Review on the sustainability of phase-change materials used in buildings

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Abstract

Phase-change materials have become a vital solution for saving energy and reducing greenhouse gas emissions from buildings. However, the production processes of phase-change materials affect their cost, impact societies, and may result in harmful emissions to the environment. In this study, we perform a review on the sustainability of phase-change materials considering performance, economic, environmental, and social aspects. While there is an extensive literature on the performance and efficiency of phase-change materials, there is limited consideration of social fairness and the environmental impact. So, we analyze the lifecycles of four different phase-change materials: a salt hydrate, a hydrocarbon, and two types of biobased materials. Our results show that hydrocarbon phase-change materials have the highest purchasing cost, the highest effect on the environment, and their production is associated with social risks related to safety and health. On the other hand, biobased (plant-based) materials are affordable, safe, provide new market opportunities for crops, and have minimal environmental harm if biofertilizers are used. The use of manurial fertilizers do not give biobased phase-change materials an advantage over other types. We also note that social fairness in production should be respected for sustainable phase-change materials solutions.

Keywords

Sustainability, Buildings, Life Cycle Assessment (LCA), Phase Change Materials (PCM), Environmental Cost Indicator (ECI), Social Impact.

Nomenclature		**Units**	
Abbreviations		Melting Temp	°C
Environmental Cost Indicator	ECI	Enthalpy (ΔH)	kJ/kg
Phase Change Materials	PCM	Specific heat (Cp)	J/g. °C
Life Cycle Assessment	LCA	Thermal conductivity (K)	W/m.°C
Energy Storage Systems	ESSs	Density	g/cm^3
Thermal Energy Storage	TES	**Prices**	
Cumulative Energy Demand	CED	Dollar	$
Global Warming Potential	GWP	Euro	£

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1. Introduction

The rapid universal development of using energy has driven the world to serious concerns such as depletion of energy resources and undesirable environmental issues represented by high emissions of CO_2, global warming, air pollution, and ecosystem decline [1]. Besides, the consumption of energy has been escalating during the last decade. Thus, the challenge is to increase energy resources with less harm to nature and at minimal cost [2]. Studies show that buildings have a considerable share of around 40% of global energy consumption. For instance, their share in some countries exceeds one-third of the energy consumption, consequently, buildings are predominantly responsible for greenhouse gas emissions and global warming [3, 4]. Accordingly, it is critical to take prompt action in this regard.

To manage the high energy demand, the depletion of natural resources and climate change issues, sustainable renewable energy systems and management methods have been developed to form better alternatives to the conventional energy generation systems. These systems constitute essential solutions as vital as finding a new source of energy, however, renewable energy systems have some limitations such as being not effective at all periods, having low efficiency, and requiring continual development. Hence, Energy Storage Systems (ESSs) were integrated to enhance efficiency and save energy while being eco-friendly [5, 6]. The importance of energy storage is represented by storing excess energy at a time and releasing it for later use. This method diminishes the imbalances between the demand and supply of energy and insure reliability, economic, and environmental benefits [7].

As mentioned previously, buildings have a high share of energy consumption and are responsible for a significant amount of CO_2. In Europe, around 4×10^8 tons of CO_2 emissions in buildings and industries have been avoided and 1.4 million GWh/year has been saved by employing Thermal Energy Storage (TES) systems [8]. TES systems store thermal energy in a building at its off-peak load periods to counterpart the on-peak demand situation.

TES in buildings [9] is classified into (1) Active and (2) Passive methods. An active storage system is represented mainly by forced convective heat transfer and, in certain situations, mass transfer. The use of TES in building active systems is an appealing and customizable solution for a variety of applications for new or redeveloped buildings, such as the deployment of Renewable Energy Sources (RES) in the HVAC for space heating/cooling, the upgrading of existing installations' performance, and the potential uses of peak load-shifting strategies [10]. Although active TES are well known and effective, however, they consume power and/or require external energy to function. On contrary, passive methods, which do not require external power, can be applied through sensible thermal storage, which are materials of high thermal mass, and latent thermal storage using phase-change materials (PCMs) in the building walls, floor, or ceiling. Through latent heat storage features, PCMs function upon transferring latent heat energy through solidification or fusion processes, unlike sensible storage materials, PCMs charge and discharge heat at almost a constant temperature [11, 12]. The high interest in thermal latent storage systems, which is mainly represented by phase-change materials (PCMs) [13], encourages us to go deep in studying PCM in buildings.

In this research, we study the sustainability of PCMs integrated into buildings, review the efficacy of various PCMs, compare their prices, and evaluate their environmental impacts and possible social strains associated with their production. We also highlight the importance of promoting social fairness as an important factor in sustainability. An analysis is done to highlight the most convenient materials in terms of efficiency, cost, and eco-friendliness, and discuss the factors that make PCM usage a sustainable solution for reducing energy consumption in buildings.

The paper is organized as follows. We start in section 2 with a review of the types of PCMs, their thermophysical properties, their problems, and their incorporation into buildings. In section 3, we address the sustainability of PCMs. We summarize the efficiency of their use based on various studies, their economic benefit and payback periods, and some inferred environmental effects. Due to the lack of sufficient literature on the environmental and social aspects, we perform a lifecycle analysis, in section 4, to calculate the environmental impact of four PCMs selected from different categories. In section 5, we highlight some of the potential social impacts that can be associated with PCM production based on data from different production sectors. We end the paper by recommending how to improve the sustainability of PCM usage in buildings.

2. Review on types, properties, and uses of PCMs in buildings

PCMs can save 5 to 14 times more energy in one unit volume than conventional sensible storage materials (water, masonry, or rock) [14]. Kuznik, F et al. [15] experimented with the storage capacity of different storage materials functioning under the same conditions as shown in Figure 1. They found that PCM has considerably the highest storage capacity and it can store heat or cold with high storage density.

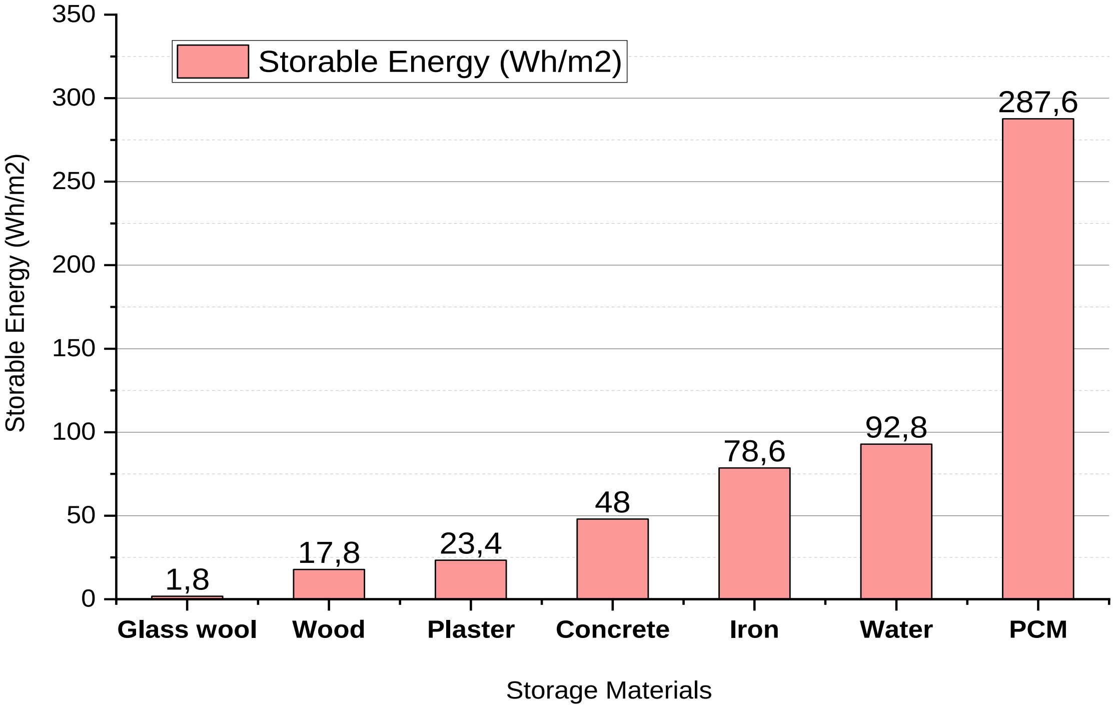


***Figure** 1: Storage energy capacity of different materials under the same conditions (reproduced from [15])*

As noticed in Figure 1, PCM has the highest energy storage capacity, this merit encourages the researchers to involve PCM in buildings rather than other TES techniques. Consequently, integrating PCM in buildings is likely to acquire large potential and compatibility, where PCMs can store a considerable amount of thermal energy in a building at its off-peak load periods to counterpart the on-peak demand situation [15]. Furthermore, latent heat devices are better than sensible because they can store a large amount of heat (with only a small to no temperature difference [16].

2.1. Selection criteria of PCM materials

Although the fusion of PCMs takes place in any desired range, PCMs must display specific eligible thermodynamic (thermal and physical), chemical, kinetic, and environmental properties [14, 17]. Furthermore, economic aspects and the availability of PCM must be taken into consideration. The PCM selection criteria presented in Figure 2 summarize the important factors that affect the employment of PCM materials not just in buildings but in various applications as well.

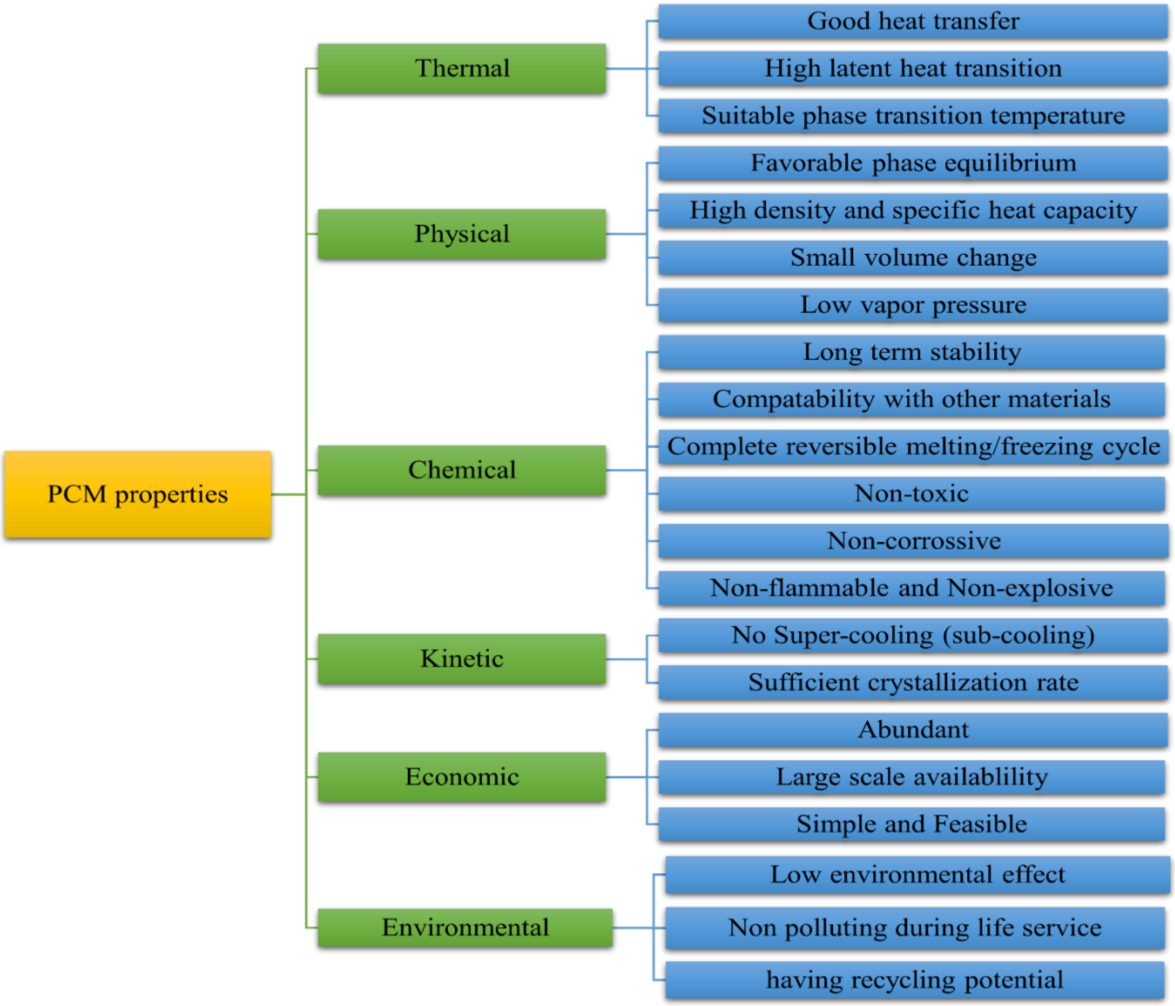


Figure *2: PCM selection criteria*

2.2. Types of PCM materials used in buildings

PCMs come in four different states: solid-solid, solid-liquid, gas-solid, and gas-liquid. These four states differ from one another, for instance, solid-gas and liquid-gas are incompatible with building materials because of some technical limitations such as (1) major volume changes within the process of phase transition, and (2) presence of high pressure of the gas phase in the system [18, 19]; thus, these states will not be discussed further. The solid-liquid PCMs are mostly used due to their practicality and their compatibility with building materials [20]. PCMs of the solid-liquid phase come in three different types: organic, inorganic, and eutectic [21] as shown in Figure 3.

