall [19]. The stored energy is then transferred to the interior of the structure for space heating or air circulation. The heating/cooling performance is dependent on the thermal conductivity of the massive wall, the air movement pattern, parameters in the convective air cavity, and the indoor premises [20].

A rendering of a classical Trombe wall system is shown in Figure 1. It illustrates the operation of a Trombe wall in winter (for heating) and in summer (for cooling), utilizing fresh air inlet dampers. In the heating scenario, the fresh air inlet damper (at the bottom) is open, enabling the mass entrance of fresh air into the thermal wall's air channel, where it is heated and distributed into the premise. Alternatively, to facilitate air movement and the desired air circulation pattern, a supply fan may be incorporated. This ensures that the heated air mass is delivered into the premise while being replaced with fresh air mass, improving the overall thermal performance of the Trombe wall [21,22].

In the cooling scenario, the bottom room air vent and top fresh air inlet/outlet vent are open to enable room air circulation and discharge through the outlet vent due to the stack effect. As this air circulation pattern occurs naturally, in this case, a fresh air inlet through an opening must be ensured (usually an open window or vent).

While Trombe wall systems offer substantial energy saving when the solar resource is available, in conditions of insufficient solar radiation, these systems do not generate sufficient thermal energy (overcast or cloudy sky); therefore, efficient thermal storage must be incorporated to accumulate and retain the thermal energy for a potentially longer timeframe [23].

3.2. Performance-Improving Trombe Wall Modifications

One of the greatest challenges in passive solar energy utilization technology is unsteady weather, i.e., solar radiation and cloud condition patterns. This factor poses various challenges, particularly in mid- and low-sunshine regions [24,25], as per the feasibility and economic sense of solar energy systems in these climatic regions [26,27].

However, due to the rapid spike in energy prices across the world, passive solar energy technology has attracted more attention. Supplemented with a number of performance-improving modifications [28], these systems offer a reasonable return on investment, even in mid-sunshine regions [29,30] because, in several applications (industrial, unclassified buildings), these systems may be used to preheat the supply air, for instance, before the heat exchanger units in mechanical ventilation systems [31].

More advanced Trombe wall applications may feature components to facilitate solar energy utilization. As such, to enhance the performance of the traditional Trombe wall, numerous scholars proposed a series of structural modifications to the original design [32,33]. Trombe walls feature low thermal resistance and specific heat capacity. Furthermore, heat transfer in Trombe walls occurs in an uncertain pattern, as solar intensity fluctuations translate into unsteady heat generation and heat transfer patterns [34,35]. Several solutions were reviewed to employ thermal and energy-efficient façades, including the use of nanomaterials with high solar transmittance [36] or reflectance [37], photothermally treated surfaces [38], and the application of novel solar control films [39,40]. Performance-worsening challenges, such as dust and soil particles, and windborne debris that impact Trombe wall systems were also reviewed with regard to the application of nanomaterials on the outer Trombe wall surface [41,42].

Nevertheless, the performance of Trombe walls can be significantly improved through various performance-enhancing modifications, such as the utilization of phase-change materials (PCMs) or the integration of supplementary energy-generating components such as PV/BIPV cells [43,44]. By utilizing the high storage capacity of PCMs, the thermal resistance of a Trombe wall can be increased to reduce heat dissipation and improve solar radiation gain control [45], while the integration of PV/BIPV cells onto the glazing or frame allows for electricity production [46,47].

Trombe walls provide sensible heat storage, but due to the potential of PCMs to store high rate of thermal energy, the combination of PCMs with Trombe walls is a feasible solution for increasing the thermal storage of conventional Trombe walls through latent heat storage [48,49].