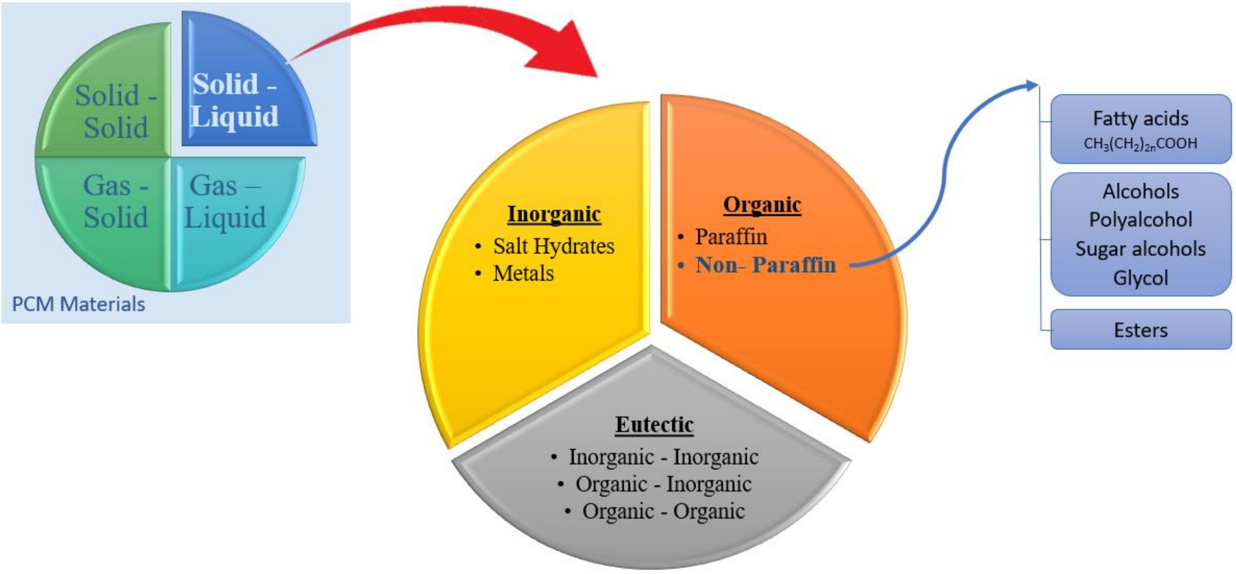


***Figure** 3: Types of PCMs*

Figure 3 shows three types of PCMs: organic (O), inorganic (I), and eutectic. Each one has specific characteristics and forms [21] as represented below:

2.2.1. Inorganic

Inorganic PCMs cover a wide range of temperatures. Although inorganic PCMs have comparable latent heat per unit mass to organic PCMs, their latent heat per unit volume is generally higher due to their higher density. Salt hydrates are one type of inorganic salts consisting of inorganic salts (AB) and one or multiple water (H_2O) molecules, which result in a crystalline solid form ($AB.xH_2O$) [22]. There is a long list of salt hydrates that have a wide range of melting point temperatures between 5 and 130°C, which is a suitable range for various applications. Some examples of salt hydrates are listed in Table 1. Metallic is another type of inorganic material that has a high melting temperature such as rocks, concrete, stones, etc. However, our study will be concerned with building applications that require PCM materials that have melting points between 18 and 30 degrees.

2.2.2. Organic

Organic PCM (OPCM) includes paraffin [23], and non-paraffin. OPCMs are known for their availability in wide a temperature range and freeze with low supercooling possibility [24, 25]. Paraffins are classified into two types [26]: (1) saturated hydrocarbons that follow the linear alkanes' general formula C_nH_{2n+2} with several carbons that vary from 12 to 40, and (2) blend of alkanes with other hydrocarbons of the form $CH_3(CH_2)nCH_3$, which are known as "paraffin wax" [27, 28]. It is noted that the pure alkanes are more expensive than blends, however in both cases, as the number of carbons increases the melting temperature and heat of fusion increase [26]. Besides, the more purity the paraffin is the higher the cost [29]. Hence, pure paraffin wax (more than 99%) costs more than practical paraffin wax (90 - 95%). Non-paraffin is another type of organic PCM. The well-known types of non-paraffin are fatty acids, glycol, polyalcohol, and sugar alcohols [30]. Fatty Acids are organic compounds that follow the form $CH_3(CH_2)2nCOOH$. They have not been comprehensively investigated as salt hydrates or paraffin; however saturated fatty acids are of great benefit for TES purposes. Besides, they show a wide range of melting temperatures that range from 8 to 64 ℃, with the enthalpy of fusion varying from 149 to 222 kJ/kg. Furthermore, fatty acids have a relatively low thermal conductivity

2.2.3. Eutectic

Eutectic PCM is a mixture of two or more chemicals, which when mixed offer several [31] benefits such as the capability to acquire more desired properties (higher heat storage capacity, specific melting point) [32]. Eutectics can be a mixture of inorganic or/and inorganic (organic - organic, organic-inorganic, inorganic - inorganic).

2.3. Comparison among PCM types

2.3.1. Thermophysical properties and Cost

PCMs used for building applications should have a melting point in the range of human comfort temperature (25–30ºC) [33]. Consequently, Table 1 shows the thermophysical properties in Solid (S) and Liquid (L) states, and the price of PCM materials of different types that have a melting temperature that ranges between 18℃ and 30℃.

Table 1: Thermophysical properties of some PCM materials

	PCM materials	*Melting Temp. (ºC)*	*ΔH (kJ/kg)*	*Specific heat Cp (J/g.ºC)*		*Thermal conductivity K (W/m.ºC)*		*Density (g/cm³)*		*Price \$/Kg [34]*
				S	L	S	L	S	L	
salt hydrates	Potassium fluoride tetrahydrate $KF.4H_2O$ [35, 36]	19	231	1.84	2.59	0.584	0.479	1.445	1.456	4.85
	Iron (III) bromide hexahydrate $FeBr_3{\cdot}6H_2O$	21	105	NA	NA	NA		NA	NA	NA
	calcium chloride hexahydrate $CaCl_2.6H_2O$ [34, 35, 37]	24	140	1.4	2.1	1.09	0.54	1.71	1.47	0.39
		28	188.34	1.25	2.13	1.09	0.54	1.71	1.5	
		29.6	190.8	1.42	2.1	1.088	0.54	1.802	1.562	
	Manganese Nitrate Hexahydrate Mn(NO3)2·6H2O [38, 35]	25	125.9	NA	NA	NA	NA	1.6	1.738	0.29
	Lithium nitrate trihydrate $LiNO_3.3H_2O$ [38, 39, 40]	30	256	1.79	2.75	0.89	0.584	1.46	1.425	4.71 [41]

Paraffin	heptadecane $C_{17}H_{36}$ [42]	22	240	NA		0.2		0.774	0.776	8.17
	Octadecane $C_{18}H_{38}$ [27, 42]	28	244	1.934	2.196	0.358	0.148	0.814	0.774	
	$CH_3(CH_2)15CH_3$ [43, 44]	22	171	NA		0.149		0.777		1.88 – 2 [45]
	$CH_3(CH_2)16CH_3$ [43, 46]	29	244	1.2		NA	0.26	0.779		
Non-paraffin	polyalcohol PEG E600	22	127.2	NA	2.49	NA	0.189	1.126		
	Oleic Acid (Fatty acid) $C_{17}H_{33}COOH$ $C_{18}H_{34}O_2$	16		2.046						
Eutectics [40]	75%$CaCl_2.6H_2O$ + 25%$MgCl_2.6H_2O$	21.4	102.3	NA	NA	NA	NA	1.59		
	66%$CaCl_2.6H_2O$ + 33%$MgCl_2.6H_2O$	25	127	NA	NA	NA	NA			
	45%$Ca(NO_3)_2{\cdot}6H_2O$ + 55% $Zn(NO_3)_2{\cdot}6H_2O$	25	130	NA	NA	NA	NA			
	40%$Na_2CO_3{\cdot}10H_2O$ + 60% $Na_2HPO_4{\cdot}12H_2O$	27.3	220.2	NA	NA	NA	NA			
	Trimethylolethane + urea	29.8	218	NA	NA	NA	NA			
	67%$Ca(NO_3)_2{\cdot}4H_2O$ + 33% $Mg(NO_3)_2{\cdot}6H_2O$	30	136	NA	NA	NA	NA			
Other organic	d-lactic acid CH3CH(OH)COOH	26								
	Capric acid CH3(CH2)8COOH	21-30								
	Coconut oil [47, 48]	21	70	2.23	2.35			0.918		1.95 - 2
	Palm Kernel oil [49, 50]	25	12.30					0.911		1.32
	50% Beef tallow + 50% Coconut oil [51]	30.1	72.32	2.19	2.25					
	Beef tallow [51]	37.4	101	2.59	2.96					

2.3.2. Graphical representation

In the following section, a comparison among the PCM materials is held to find out which one has the best desirable properties. Figure 4 shows the thermal conductivity (W/m.ºC), specific heat (J/g.ºC), and prices ($/Kg) of some salt hydrates that have melting points between 19 and 30 C.

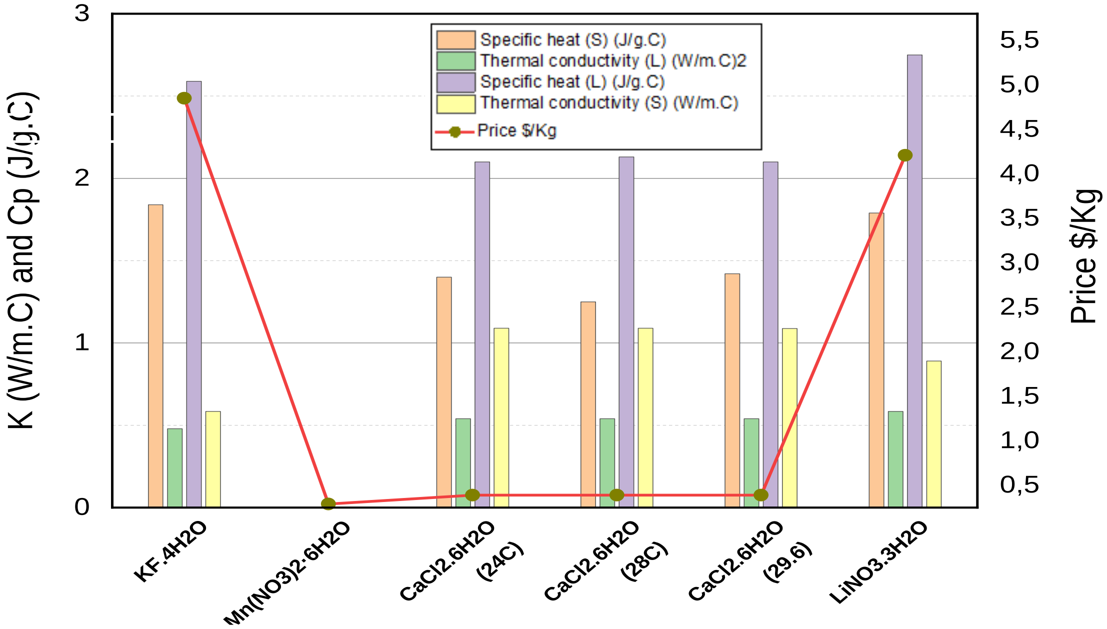


***Figure** 4: Thermal conductivity (W/m.°C), Specific heat (J/g.°C), and prices ($/Kg) of some Salt hydrates that have melting points between 19 and 30 °C.*

As noticed in Figure 4, all salt hydrates have almost the same thermal conductivity in the liquid phase. Besides, calcium chloride hexahydrate at different melting temperatures has similar thermophysical properties with the lowest cost per kg. However, Lithium nitrate trihydrate has the highest specific heat in the liquid phase and Potassium fluoride tetrahydrate has the highest specific heat in the solid phase. We note that calcium chloride hexahydrate and Manganese Nitrate Hexahydrate have a considerable difference from a cost perspective, which makes them used more often than the other materials.

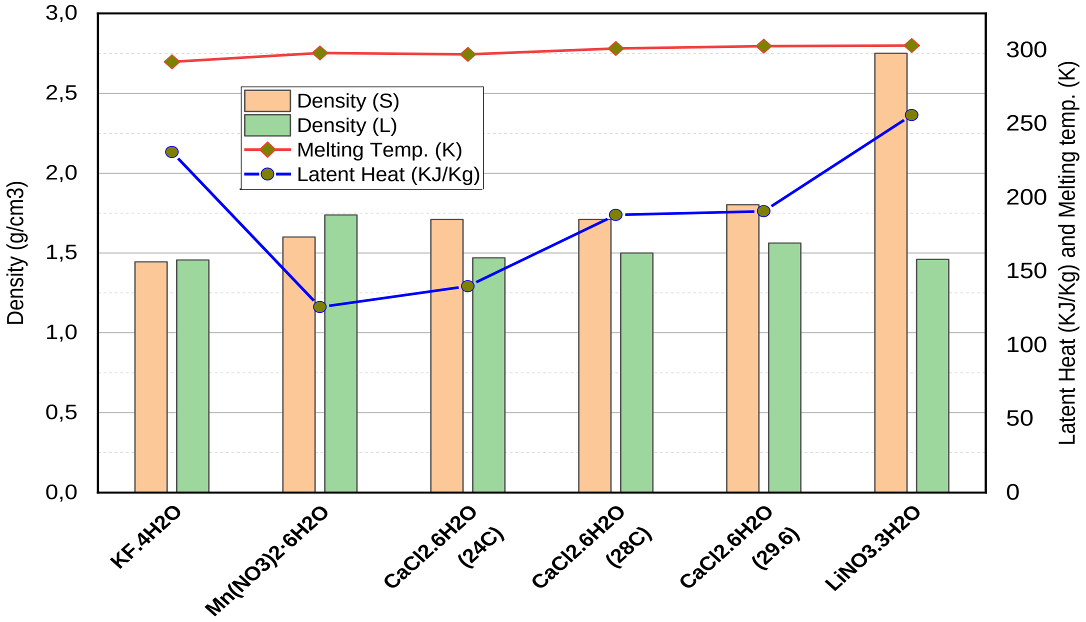


***Figure** 5: Latent Heat (KJ/Kg), Melting Temp. (K), and Density (g/cm3) of some Salt hydrates that have melting points between 19 and 30 °C.*

Figure 5 shows that Lithium nitrate trihydrate has the highest density in the solid phase, on the other side Potassium fluoride tetrahydrate has the highest latent heat. Besides, it was noticed that as the melting temperature of the calcium chloride hexahydrate increases, affected by saturation values, the latent heat increases. Thus, an accurate study must be held to choose among the materials, where Lithium Nitrate Trihydrate and Potassium Fluoride Tetrahydrate have the highest latent heat yet the highest cost. On the other side, Calcium Chloride Hexahydrate has the lowest cost and low latent heat. Accordingly, the superlative material depends on the application used such as the compatibility of the latent heat storage with the size of the construction. The energy-saving is affected mainly by the amount of latent heat of fusion and the amount of PCM used. Thus, it is important to calculate the payback period of the PCM, which signifies the time needed so the cost of the saved energy offsets the initial price of the material.

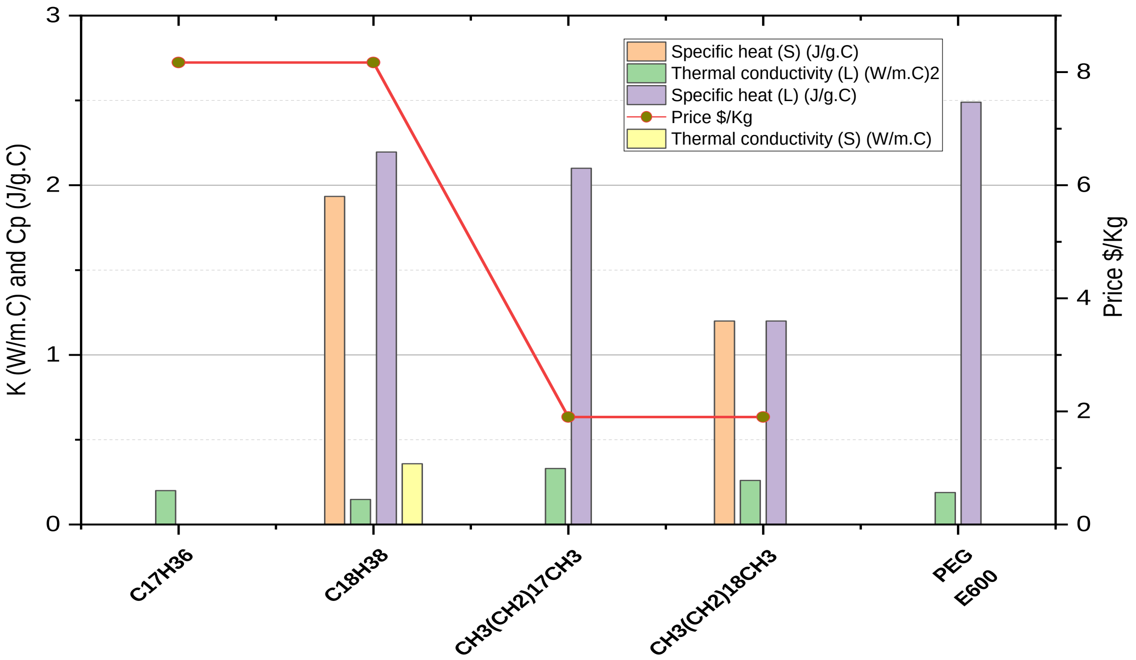


***Figure** 6: Thermal conductivity (W/m.C), Specific heat (J/g.C), and prices ($/Kg) of some Paraffin and non-paraffins that have melting points between 19 and 30 °C.*

Figure 6 shows that the thermal conductivity is very close for all the paraffin and nonparaffin materials. However, the prices vary from one type to another, for instance, paraffins are more expensive than nonparaffins. On the other side, PEG E600 polyalcohols have the highest specific heat in the liquid phase, this made them a desirable choice for building applications, where they can be directly integrated into Hollow Brick cavities and employed in building facades.

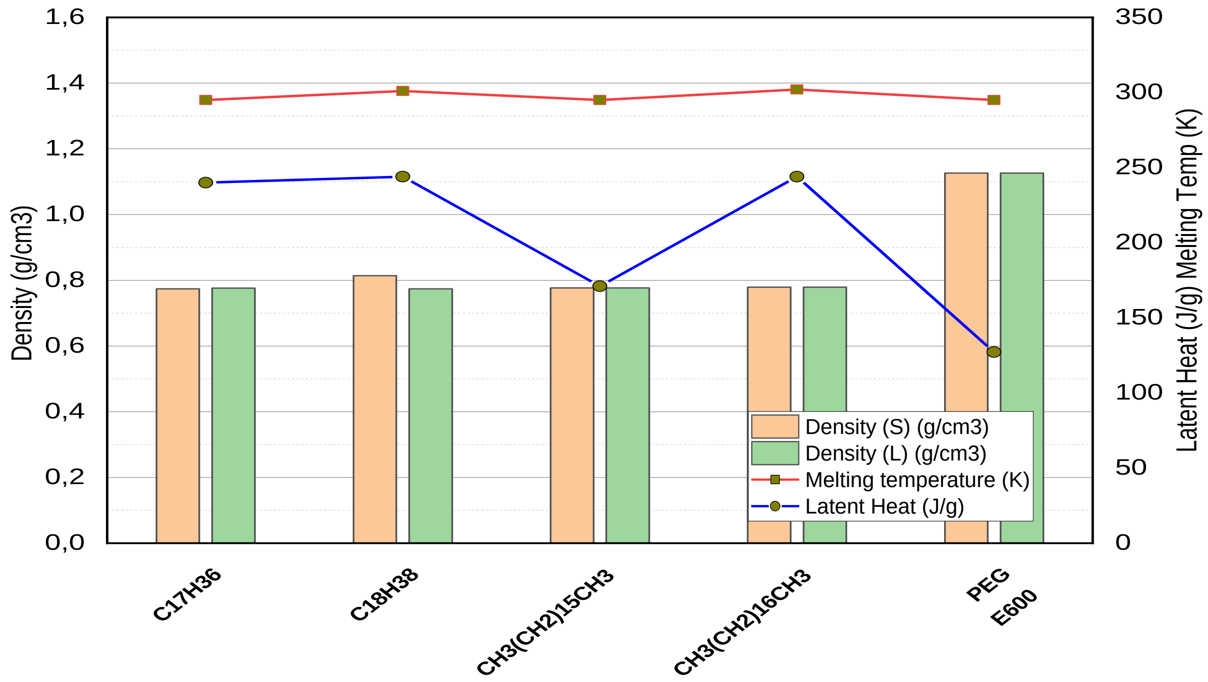


***Figure** 7: Latent Heat (KJ/Kg), Melting Temp. (K), and Density (g/cm3) of some paraffin and non-paraffin that have melting points between 19 and 30 °C.*

As noticed from Figure 7, there is a slight difference between the density (L and S) of paraffins and nonparaffins, whereas PEG E600 has the highest density. On the other side, latent heat differs from one material to another with being minimum for PEG E600.

So, every PCM material has its own set of criteria and qualities that contribute to the system's overall performance. As a result, selecting the best material for the system will aid in improving the TES performance. However, each PCM has flaws that necessitate the incorporation of an element/material as a matrix filler in enhancing its qualities.

2.4. PCM incorporation methods

PCM incorporated in the building envelope controls the thermal capacity, regulates human comfort, and affects the demand for heating and cooling. There are different types of incorporation of PCM in building as illustrated in Table 2 [52, 53]. We highlight, thereby, the advantages and drawbacks associated with each method.

The simplest, most practical, and cost-effective method is direct incorporation, in which the PCM is integrated with the construction material. The PCMs are added to a mixture of components such as lime, gypsum, cement paste, or concrete in the form of powdered and liquid phases throughout the manufacturing process. The main advantage is in the ease and low cost of this method due to the no need for additional equipment. However, some issues, summarized in Figure 8, may arise because of PCM leakage while it is melting, resulting in the low fire resistance of the impregnated materials and even incompatibility between the combined components [17]. Nevertheless, microencapsulated PCM and shape-stabilized have less leakage during the phase change yet microencapsulated is expensive. On the other side, macro encapsulation is simple and can be used in various applications, yet it has a low thermal conductivity and a tendency to solidify at the edges. Form stabilized PCM is cheap and with no leakage above the melting point, still, it requires complex equipment while assembly.