Figure 2 illustrates the operational principle of PCM-enhanced Trombe wall. The PCM is melted by incoming solar radiation, which heats the wall during the day. When the air channel and subsequently the thermal wall cool down (after prolonged cloud cover or sunset), the PCM starts to gradually solidify [50], i.e., change its state from liquid into solid. This is accompanied by heat release; thus, the thermal energy is released during the evening and night hours to warm the building. Furthermore, PCM-enhanced units require far less space than that of traditional Trombe walls to store the same amount of heat and are significantly lighter. The duration and intensity of the released thermal energy during nonsolar hours in a PCM-enhanced Trombe wall depend on the PCM material itself, and the volume and thickness of a PCM-filled thermal wall [51].

Compared to a conventional Trombe wall, the PCM–Trombe wall can achieve greater total energy saving. Optimal parameters such as the temperature of the phase change and the thickness of the PCM depend significantly on latitude, altitude, and local shading conditions [52]. As a result of its high latent heat and thermal conductivity, hydrated salt exhibits fewer fluctuations in indoor temperature than paraffins do [46]. PCM-enhanced Trombe walls (Figure 2) also demonstrate effective overheating prevention in the summer and satisfactory heating effects in the winter [53].

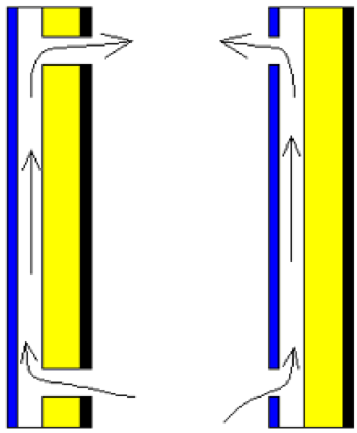

Figure 2. Schematic diagram of PCM-enhanced Trombe wall. (**left**) Winter heating; (**right**) summer cooling.

4. Determination of Solar Heat Gain in Trombe Walls

While Trombe wall systems have certain advantages, the system must be designed thoroughly while considering the specifics of climatic regions, local factors, and detailed building aspects, as this technology has a number of limitations. The performance of a typical Trombe wall is dependent not only on its construction, but also on external factors such as the ambient temperature and the incident solar radiation [54]. Consequently, it can offset space heating energy needs and contribute to the thermal comfort of a building [55], but it must be combined with other nonpassive systems that can provide heating when necessary [56,57].

For instance, full-height Trombe walls completely block the sun's direct rays from entering the building, necessitating an electrical lighting system in the back room even during the day, thereby increasing the building's supplementary energy consumption [58]. Even if Trombe walls reduce the building's energy consumption during the heating season, if they are poorly designed, they can act as additional cooling loads during the cooling season, consequently increasing cooling energy requirements [59].

While Trombe wall systems are primarily used for winter heating, these systems can also be employed to reduce the summer solar heating effect. However, rather than venting the heated air mass, the energy can be used to heat domestic water. Moreover, the system can contribute to indoor ventilation through the chimney effect [17,57,60].

Incorporating a solar chimney into a Trombe wall can improve natural ventilation and reduce cooling loads during the cooling season [5].

The amount and intensity of solar heat capture through a Trombe wall is determined via various factors, such as [61]:

- The effective surface area of the Trombe wall glazing layer, m^2.
- The technical properties of glass (material and thickness, transmission ratio, U-value, SHGC, etc.).
- Wall orientation in reference to the incident solar radiation.

However, not all incident solar radiation can be used entirely (due to several factors, such as diffusion, resistance, and losses); therefore, solar heat gain through a Trombe wall glass layer can be calculated with the following equation [62]:

$$S_i = \sum_{n=1}^{4} [S_{inc,n,i}(1 - D_{n,i})SHGC_n \cdot A_n] \cdot 0.93 N_{h,i} \quad (1)$$

where:

S_i—solar heat gains, W;

$S_{inc,n,i}$—daily solar radiation component on a vertically oriented surface, W;

$D_{n,i}$—shading coefficient;
$SHGC_n$—solar heat gain coefficient.