***Table** 2: Methods of PCM incorporation*

	PCM Methods	Example	Pros / Cons
Methods of PCM in building	**Direct incorporation** PCM is added directly to the material's construction	Concrete	• The simplest and most economical method. • Easy to incorporate. • Leakage of PCM leads to incompatibility and raises the risk of fire (for flammable PCMs). • Reduces the mechanical properties of constructed elements through high temperatures.
		Plaster/gypsum	
		Cement	
	Immersion a porous construction material immerses into the liquid PCM; it is absorbed due to capillarity	**Immersion**	The major drawbacks are: • Leakage • Construction incompatibility • Corrosion of fortified steel when combined with concrete elements, thus impacting the lifetime.
		Imbibing	
	Encapsulation Encapsulation is carried out by wrapping the PCM with a shell for prevention from the outer ambience as well as for leakage precaution.	**Macro-encapsulation** (shells, channel, tube thin plates)	This method is substantial for: • Enhancing heat transfer area, which increases the thermal conductivity of PCM as well, to guarantee efficient employment of storage load. • Dodging the leakage concerns of PCM and improving its compatibility with the building structure. Encapsulation material must have specific characteristics: • Prevent leakage and do not react with PCM • Preserve all thermal characteristics of PCM • Compatible with PCM and its application, • Provide structural stability and securing handling. • It must control any volumetric change of PCM through phase changes • Provide proper protection for the PCM versus environmental regression, and good thermal conductivity over PCM life cycles.
		Microencapsulation Specific polymeric material	

		• Aluminum, stainless steel, and copper foils, pipes, and panels are mostly used for macro encapsulation as they provide suitable compatibility, thermal conductivity, and mechanical power to building materials
Stabilization A method used to turn something to be physically more stable and secured.	**shape-stabilized** is a method that includes the PCM within a carrier matrix.	This method is promising because it: • Provides optimal thermal conductivity, high specific heat, and preserves the shape through abundant cycles of phase transition.
	form-stabilized is a developed method of incorporation.	It is a particular method of composite material, which: • Possesses a better amount of PCM types. • Displays no leakage at melting points. • Expensive to execute, yet the most reliable. • Reliability shows that the melting-solidification cycles of PCM are performed without regression, and this merit is pivotal for long-term applications, such as buildings

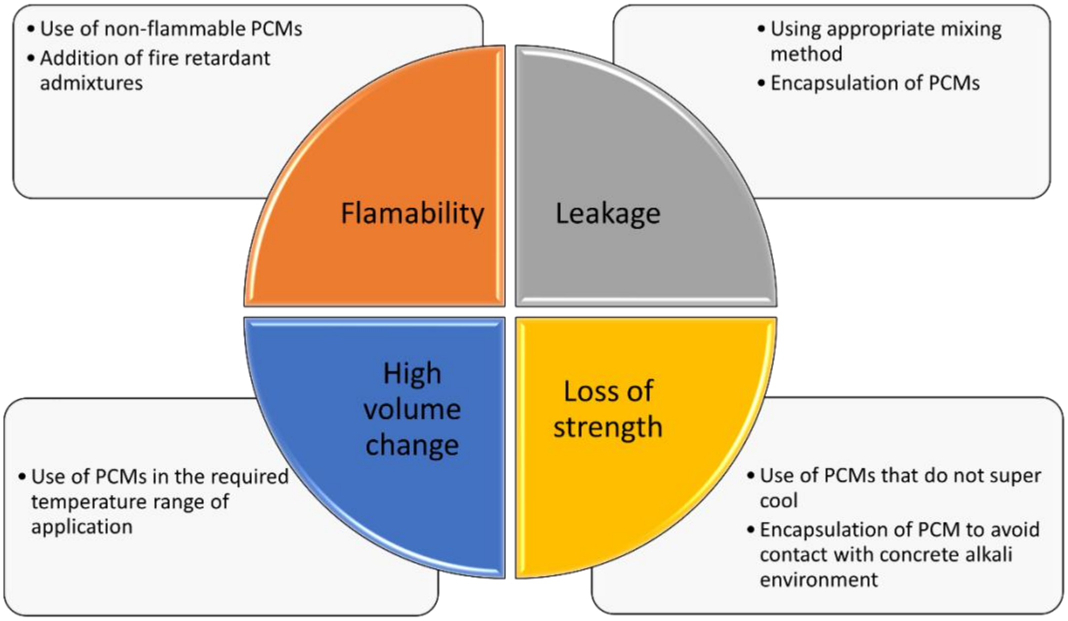


***Figure** 8: Possible solutions for challenges of PCM in concrete based on [16].*

2.5. Passive and active systems in PCM

PCM in buildings can be classified into two categories PCM in passive and active systems as shown in Figure 9 [54]:

- PCM in passive systems, where no external energy is involved, the system uses natural convection to store energy.
    - PCM in building materials, which means involving the PCM inside the structure of the building during the construction such as inside the concrete.
    - PCM as a component, which can be done by fabricating components of PCM that can be assembled later or in an existing building such as PCM panels.

- PCM in active systems, where external mechanical energy is required to offer a better heat transfer coefficient, this is done by replacing the free convection with forced convection, for example adding a small fan.

The active system offers higher storage than the passive one; however, it requires consuming external energy. Thus, the improvement that the forced system offer must fulfill the investment of involving an additional extra mechanical energy system.

3. Review on the sustainability of PCMs

The sustainability of PCMs in the building industry depends on four aspects: performance and efficiency, cost and payback duration, environmental assessment, and social impact. While there is extensive literature on the performance and efficiency of PCMs, there is a limited number of studies that looked at the social fairness aspect and the environmental impact during the production of PCMs. We limit this section to the existing information on the performance of PCMs, their cost, and a brief overview of the environmental impact. In the next sections, we perform detailed lifecycle assessments and address the possible social strains that can result from PCM production.

3.1. Framework

To review the sustainability of PCMs used in the building sector, we collect and compare data related to different study cases and applications following the framework described in Figure 9. Additional calculations using lifecycle assessment method is done for analyzing the environmental impact due to the lack of data in the current literature.

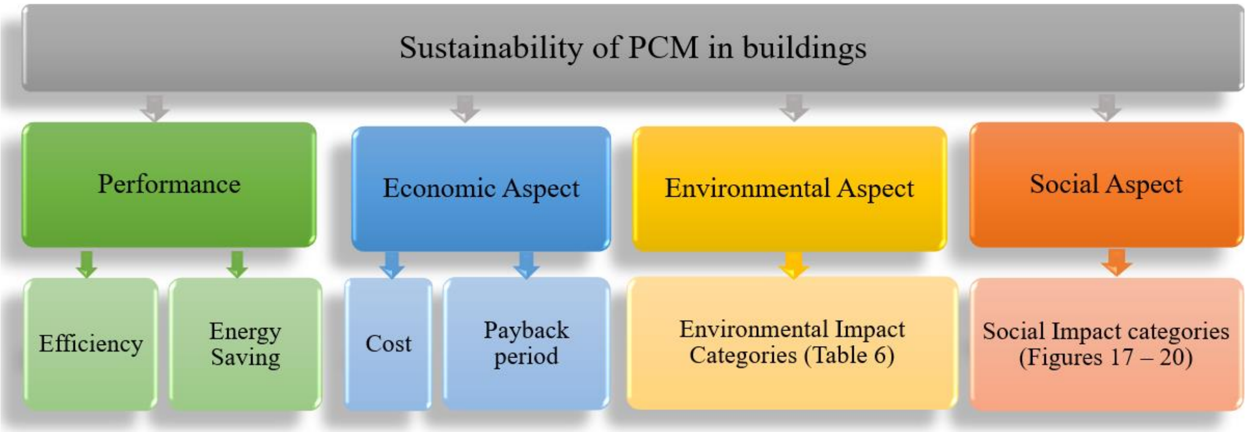


***Figure** 9: Conceptual Framework to study the sustainability of PCM in buildings*

3.2. The efficiency of PCM used in buildings

The efficiency of a system is a critical criterion that specifies whether it is worth the employment. Thus, Table 3 contains studies of the previous work, each study shows the effectiveness of PCM when it is employed under different conditions.

From Table 3, it was noticed that all types of PCM in buildings were desirable and effective, however at different levels. Besides, PCM is affected by several factors environmental, seasonal (climatic), material, and involvement in various applications. As well, it was noticed that PCM can be involved in various ways inside a building, for instance in old buildings PCM is integrated into external windows as it is the simplest way to be used in such cases, however in a new construction PCM can be involved inside the structure of the building such as ceiling, floor, roof, walls. Furthermore, it was shown that PCM passive cooling methods demonstrate promising results in various regions, especially in a moderate climate, however, in some other cases, PCM cooling methods show disappointing results according to the mentioned factors.

Although PCM shows success and efficiency in most cases, however, other factors should be studied to check if employing such a system is worth it. For instance, if the system shows high efficiency but it costs more than it saves, then the overall efficacy of the system is not effective. Also, there is a lot of interest nowadays in the use of eco-friendly materials that do not harm either the planet or humans throughout their lifecycle and reduce the carbon footprint of buildings. Thus, in the next section, a review of the PCMs from a cost and environmental perspective is done.