Analyzing the sources of scientific literature, it can be concluded that passive solar energy systems can be directly or indirectly evaluated. Directly, the methodology includes calculations that describe in detail the thermal performance of a given system element, including temperature graphs and CFD simulations [63].

Indirectly, passive solar energy systems can be evaluated using various standards and regulations that were designed to evaluate the overall energy efficiency of a building [64,65]. In this case, the efficiency of the system is expressed as energy savings from the total energy consumption of the building or as total solar heat gains [66,67].

The simplest method is to calculate heat flow q_w using Trombe wall heat transfer coefficient U and the minimal outdoor air temperature according to the following formula:

$$q_w = U \cdot (T_i - T_e) \tag{2}$$

In this case, the calculated heat flow characterizes the heat loss through the Trombe wall without taking into account the heat capacity of the structure, and assuming that no solar radiation is available. For a more accurate calculation of the heat flow, the hourly outdoor air (so-called sol-air) temperature can be used [68,69].

$T_{sol\text{-}air}$ is the assumed outdoor air temperature that, in the absence of direct solar radiation and air movement, produces the same heat transfer in the building as that caused by the interaction of all existing atmospheric conditions, which is calculated with Equation (3):

$$T_{sol\text{-}air} = T_e + \frac{\alpha \cdot I_g}{h_e} \tag{3}$$

This, in turn, produces (4):

$$q_w = U \cdot \left(T_i - T_{sol\text{-}air} - \frac{\alpha \cdot I_g}{h_e} \right) \tag{4}$$

When calculating the heat flows according to Formula (4), the characteristics of the glass layer [42] of the Trombe wall are not taken into account.

By including the solar energy transmission coefficient τ and thermal transmittance coefficient of the glass, the corrected sol-air temperature can be calculated with Equation (5):

$$T_{sol\text{-}air,c} = T_e + \frac{\tau \cdot \alpha \cdot I_g}{U_{TI}} \tag{5}$$

The provided equations reflect a steady-state setting; however, Trombe wall systems operate under nonsteady conditions. To reflect real applications, the transient-state behavior should be explored.

The heat gain for a transient state is determined via the heat balance between the heat flux caused by solar radiation, and the heat loss caused by the temperature difference between the indoor and outdoor environments [47].

$$q_i = q_g + q_h \tag{6}$$

where:

q_i—heat flux density on the inner surface of the lime silica bricks wall (W/m^2);
q_g—heat flux density from the absorption of solar radiation;
q_h—heat loss due to the difference in air temperature on the two sides of the wall.

The solar thermal gains Q_g (Wh) generated by the absorption of solar radiation in the Trombe wall unit at its operational state can be calculated as follows [47]:

$$Q_g = A_w \cdot \int (q_i - q_h) dt \tag{7}$$

Trombe wall systems could reduce or partly offset heating needs in residential, commercial, and industrial applications.

As such, these systems may also be used to preheat the primary air supply in cold (and moderate) times of year before entering heat recovery units into industrial/commercial buildings equipped with mechanical ventilation systems [60].

Even a slight temperature increase above the outdoor temperature before the heat recovery unit may result in significant savings if viewed across the entire year.

Trombe walls have not been studied sufficiently in moderate and cold climatic conditions with variable precipitation and a few hours of sunshine, so it is not possible to predict the impact of ice on the importance of the structural surface and albedo effect in winter conditions.

5. Review of Performance Improving Trombe Wall Modifications

Table 1 compiles some of the most significant literature sources over the past 15 years on Trombe wall performance-improving case studies, including numerical (mathematical and computer-aided design simulations) and experimental (full-scale tests, real-time measurements) studies. The main features of the improved Trombe wall design (such as PCM enhancement, and structural modification such as PV and BIPV) and the main results are provided.

Table 1. Literature analysis of Trombe wall modifications for performance enhancement.