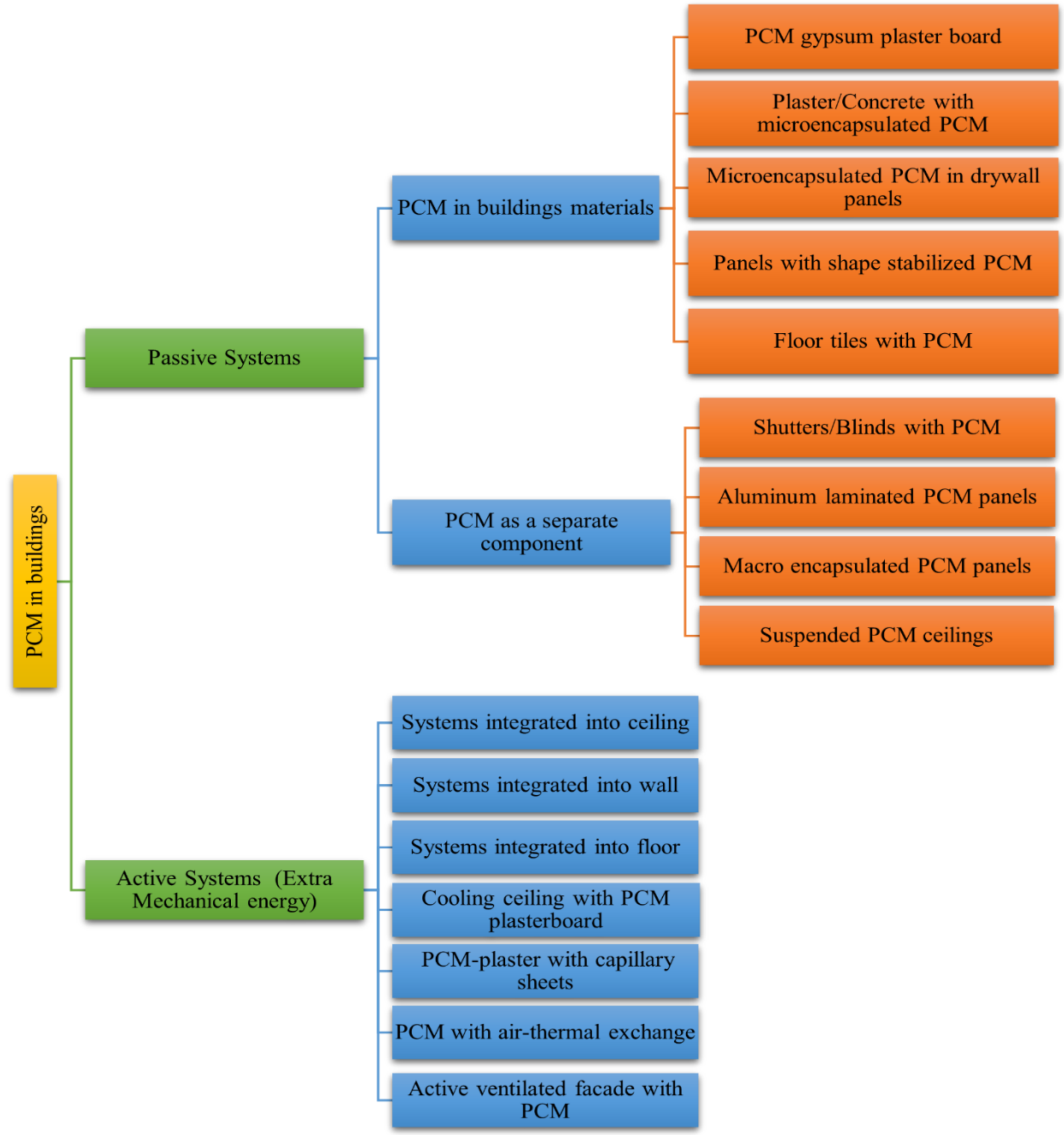


Figure 10: Applications of PCM in buildings

***Table** 3: PCM in building from efficiency and energy savings perspective in the previous work.*

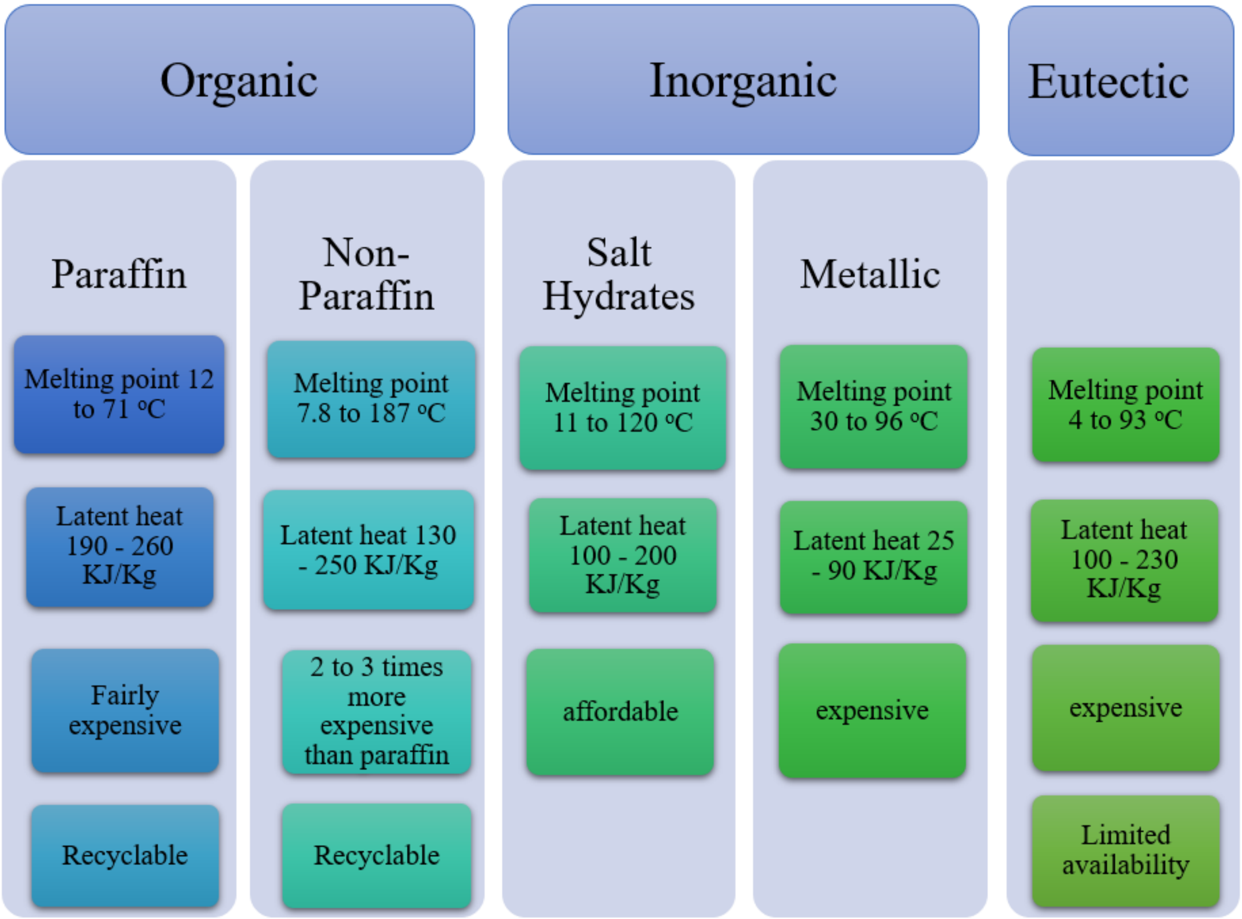
Authors	Description of the work	Results
Esbati et al. 2019 [3]	Simulation and experimental studies to investigate the effect of ES by PCM on decreasing the heating and cooling load. The results compared the effect of the position of	Results show that a combined insulation-PCM system reduced the heating capacity by around 28%. Besides, PCM saved up to 8% of the

		the insulation and PCM within the building envelope.	cooling load and 30% of the heating energy of the building.
Windows – floor- roof – Ceilings – walls	C. Araújo et al. 2017 [55]	In this study, 8 different PCMs with distinct melting points that vary from 15 ºC to 28 ºC were studied. This investigation was done through two different dynamic simulations of the energy performance, one with and another without PCM. The study was held in a building located in North Portuguese at a height that exceeds 100 m.	The results show that the use of PCM led to a drop of 13% in energy needed for heating, 92% of the energy needed for cooling, and 13% of overall energy demand. Yet, the economic analysis showed that the initial PCM cost is not compensated by the drop in energy during the cooling process. This could be attributed to the location and climatic conditions that require heating more than cooling.
	Jin-Mei; F. et al 2013 [56]	Experimental study on using PCM in an old building in Shanghai, China integrated into windows or doors as it is difficult to employ conventional PCM in the envelope. The experimental study has investigated the effect of PCM on the density of heat flow and indoor temperature.	Results show that during the daytime the indoor average temperature is reduced by 1.67°C and rose 1.71°C during the night. Besides, when using PCM, the space heat capacity declined 61% during the day and improved 230% during the night. The period of the payoff was estimated to be 4 years.
	Al-Yasiri Q. et al. 2021 [57]	Studies on incorporating PCMs with building for heating and investigating how PCM, passive and active techniques, would improve the cooling/heating systems and improve the savings of buildings.	Results revealed that all techniques and types of PCMs in the buildings could enhance energy savings by up to 44.16%. Besides, it was concluded that PCMs enhance buildings' efficiency by decreasing heating/ cooling loads and endorsing renewable energy sources.
	Guo J. et al. 2021 [58]	PCM performance in wallboard was investigated under various seasonal weather conditions and different melting point values 22, 24, and 26 °C. An enthalpy-porous model taking radiation, convection, and conduction into consideration is implemented.	Results indicated that the PCM layer does not always offer desirable output, where over 5% of negative effect on energy loss was noticed. Hence, the PCM performance is affected by various factors such as its volume and climatic conditions.
	Devaux et al 2017 [59]	Displays the profits of PCM usage in ceiling, walls and in underfloor heating systems through two dissimilar kinds of PCMs. Besides, two similar huts models at Tamaki Campus of the University of Auckland (New Zealand) are studied experimentally and numerically.	Results showed that using higher melting point PCM in the underfloor heating system led to considerable peak load shifting and employing lower melting point PCM inside the ceilings and walls provided the needed thermal comfort. After ten days, the peak load shifting in the morning and evening showed cost and energy savings of 42% and 32%, respectively.
	Schmerse E. et al. 2020 [60]	The thermal behavior of two suggested structures and the benefits of using various forms of PCM in a moderate climate is studied. Accordingly, Design Builder simulation software was used to perform more than 300 numerical simulations.	Results displayed substantial savings of energy and comfort improvement when using PCMs. The incorporation of PCM in single-structure constituents led to significant energy savings from 19% to 27% per annum.
TRC	Ilyes Z. et al 2021 [61]	This paper studies the impact of PCMs on the thermal and mechanical performances of Textile-Reinforced Concrete (TRCs). The efficiency of the innovative PCM–TRC model was thermally and mechanically calculated.	Results show that when comparing PCM-TRC to TRC concerning thermal performance, a 4.5 cm thickness of PCM–TRC slab could save 37% of energy, as well, as a temperature reduction of 4 °C at the peak.
Natural ventilation	Prabhakar M. et al 2020 [62]	A study for 15 different regions was held, to optimize the melting temperature of PCM in an office building. Ventilation control approaches were employed to enhance the PCM performance.	In a moderate climate, the efficiency of PCM improved from 3.32% to 25.62% by integrating a passive night ventilation system. In a hot arid climate, the PCM passive cooling system was ineffectual. Also, it was noticed that a smart

			control system of ventilation showed significant energy savings.
	Piselli, C. et al 2020 [63]	The study measures the effect of natural ventilation control when integrated with PCM. Two natural ventilation controls were considered (1) whole-day temperature-controlled, and (2) nighttime ventilation. This study aims to optimize the melting temperature of PCM to reduce the cooling energy in various climate conditions.	The efficiency of the thermal energy storage charge-discharge cycle of PCMs is increased when implementing both natural ventilation controls. However, the highest cooling energy savings are obtained by coupling optimized PCMs with temperature-controlled natural ventilation in all climate zones.
	Saffari M. et al. 2019 [64]	PCM with natural ventilation passive technologies in an office located in moderate weather was investigated numerically to study the efficiency of cooling energy savings that the combined system would offer.	Results revealed that the savings of cooling energy range from 8% to 15%. Besides, natural ventilation enhanced the performance of PCM and increased its efficiency by 8%.
	Elashmawy M. et al 2021 [65]	An innovative PCM-tubes geometry was developed to be employed inside a tube-shaped solar still with a parabolic solar concentrator for a desalination plant. The experimental study was carried out in Saudi Arabia under the climatic conditions of Ha'il city of 965 m above sea level.	Results showed that PCM tubes boost efficiency and productivity by 38.25% and 40.51%, respectively. Also, the cost per liter, yield, and efficiency were 0.00782 USD, 5.55 L/m^{2}day, and 44.1% when using PCM-tubes, however, the cost per liter, yield, and efficiency were 0.0163 USD, 3.95 L/m^{2}day, and 31.9% without PCM-tubes.
Water Tank	Koželj R. et al. 2021 [66]	A hybrid latent system for heat storage was studied, where PCM was incorporated into the water tank to enhance the energy density of the traditional sensible water tank.	Results revealed that 15% of PCM in the water storage tank enhances heat storage by 70% as compared to the conventional water tank heat storage.
	Bayomy A. et al. 2019 [67]	This research conducted a CFD numerical study for a domestic hot water tank when involving PCM material as a storage medium. The study calculated the storage efficiency that PCM could offer.	Results showed that during the charging process, the growth in the hot water supply amplified the efficiency of the storage from 35% to 39%. Besides, at specific hot water amounts, the efficiency improved from 35% for one family to 82% for four families.

3.3. Economic and environmental effects of PCM

During the last decade, ecological problems associated with the escalating consumption of energy and the overuse of fossil resources for producing energy have formed anxieties. Thus, the economic effect is an important factor that should be taken into consideration when designing the PCM integration system. Cost analysis is a way to express the economic effect, where it contributes substantially to planning, monitoring, and decision-making. Consequently, this has a substantial role in determining the best choice type of PCM. Furthermore, with the rise of global warming and pollution effects on the world, the environmental effect became another crucial factor that should be taken into consideration while designing the PCM integration system. Accordingly, Figure 11 presents the previous work [68, 69] that studied the PCM from the aforementioned criteria i.e., economic, and environmental perspectives.



Organic		Inorganic		Eutectic
Paraffin	Non-Paraffin	Salt Hydrates	Metallic	
Melting point 12 to 71 °C	Melting point 7.8 to 187 °C	Melting point 11 to 120 °C	Melting point 30 to 96 °C	Melting point 4 to 93 °C
Latent heat 190 - 260 KJ/Kg	Latent heat 130 - 250 KJ/Kg	Latent heat 100 - 200 KJ/Kg	Latent heat 25 - 90 KJ/Kg	Latent heat 100 - 230 KJ/Kg
Fairly expensive	2 to 3 times more expensive than paraffin	affordable	expensive	expensive
Recyclable	Recyclable			Limited availability

***Figure** 11: Environmental and cost comparison between different PCM types [68, 69].*

Table 4: PCM in building from an economical perspective in the previous work.

	Authors	Description of the work	Results
Economic Effect	Souayfane F. et al 2018 [70]	An innovative transparent super-insulated latent heat storage wall approach of merging translucent insulation material and PCM was investigated. Economic and energy analysis of the wall under various climatic conditions for the whole year, in a typical office building, was assessed.	Results displayed that, in subarctic and polar climates, the wall shows a feasible investment and worthy economic value, where the payback period was 7.8 years and 10.5 years respectively. Yet, in a continental climate, the wall was economically unfeasible.
	Panayiotou, G. P. et al 2016 [71]	Macro encapsulated PCM is studied on a typical envelope in the Mediterranean region. The simulation process is carried out using two forms of simulations on Transient Systems Simulation software (TRNSYS). The energy savings of both cases with and without the PCM layer on the envelope were tested, evaluated, and assessed by Life Cycle Cost (LCC).	The energy savings attained with the presence of the PCM layer was improved by 21.7 and 28.6% with a maximum of 66.2% energy savings per year. In the temperature level control test, the buildings with PCM achieved better performance during summer. The results revealed that the PCM has a 14 ½ years as a payback period, which is typically a long time, while the case combined with insulation reduced the payback period to 7 ½ years.

	Poudel N. et al. 2014 [72]	A simulation study on the performance of PCM boards for a simple building under 15 different climates was held. PCM boards were incorporated in all the interior faces of the building except for the floor.	PCM boards showed optimum output in dry, marine, and hot climates. On the contrary, it revealed opposite results in humid and cold climates. Further, results displayed that a cost of about $1/kg with the high heat storage capacity of a PCM board is economically feasible. Besides, PCM optimum temperature has a high impact on energy savings, a small difference from the finest temperatures for each climate leads to a decrease in energy saving by 5 to 10 %.
Environmental Effect	Subieh M 2017 [73]	PCM was tested in a room with PCM walls. This experiment aims to define the energy improvement and environmental effects that PCM would offer. The thermal energy balance of the test room was determined to calculate the reduction in CO_2 emission due to the PCM walls.	Experimental data during a year shows that CO_2 calculations and solar energy gains by PCM walls in the room minimized the emission of CO_2 from the test room by an average of 14% annually.
	Frigione M. et al. 2019 [74]	A review of the usage of PCMs in the building was held mainly for passive building systems. The advantages, environmental, and economic effects of PCM in buildings were stated.	PCM in buildings can reduce energy consumption, although it may not result in a high reduction in the global environment. The application of PCMs, in most cases, does not economically offer a feasible output, this is due to the high initial investment of PCM. Environmentally, the PCMs effect could be better than the conventional construction materials, yet this depends on the climate and the type of PCM.