No	Reference	Type of Study	Year	Location	Type of Trombe Wall	Performance-Improving Modifications	Main Results
1	Jie, J., Hua, Y., Wei, H., Gang, P., Jianping, L., and Bin, J [70]	Experimental	2007	Tianjin, China	Solar hybrid double wall	Conventional glass panel converted into PV glass panel	The thermal performance of the examined Trombe wall was improved, suggesting that a PV-enhanced Trombe wall system can provide both thermal energy (for space heating) and electrical energy. Furthermore, higher amounts of electrical energy could be achieved via individual modifications.
2	Cabeza, L. F., Castellón, C., Nogués, M., Medrano, M., Leppers, R., and Zubillaga, O. [71]	Experimental	2007	Lleida, Spain	Microencapsulated PCM in concrete wall	Commercial modified PCM with a melting point of 26 °C and a phase change enthalpy of 110 kJ/kg	The PCM-enhanced Trombe wall demonstrated an improvement in indoor thermal comfort compared with the one without PCM. Higher thermal inertia was achieved by encapsulating PCMs.
3	Abass Kh.I.; Chaichan M.T. [72]	Experimental	2009	Baghdad, Iraq	Classical Trombe wall	Paraffin wax	The wall containing PCM was an effective storing medium that enhanced the overall thermal performance of Trombe walls. Results showed the ability of this wall type to heat spaces efficiently during Iraqi winters starting from sunset till 5.30 the next morning, utilizing the collected and stored solar thermal energy during the day.
4	Abass Kh.I.; Chaichan M.T. [72]	Experimental	2015	Baghdad, Iraq	Water Trombe wall	Paraffin wax	The PCM wall was effective at storing solar energy, and paraffin wax played a significant role in storing heat during the phase-change period and in heating the air during discharge.
5	Fiorito, F. [73]	Numerical	2012	Five Australian cities (Hobart, Melbourne, Sydney, Brisbane, and Alice)	Classical Trombe wall	Four different commercial paraffin PCMs (RT21, RT27, RT31, and RT42)	The incorporation of various PCMs resulted in an optimal reduction in indoor temperature fluctuations in cool climates and a reduction in the variability of surface temperatures in warm, and hot and dry climates.

Table 1. *Cont.*

No	Reference	Type of Study	Year	Location	Type of Trombe Wall	Performance-Improving Modifications	Main Results
6	Kara, Y. A., and Kurnuç, A. [74]	Experimental	2012	Erzurum, Turkey	Trombe wall with novel triple glass	Commercial GR35 and GR41	The ratio of solar energy gain (RSEG) to the heat load of the test room per month varied strongly, but the resulting overall efficiency was between 20% and 36%.
7	Kara, Y. A., and Kurnuç, A. [75]	Experimental	2012	Erzurum, Turkey	Trombe wall with novel triple glass	Commercial GR35 and GR41	During summer months, the solar transmittance of the TGU decreased by approximately 100% to that of winter, eliminating overheating concerns in the summer.
8	ben Romdhane, S., Amamou, A., ben Khalifa, R., Saïd, N. M., Younsi, Z., and Jemni, A. [76]	Numerical	2012	Baghdad, Iraq	Classical Trombe wall	$CaCl_2 \cdot 6H_2O$ and paraffin wax (*n*-eicosane)	Integrating PCMs into building envelopes is the best way to maximize the PCM potential for reducing energy costs, the peak indoor air temperature, and temperature fluctuations. In addition, they were capable of delivering superior performance and enhancing the thermal comfort of buildings.
9	Zalewski, L., Joulin, A., Lassue, S., Dutil, Y., and Rousse, D. [77]	Experimental	2012	Béthune, France	Trombe Michel wall	PCM (mixture of hydrated salts with melting point of 27 °C)	In the same temperature range, PCM-enhanced wall can store more thermal energy than the same volume of concrete wall. The melting phase of PCM at 27 °C was identified as the phase of sensible energy storage.
10	Bourdeau, L., and Jaffrin, A. [78]	Experimental and numerical	2013	Valbonne, France	Classical Trombe wall	$CaCl_2 \cdot 6H_2O$	Using PCMs instead of masonry wall resulted in 10% higher thermal energy output.
11	Aelenei, L., Pereira, R., Gonçalves, H., and Athienitis, A. [79]	Experimental and numerical	2014	Lisbon, Portugal	Hybrid BIPV–PCM Trombe wall	PCM (melting temp.: 18 to 23 °C; latent heat: 120 kJ/kg)	A BIPV–PCM installed in an office building façade was investigated to approach the practical application of PV–PCM. The calculated thermal and electric efficiencies revealed a thermal system efficiency of approximately 10%, and an overall (electrical and thermal) system efficiency of approximately 20%.
12	Kolaitis, D., Garay, R., Astudillo, J., and Founti, M. [80]	Experimental and numerical	2015	Derio, Spain	Classical Trombe wall	PCM (melting point: 28 to 30 °C; latent heat 190 kJ/kg	The primary objective of this study was to examine the thermal behavior of a PCM-enhanced solar wall (PCMESW) using experimental and numerical simulation methods. The examined system demonstrated reasonable capacity to contribute to space heating.
13	Zhou, G., and Pang, M. [81]	Experimental	2015	Beijing, China	Classical Trombe wall	$CaCl_2 \cdot 6H_2O$	Utilizing PCMs in the Trombe wall could sustain indoor thermal comfort for extended durations. During charging and discharging processes, the vortex generator pairs (for heat transfer enhancement) significantly increased the heat transfer rate at the surface of the PCM panel.
14	Favier, P., Zalewski, L., Lassue, S., and Anwar, S. [82]	Experimental	2016	Croisilles, France	Classical Trombe wall	PCM with melting point of 27 °C	The results suggested that the PCM was effective in protecting solar walls from overheating and improving the energy management efficacy.
15	Kolaitis, D., Garay, R., Astudillo, J., and Founti, M. [80]	Numerical	2016	Five different European cities (Athens, Madrid, Paris, Berlin, and Helsinki)	Classical Trombe wall	Commercial PCM (phase-change temperature: 22 to 28 °C)	The PCMESW demonstrated higher efficiency in compared with the conventional solar wall with regards to thermal energy generation.