Table 4 shows that the payback period is acceptable in some cases, especially when the system is insulated. Besides, some studies show that the investment of PCM was feasible and worthy of economic value, however, the climatic conditions have a major effect on the feasibility of employing PCM, which made it efficient in some countries and not others.

On the other side, it is noticed that PCM materials reduce energy consumption, and consequently, CO_2 emissions. However, PCM may not result in a high reduction on the global environmental level. Unfortunately, the literature still lacks work on PCM from an environmental perspective, where it was hard to find research that investigated the PCM from this concern. This encourages us to study further the PCM from an environmental perspective, which is the topic of the coming section.

4. Life Cycle Assessment of selected PCMs

To complete the comparison study of the PCM types from the environmental perspective, four different PCM materials of different types have been studied: salt hydrates represented by Magnesium Nitrate Hexahydrate, paraffin represented by Octadecane (hydrocarbon), and two types of bio-based materials represented by Coconut oil produced using manurial fertilizers, and Coconut oil produced using bio-fertilizers. Bio-based and plant-based materials can constitute an eco-friendly alternative to the conventional PCMs studied previously. Therefore, we decided to investigate them further.

4.1. Methodology

To calculate the environmental impact associated with the production of selected PCMs used in buildings, the production process of each type of PCM is defined, then all the information regarding material flow is gathered. Material flow analysis is conducted with a calculation of energy consumption. Then the processes are inserted on OpenLCA, which uses Ecoinvent databases [77], to evaluate the environmental impacts of the production cycle from cradle-to-gate, on the environmental and health categories listed in Table 5. After that, the values of all the emissions are transferred into a common unit, where each category has a weighting factor in £ that signifies an estimate cost to restore damage from each emission type. Then, the sum of the equivalent value in £ of all the categories is obtained to find the total environmental cost indicator (ECI) of each PCM.

The comparison between the four types of PCM is held on two functional units:

1- 1 Kg of PCM: to obtain the impact of producing a specific quantity of materials.

2- 100 KJ of energy storage/ release during phase-change: PCMs store and release different quantities of energy depending on their latent heat of fusion. The amount of materials needed varies accordingly. So, a better comparison, which embeds PCM performance, is to use a functional unit related to energy and find the equivalent mass needed to store/ release this energy.

Finally, a conclusion on the analysis is drawn and some recommendations on the selection of PCMs are proposed to improve the sustainability of the building sector.

4.2. Lifecycle Process from cradle to gate

Life cycle assessment (LCA) has been employed for buildings to study the environmental effect of materials through their lifecycle [75, 76]. This technique shows the environmental impact associated with production phases of each material from cradle to grave, where in every phase some emissions could be harmful to the environment. Each type of emission has a specific cost to account for its potential damage. The rate of emissions differs from one type of PCM to another. Thus, the LCA of the four mentioned materials is studied to evaluate the environmental effects associated with all the phases that the product goes through from cradle to gate, which means from raw materials mining through manufacturing and processing, to the end-user. In this section, the process of each type of PCM is obtained and its LCA is performed to determine the emissions of each type of PCM using OpenLCA software and Ecoinvent databases [77].

4.2.1. Process of Manganese nitrate hexahydrate

Figure 12 shows a flow chart of the manufacturing process of Manganese Nitrate Hexahydrate from cradle to gate, where the extracted Manganese ore and produced nitric acid pass through nitric acid treatment to obtain the Manganese nitrate hexahydrate.

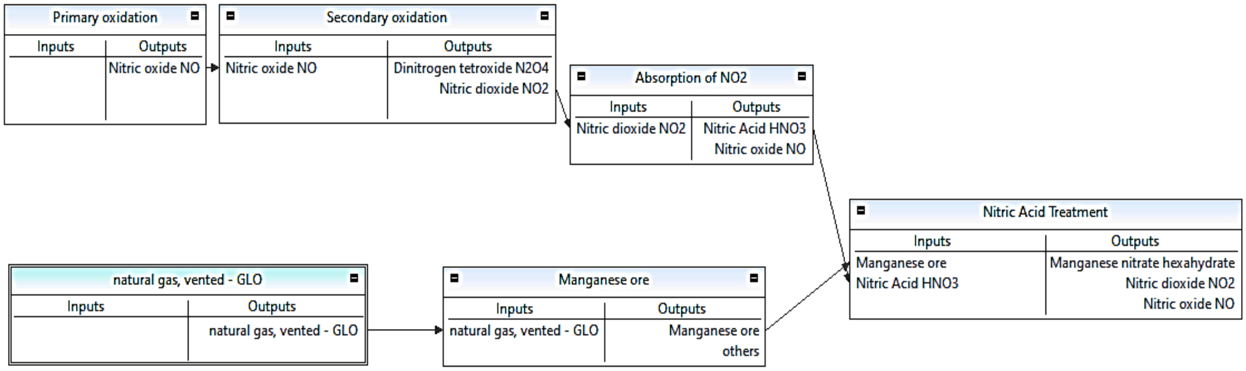


***Figure** 12: Production chain of Manganese nitrate hexahydrate*

4.2.2. Process of Octadecane

Figure 13 shows the production chain of Octadecane from cradle to gate, where crude oil is produced, then it goes through the refinery process to obtain lubricant oils, paraffin wax, after that a filter house process is done to obtain the Octadecane [78, 23].

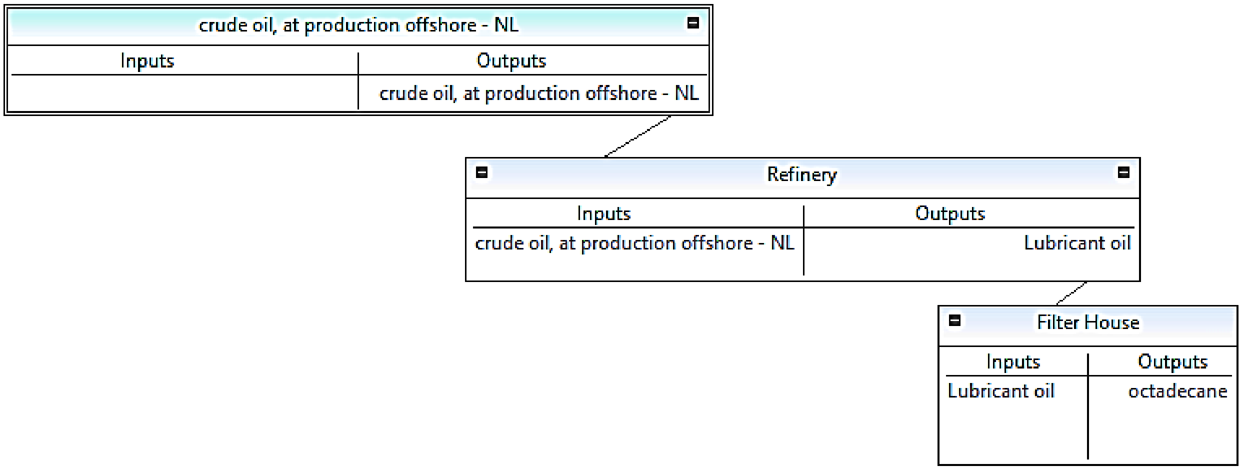


***Figure** 13: Production chain of Octadecane*

4.2.3. Process of Coconut oil

Figure 14 shows a model graph of the fabrication process of Coconut oil PCM from cradle to gate. The process starts with planting the tree and adding the fertilizers. Two types of Coconut oil PCM are studied, and both types go through the same process, however, the first one uses biofertilizers as shown in Figure 14a, and the other one uses manurial fertilizers as shown in Figure 14b.

After adding the fertilizers, the coconut fruits are collected then shredded and mixed with water. Later, Coconut oil is extracted from coconut milk by the separating oil-water technique. Finally, cooling and freezing are done to obtain the final Coconut oil PCM.

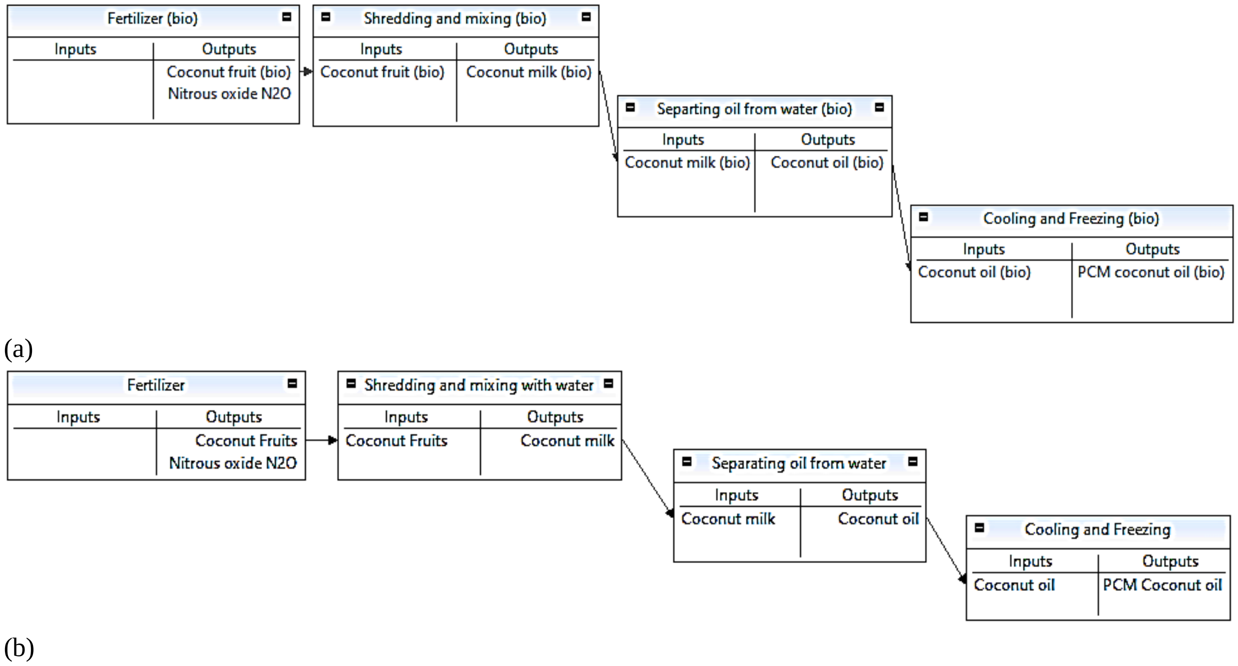


***Figure** 14 Production chain of Coconut oil PCM based (a) biofertilizers and (b) ordinary fertilizers*

4.3. Energy consumption to produce each PCM type

The first functional unit that is used in OpenLCA is 1 kg of PCM produced. We estimate, for each of the three materials, the Cumulative Energy Demand (CED), which stands for the total amount of direct and indirect energy utilized throughout a product's life. The results are shown in Figure 15. In this study, the emissions associated with energy consumption are not included due to the different sources of energy that each country/region depends on. Similarly, transportation impact is neglected due to different types of vehicles and the landforms that differ from one country to another.

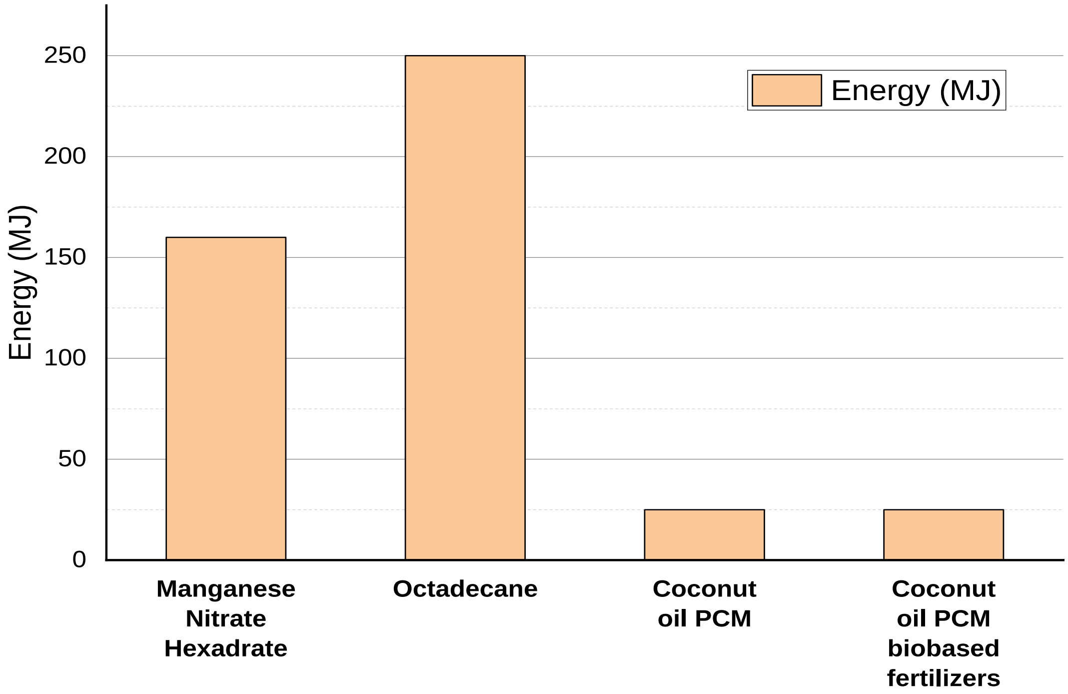


***Figure** 15: CED values for the studied PCM materials*

Figure 15 shows that the manufacturing of Octadecane demands the highest amount of energy, whereas Coconut oil requires the least amount. This is due to the drilling process to recover crude oil, then the refinery process to produce the lubricant oil that is necessary to make Octadecane. On the other hand, Manganese Nitrate Hexahydrate has high CED as well, which is due to the processes followed to complete the production beginning with the manganese alloy production and then nitric acid treatment. On contrary, the Coconut oil process does not require a large amount of energy, where the processes that require energy are (1) the electric energy for distillation and shredding which constitute 72% of the total energy, and (2) thermal energy for heating the coconut milk which is responsible for the remaining 28%.

4.4. Environmental Impact of each PCM type

Along each of the above processes, there are emissions for each stage. These emissions differ from one process to another, consequently, each type has a different hazardous effect. Thus, the impact on each category is calculated, and then the Eco-cost based on the Environmental Cost Indicator (ECI) is estimated to do a comparison among all the types. In this LCA, the studied impact categories are divided into two sectors: (1) Abiotic Ecosystem Impact, which is related to the impact on the ecosystem in general, and (2) Potential Human Health and Eco-Toxicity Impacts, which is related to the impact on human and natural resources [79]. Table 5 illustrates all the categories, their impact indicators, and damage points.

Table 5: Definitions and indicators of some impact categories

	Impact category	**Definition**	**Impact indicator**	**Damage categories (endpoint)**
Abiotic Ecosystem Impact	Climate change: Global Warming Potential (GWP100) (Kg CO2 equivalent)	Change of global temperature affected by greenhouse gases over 100 years, hence signified by GWP100 [80].	Disruptions in universal temperature and climatical phenomenon	Forests, crops, coral reefs, etc. (generally, biodiversity declination) Temperature instabilities Climatic phenomenon malfunction (more effective cyclones, torrential storms, etc.)
	Ozone layer depletion	Reduction of the stratospheric ozone layer due to anthropogenic releases of ozone-depleting substances	Growth of ultraviolet UV-B radiation and number of cases of skin diseases.	Human health and ecosystem quality
	Depletion of abiotic resources fossil fuel	Reduce the accessibility of non-renewable resources due to their unsustainable use	Reduction of resources	Destruction of natural resources and the probability of ecosystem crisis
	photochemical Oxidation	Sort of smog formed from the sunlight effect, heat and non-methane volatile organic compounds (NMVOCs), and NOx	Growth in the summer smog	Human health and ecosystem quality
	Eutrophication	The buildup of nutrients in aquatic systems	High nitrogen and phosphorus concentrations. Creation of biomass (algae)	Harmful to the ecosystem quality
	Acidification potential	Decrease of the pH due to the acidifying impacts of anthropogenic releases	High acidity in soil and water systems	Harmful to the quality of ecosystems and diminution in biodiversity
Human Health and EcoToxicity	Human toxicity	Toxic impacts due to chemicals effect on humans	Respiratory diseases cancer, other non-carcinogenic impacts, and consequences of ionizing radiation	Human health
	Marine aquatic ecotoxicity [81]	Toxic substances on the marine ecosystem	Biodiversity loss and/or destruction of marine life species	Harmful to the marine ecosystem quality and extinction of marine species

Freshwater aquatic ecotoxicity [81]	Toxic substances in freshwater	Formation of new diseases	Harmful to the marine ecosystem quality and extinction of marine species
Terrestrial Ecotoxicity	Toxic impacts due to chemicals effect on the ecosystem	Biodiversity damage and disappearance of species	Destruction to the ecosystem value and extinction of species

The functional unit of the LCA calculation is 1 kg of PCM. This means that the calculated emissions are released to produce 1 kg of the PCM. Table 6 shows the values of impact analysis of Magnesium Nitrate Hexahydrate, Octadecane, Coconut oil using manurial fertilizers, and Coconut oil using biofertilizers PCM materials. Furthermore, eco-cost ECI is determined for each PCM type, where each impact category has a specific coefficient that unites all appropriate environmental effects into a single outcome of environmental costs, indicating the environmental cost of the product [82]. So, for each type of PCM, the values of each of the mentioned impact categories are combined using ECI to provide a common unit which is euros (£).

Table 6: Impact analysis of four different PCM materials

Impact categories	Magnesium Nitrate Hexahydrate	Octadecane	Coconut oil using biofertilizers	Coconut oil using manurial fertilizers
GWP100 0.05£/Kg CO2	11.78 Kg CO_2-eq	4.08 Kg CO_2-eq	1 Kg CO_2-eq	3.13 Kg CO_2-eq
	0.589 £	0.204 £	0.05 £	0.1565 £
Ozone layer depletion 30£/ kg CFC-11-eq	0 kg CFC-11-eq	6.5×10^{-7} kg CFC-11-eq	0 kg CFC-11-eq	0 kg CFC-11-eq
	0 £	1.95×10^{-5} £	0 £	0 £
Human toxicity 0.09£/ kg 1,4 DB-eq	0.05301 kg 1,4 DB-eq	49.2 kg 1,4 DB-eq	0 kg 1,4 DB-eq	0 kg 1,4 DB-eq
	0.00478 £	4.428 £	0 £	0 £
Depletion of abiotic resources fossil fuel	6.79993 MJ	3362.5 MJ	0.04667 MJ	0.04667 MJ
Depletion of abiotic resources fossil fuel - elements ultimate reserves 0.16£/Kg Sb eq	0 Kg Sb eq	2.67×10^{-7} Kg Sb eq	0.00467 Kg Sb eq	0 Kg Sb eq
	0 £	4.272×10^{-8} £	7.47×10^{-4} £	0 £
Terrestrial Eco toxicity 0.06£/ kg 1,4 DB-eq	5.05381×10^{-5} kg 1,4 DB-eq	0.0134 kg 1,4 DB-eq	0 kg 1,4 DB-eq	0 kg 1,4 DB-eq
	3.03×10^{-6} £	8.04×10^{-4} £	0 £	0 £
photochemical Oxidation	0.00198 Kg ethylene eq	0.00101 Kg ethylene eq	0.0054 Kg ethylene eq	0.00582 Kg ethylene eq

2£/Kg ethylene eq	0.00396 £	2.02 x 10^{-3} £	0.0108 £	0.012 £
Eutrophication 9£/Kg PO4 eq	0.1855 Kg PO4 eq	0.00658 Kg PO4 eq	0 Kg PO4 eq	2.8 Kg PO4 eq
	1.6695 £	0.05922 £	0 £	5.67 £
Acidification potential	0.848 Kg SO2 eq	0.01951 Kg SO2 eq	0 Kg SO2 eq	0 Kg SO2 eq
4£/Kg SO2 eq	3.392 £	0.07804 £	0 £	0 £
Marine aquatic ecotoxicity	0.0214 kg 1,4 DB-eq	67418.8 kg 1,4 DB-eq	0 kg 1,4 DB-eq	0 kg 1,4 DB-eq
0.0001£/kg 1,4 DB-eq	2.14 x 10^{-6} £	6.742 £	0 £	0 £
Freshwater aquatic ecotoxicity	5.66 x 10^{-7} kg 1,4 DB-eq	0.398 kg 1,4 DB-eq	0 kg 1,4 DB-eq	0 kg 1,4 DB-eq
0.03£/kg 1,4 DB-eq	1.698 x 10^{-8} £	0.1194 £	0 £	0 £
Total	**5.7 £**	**11. 53 £**	**0.06 £**	**5.8 £**

As noticed in Table 6, Coconut oil PCM using biofertilizers has the lowest GWP effect and lowest overall eco-cost (ECI). However, Magnesium hexahydrate has the highest GWP, which is due to the hazardous greenhouse gas emissions that are produced such as carbon monoxide, nitrous oxide, and others. On the other hand, Octadecane has the highest overall environmental impact, especially on human toxicity due to the Barite that is emitted from the crude oil. The biobased PCM effect on human toxicity is null, but it is worth noting that using manurial fertilizers creates a considerable hazardous impact on the environment, mainly on GWP (climate change) due to the release of methane and nitrous oxide, and eutrophication caused by the excess nitrogen from the fertilizers in water bodies, which reduces oxygen levels and threatens the living organisms. Hence, for the plant/ fruit-based solution to be a good alternative to other PCMs, the impact of the agricultural activities should be considered. The use of bio-fertilizers is recommended for a substantial reduction in the environmental impact.

In general, the impact on each category differs from one material to another, thus all the impact categories are converted into euro currency and summed up into the ECI category which reflects the cost of each material on the environment. Overall, Coconut oil PCM using biofertilizers have the lowest negative impact on the environment as shown in Figure 16, while Octadecane, which is a hydrocarbon has the highest impact.

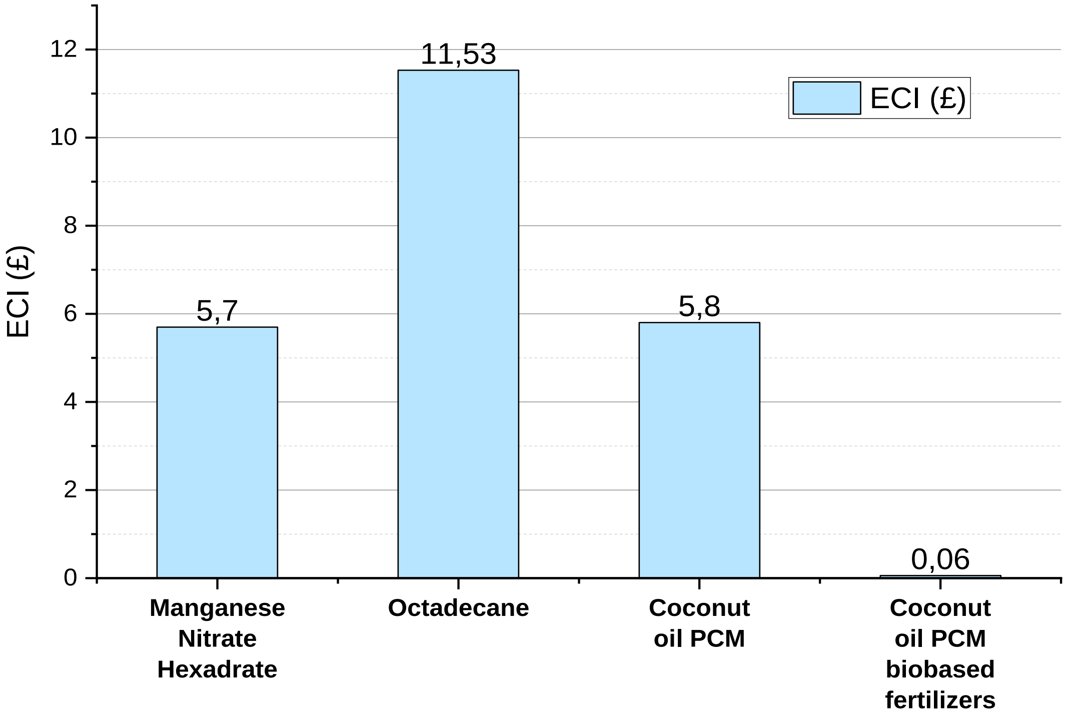


***Figure** 16: ECI of the four PCM types*

Although the ECI is a direct element for the comparison, however, the quantity of PCM needed to store and release the required energy is an important factor that should be taken into consideration, which affects directly the overall environmental impact. For instance, if the ECI of Manganese Nitrate Hexahydrate is less than that of Octadecane, however, more quantity of Manganese Nitrate Hexahydrate is required to store/ release the same amount of energy that the Octadecane produces, then this might result in having a higher negative environmental impact than Octadecane. The higher negative impact is due to the needed higher quantity. Thus, Table 7 shows the required amount of each of the four studied materials to produce the same amount of energy (100KJ) during phase-change, i.e. while maintining a constant temperature.