Table 1. *Cont.*

No	Reference	Type of Study	Year	Location	Type of Trombe Wall	Performance-Improving Modifications	Main Results
16	Sun, D., and Wang, L. [83]	Experimental and theoretical	2016	Jilin, China	Classical Trombe wall	Phase-change temperature: 19.45 °C; latent heat: 128.46 J/g.	Passive solar collector–storage wall system enhanced with PCM facilitated thermal air circulation into the room to improve the indoor temperature, and the passive solar phase-change room's (PSPCR) good heat storage capacity improved energy-saving characteristics for occupancy.
17	Leang, E., Tittelein, P., Zalewski, L., and Lassue, S. [84]	Numerical	2017	Béthune, France	Trombe Michel wall	Commercial PCM (Micronal®) with a melting point of 26 °C	The PCM storage wall demonstrated greater storage capacity than that of a concrete storage wall.
18	Luo, C., Xu, L., Ji, J., Liao, M., and Sun, D. [85]	NUmerical	2017	Nanchang, China	PV–Trombe wall	Melting point: 29 °C; latent heat: 160 kJ/kg.	A Trombe wall with PCM demonstrated an effective cooling effect and was able to reduce the working temperature of PV cells, preventing the summertime overheating of the room.
19	Hyde et. al. [86]	Experimental and numerical	2018	Los Alamos, New Mexico	Classical Trombe wall	$CaCl_2{\cdot}6H_2O$	PCM walls resulted in lower weight and size, which is deemed advantageous in various applications, especially when it comes to larger scale units.
20	Zhou, Y., Yu, C. W. F., and Zhang, G. [87]	Experimental and numerical	2018	Changsha, China	Ventilated Trombe wall	Fusion temperatures of PCMs in exterior and interior PCM wallboards were 26 and 22 °C, respectively.	The thermal performance of new ventilated Trombe incorporating phase-change materials (PCM–VTW) in a building in a remote region of China with hot summers and cold winters was evaluated. The examined PCMVTW contributed to a 14% reduction in cooling and heating loads.
21	Zhou, Y., Yu, C. W. F., and Zhang, G. [88]	Numerical	2018	Wuhan, China	Trombe wall with solar chimney	SSPCM (mass composition: 80% paraffin, 15% high-density polyethylene, and 5% expanded graphite)	The peak cooling and heating loads in PCM Trombe rooms were reduced by 9% and 15%, respectively, when compared to conventional Trombe rooms. Comparatively, the PCM room had 3.28 °C lower average summer temperature and a 0.11 °C higher winter temperature than those of the reference room.
22	Li, S., Zhu, N., Hu, P., Lei, F., and Deng, R. [89]	Numerical	2019	Wuhan, China	Classical Trombe wall	Phase-change temperature of external PCM: 30 °C; internal PCM: 18 °C.	In comparison to traditional Trombe walls, PCM Trombe walls could reduce cooling and heating loads throughout the entire year, and improve indoor thermal comfort.
23	Li, W., and Chen, W. [90,91]	Numerical	2019	Shanghai, China	Classical Trombe wall	Eutectic hydrated salt with melting point: 27.5 °C; latent heat: 127 kJ/kg.	Incorporating PCM into the Trombe wall increased the average indoor temperature by approximately 20.2% at night in heating mode.
24	Du, L., Ping, L., and Yongming, C. [20]	Numerical	2020	Yancheng, China	Classical Trombe wall	Air flow enhancement through Trombe wall channel	Trombe walls could be utilized for building ventilation due to the relatively high air-flow mass. In the winter, they can be used to heat buildings with relatively low air-flow mass that was heated by sunlight.
25	Yan, T., Luo, Y., Xu, T., Wu, H., Xu, X., and Li, J. [92]	Experimental	2020	Hefei City, Anhui Province, China	Classical Trombe wall	Phase-change temperature: 22 to 27 °C; latent heat: 160 kJ/kg.	The findings indicated that this system could effectively prevent overheating issues during the summer.

Table 1. *Cont.*

No	Reference	Type of Study	Year	Location	Type of Trombe Wall	Performance-Improving Modifications	Main Results
26	Carmona, M., Palacio Bastos, A., and García, J. D. [93]	Experimental	2021	Puigverd de Lleida, Spain	Ventilated double-skin façade	Commercial SP-22	Utilizing s PCM–Trombe wall, the thermal performance of the entire structure was enhanced. By incorporating a phase-change material (PVT–PCM) into the hybrid module, a stable and lower operating temperature was achieved.
27	Yan, T., Luo, Y., Xu, T., Wu, H., Xu, X., and Li, J. [92]	Experimental	2021	Hefei City, Anhui Province, China	Classical Trombe wall	Not known	The system was highly adaptable to meeting the climatization needs of buildings during each season of the year.
28	Onishi, J., Soeda, H., and Mizuno, M. [94]	Numerical	2021	Sapporo, Japan	Classical Trombe wall	The phase-change temperature range of the PCM WAS 35 to 36 °C	Results demonstrated the operational efficiency of PCMs and suggested that this system could be used to the further development of low-energy houses in Japan.
29	Zhang, L., Dong, J., Sun, S., and Chen, Z. [66,95]	Experimental and numerical	2021	Quebec, Canada	Classical Trombe wall	Commercial mixture (50% butyl stearate, 48% butyl palmitate; freezing point: 17 °C)	Utilizing PCM as a heat storage material could substantially lower the use of conventional construction materials. In addition, the improved Trombe wall could utilize solar energy for superior thermal efficiency space heating. Therefore, the improved Trombe wall is significantly more applicable than a traditional Trombe wall is.
30	Kong, X., Li, J., Fan, M., Li, W., and Li, H. [96]	Numerical	2022	Tianjin, China	Classical Trombe wall	New double-layered PCM-enhanced Trombe wall featuring multiple phase transition points	The results demonstrated that the average temperature in the new double-layered PCM Trombe room could be decreased by 0.4–0.93 °C during summer and increased by 0.3–6.6 °C during winter. In addition, the peak summertime temperature could be significantly delayed.
31	Li, J., Zhang, Y., Zhu, Z., Zhu, J., Luo, J., Peng, F., and Sun, X. [66]	Numerical	2022	Changsha, China	Classical Trombe wall	A single layer of an XPS–PCM composite board with a mass PCM fraction of 90% inside the wall.	Compared to the conventional building model, the Trombe wall system with PCM25 adjacent to the inner surface reduced ID by 7.01% and IDH by 14.14%.

6. Conclusions

The utilization of passive solar energy systems is a promising alternative to current energy challenges that the global community faces. However, passive solar energy systems are difficult to forecast, as the solar resource fluctuates over time.

Trombe wall systems are designed to capture and accumulate solar heat in the structure, featuring high heat inertia, and transfer the accumulated thermal energy into the building premises. However, such systems cannot deliver an independent or stable amount of thermal energy; therefore, they are not intended to be used as a primary heat source. The design of a Trombe wall is a complex procedure in which the technical solution of each construction must be adapted to the building's specific geographical and climatic parameters.

Trombe wall systems have the potential to reduce or partly offset heating needs in residential, commercial, and industrial applications. While residential and commercial applications require more attention in the pretreatment of outdoor air (such as outdoor pollution and dust filters), industrial premises such as factories and unclassified buildings that normally do not require high indoor comfort may utilize simplified Trombe wall solutions that do not stipulate thorough architectural design considerations and high investment amounts.

The Trombe wall technology offers a number of advantages as a passive solar heating system:

- Renewable and clean energy source.
- Low-budget and maintenance-free solution.
- Heating (and cooling) of the premises with proper design modifications.

However, this technology is entirely dependent on the intensity of the incident solar radiation and thereby might present a number of limitations, such as the intermittency of heat energy production and the complete absence of thermal energy production when solar radiation is insufficient. These systems are also difficult to control and operate, and in sunny regions, there is a risk of structural damage due to overheating if a Trombe wall system has been improperly designed or installed. Therefore, a number of considerations have to be taken into account with respect to overheating risk in the summer and undertemperature risk in the winter.

Moreover, if supplemented with PCM and/or PV/BIPV components, an enhanced Trombe wall system may produce a reasonable thermal energy output to substantially reduce the space heating needs of a building. As such, modified and enhanced Trombe wall systems may be applicable as a secondary heating source in cold climatic regions to offset space heating needs of up to 10% in the cold season (winter) and 25–30% in the transition season (late fall/early spring).

The reviewed literature sources offer detailed insights into numerical, experimental, and analytical studies with respect to various Trombe wall modifications to enhance the system's performance. In addition to the identified and analyzed Trombe wall modifications and enhancement techniques that were considered within the framework of this review, the forced air circulation approach should be reviewed in more detail to facilitate the (a) heat transfer rate, (b) air discharge rate, and (c) thermal comfort on the receiving end (at the end-user side), and (d) review the potential air treatment (filtering) options to avoid pollution and contamination build-up in the wall structure, and thus in the recirculated and supplied air mass.

Author Contributions: Conceptualization, A.P. and A.B.; methodology, A.B. and D.B.; resources, G.B., validation—A.B.; writing—original draft preparation, A.P.; revision—A.B. and D.B.; visualization, A.B. and G.B.; supervision, A.B. and D.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by the European Regional Development Fund project "A new concept for low-energy ecofriendly house", grant agreement no/1.1.1.1/19/A/017.

Informed Consent Statement: Not applicable.

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

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