Table 7: required quantity of each material to produce 100 KJ

Materials	Magnesium Nitrate Hexahydrate	Octadecane	Coconut oil using biofertilizers	Coconut oil using manurial fertilizers
Quantity (Kg)	0.794 Kg	0.4098 Kg	1.428 Kg	1.428 Kg

As noticed in Table 7**Table** *7*, Coconut oil PCM requires the highest amount in Kg to store/ release 100KJ, however, Octadecane requires the least quantity to store/ release the same amount of energy. Coconut oil PCM needs around 3.5 times the quantity of Octadecane and around 1.8 times the quantity of Manganese Nitrate Hexahydrate. The difference in the demanded quantity of materials to produce the same amount of energy might change the previous conclusion obtained on the environmental effect of the materials. So, a new environmental cost is in the next section to find out the best option.

To complete the comparison, the ECI of each material to produce the same amount of energy is calculated as shown in Table 8.

Table 8: ECI of each material to store/ release 100 KJ

Materials	Magnesium Nitrate Hexahydrate	Octadecane	Coconut oil using biofertilizers	Coconut oil using manurial fertilizers
ECI (£)	4.5	4.7	0.085	8.28

As noticed in Table *8*, the large difference in the environmental cost between Octadecane and Manganese Nitrate Hexahydrate is drastically reduced, yet the ECI of Octadecane is still slightly more highre than Manganese Nitrate Hexahydrate. Coconut oil with biofertilizers have the lowest ECI, however, Coconut oil using manurial fertilizers has the highest ECI, due to (1) the emissions produced from the manurial fertilizers that have hazardous effects on the environment such as methane and nitrous oxide, and (2) the lowest efficiency of Coconut oil PCM in terms of storage. Coconut oil requires 3.5 the amount of Octadecane to store/ release the same amount of energy.

5. Social impact

As previously mentioned, there are no social lifecycle assessments for PCM production. Hence, to gain insights on the possible social impacts of these materials, we rely on the studies done on various sectors that produce substances which interfere in the production cycles of PCMs used in buildings. The non-metallic minerals production sector is important for salt hydrates. The mining and quarrying sector is involved in the production of metal ores that are used in some PCMs like Manganese Nitrate Hexahydrate, in addition to the metal manufacturing sector that includes the metal processing activities. Also, crude oil production is an important process for the hydrocarbon PCMs. As for the biobased PCMs, looking at the social impacts associated with agricultural practices gives us insights into how biobased PCM production might affect societies.

For a sustainable product, it is not enough to study the economic, performance, and environmental effects only. The social impact is an important factor that should be taken into consideration for the analysis to be complete. Unfortunately, this impact is neglected in most assessments and the effect of extracting and processing the raw materials and producing agricultural goods on the workers and societies have been overlooked. For example, in the Philippines, the poor management of coconut cultivation results in earning an unreasonable livelihood, consequently trapping the public in poverty [83]. On the other side, coconut production constitutes a major income for the country, where coconut is exported to 114 countries. However, farmers are working hard and are paid low salaries, which negatively affects the society [84]. Consequently, the millions of smallholder farmers in the Philippine are not growing to become big industries, which leaves the people in poverty and the children with no access to schooling. Instead, children work in processing facilities under hazardous circumstances [85].

Recently, automation in agriculture, such as irrigation systems, field machinery, animal automation systems, greenhouse automation, and automation of fruit production systems, has been used in many developed countries [86]. Although automation in agriculture is beneficial and saves time and effort, it might have a negative effect on societies due to replacing people with machines, keeping in mind that in many undeveloped countries working in agriculture is the main skill for the locals. Besides, large industrial agriculture has a negative effect on small farms of less than 10 hectares [87].

Crude oil and mining activities open job opportunities to local societies, which has a positive social impact on livelihood [88, 89]. However, the mining strategies in some countries are not well studied. Besides, there is a risk on the health of the workers that are involved in such activities. In Uganda, for example, many companies neglect the basic standards of health and safety, although the precautions and safety regulations exist, however, employees are not usually given enough information about their job conditions and labor rights [90]. Sometimes, even with the implementation of safety regulations, fatal injuries occur, where the U.S. Bureau of labor statistics revealed that fatal injuries in private quarrying and mining sectors in 2014 and 2015 were 183 and 120 [91], whereas in 2016 and 2017 the fatal injuries were 89 and 112, respectively [92].

To assess the social impact pillar of sustainability in a quantitative approach, various categories that are related to job opportunities [93], the worker's conditions, and local communities should be studied, among these, we have [94]: child labor, fair salary, health safety, working time, respect of indigenous rights, contribution to the economic development, corruption, etc. Figures 17, 18, 19, and 20 are reproduced based on a technical report [94] by the Joint Research Centre (JRC), the European Commission’s science and knowledge service. They show the overall social risks, studied for 7 countries, to assess nine different impact categories, for three sectors: (1) Mining and quarrying, (2) Manufacture of basic metals, and (3) Manufacture of non-metallic mineral products, respectively. The study is done by the different impact categories are presented on the x-axis and the corresponding social risk for each country is represented by the colored bars. The social risk is assessed in medium risk hours (mrh), which is the number of worker hours in a lifecycle that are characterized by a specific social risk. Thus, a higher value of (mrh) means higher risks, consequently more destructive performance. Figure 19 shows the total sum of (mrh) in the studied countries and the considered sectors. From the figures 17 to 20, the higher risk for unfair salaries in the three selected sectors are seen in China and South Africa, while the highest risk associated with the health and safety of workers is estimated in the USA. Europe and Australia have relatively low risks in most categories for the studied sectors except for the respect of indigenous rights. Moreover, the mining and quarrying sector has the highest social impact on all the categories, which leads to a negative social impact on any product that relies on these activities in its product lifecycle. Also, the categories that have the highest impact on societies are fair salary, corruption, and health and safety. Thus, improving the financial conditions of workers, making sure that safety measures are employed, and limiting corruption are necessary steps to significantly reduce the negative social impacts of the production of materials.

PCMs like Manganese Nitrate Hexahydrate and Octadecane, which require mining and quarrying and metal and mineral manufacturing, have some positive social impact represented by opening job opportunities and providing significant income to the society [93], however, there will be other negative impacts represented by threatening the safety and welfare of workers. This is considered unsafe production, consequently, unsafe production is an unsustainable production. On the other hand, biobased PCM materials like Coconut oil are safe and do not involve any of the up-mentioned activities, however, the workers in agricultural communities are also paid low salaries and have no access to health insurance. Besides, in undeveloped countries, child labor exists in agricultural practices and mainly in the production of Coconut oil. These considerations should factor in when assessing the sustainability of PCMs. We do not have yet quantitative data to compare the impact of the agricultural sector relative to the other sectors, however at least in the category of Health and Safety, it should be relatively less impactful.

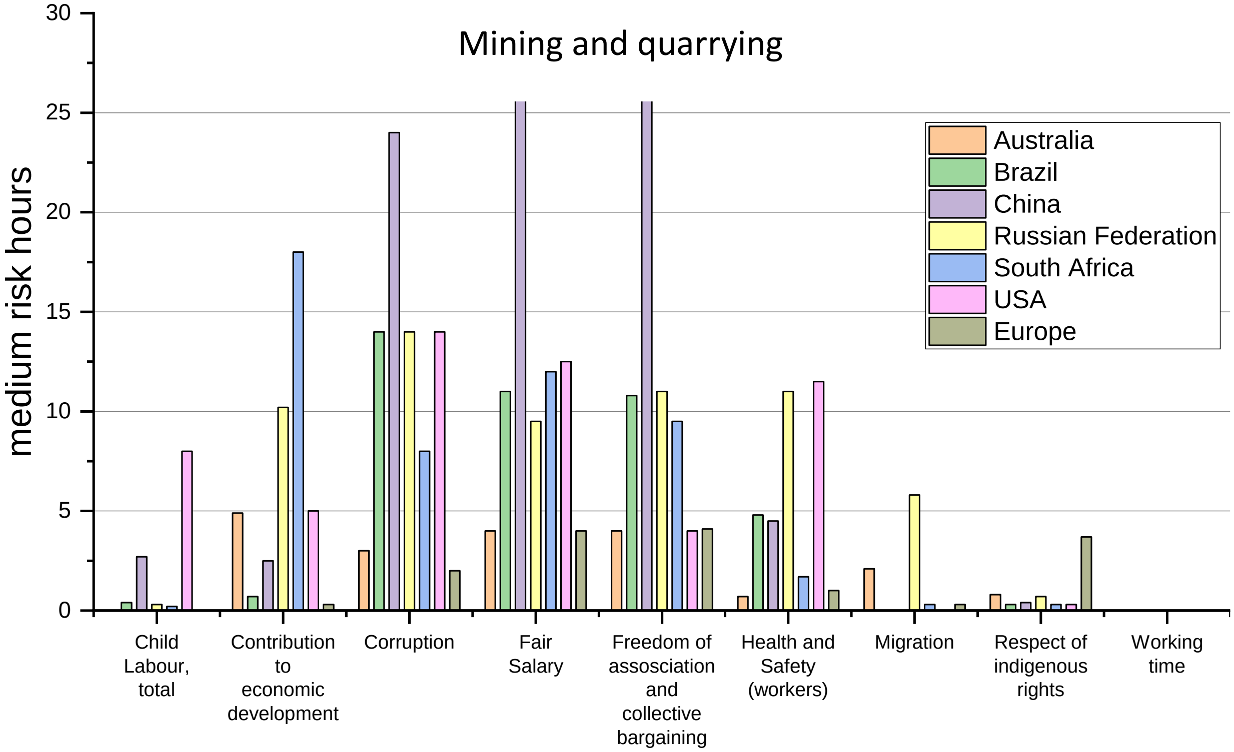


***Figure** 17: Life cycle-based results on the social risk associated with the mining and quarrying sector, in all selected countries reproduced from [94]*

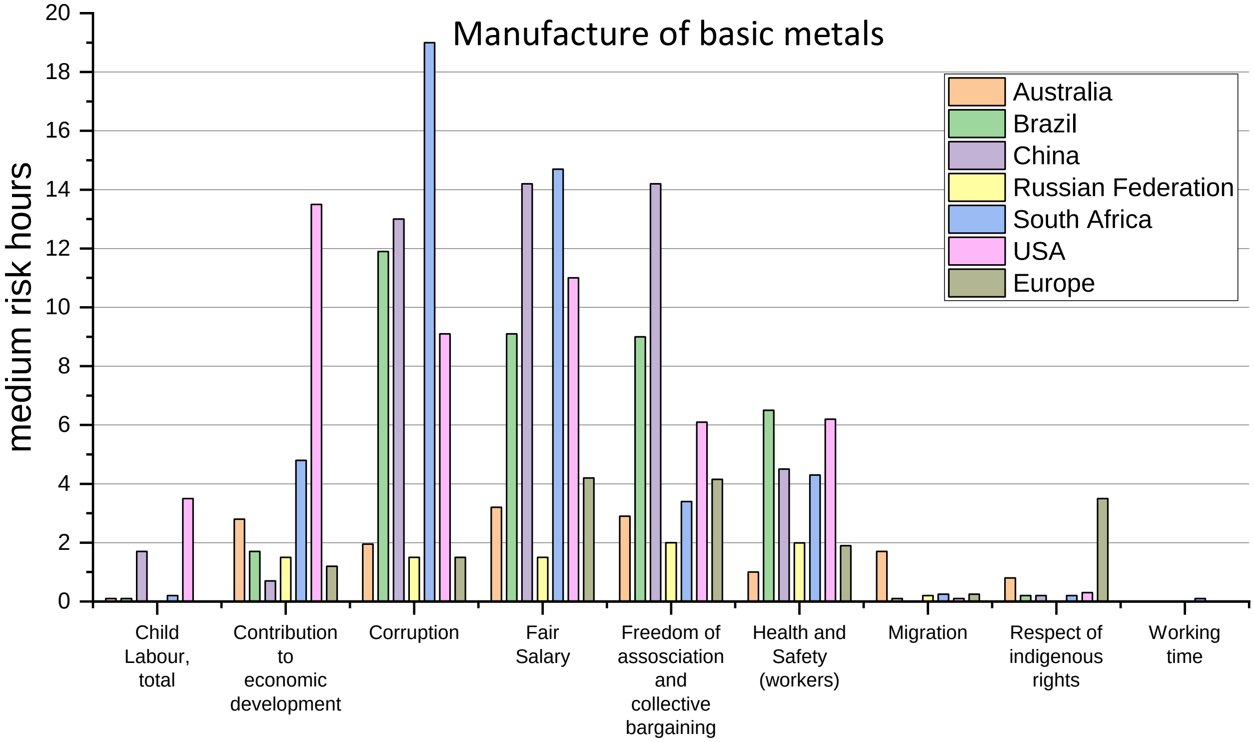


***Figure** 18: Life cycle-based results on the social risk associated with the metals manufacturing sector, in all selected countries reproduced from [94]*

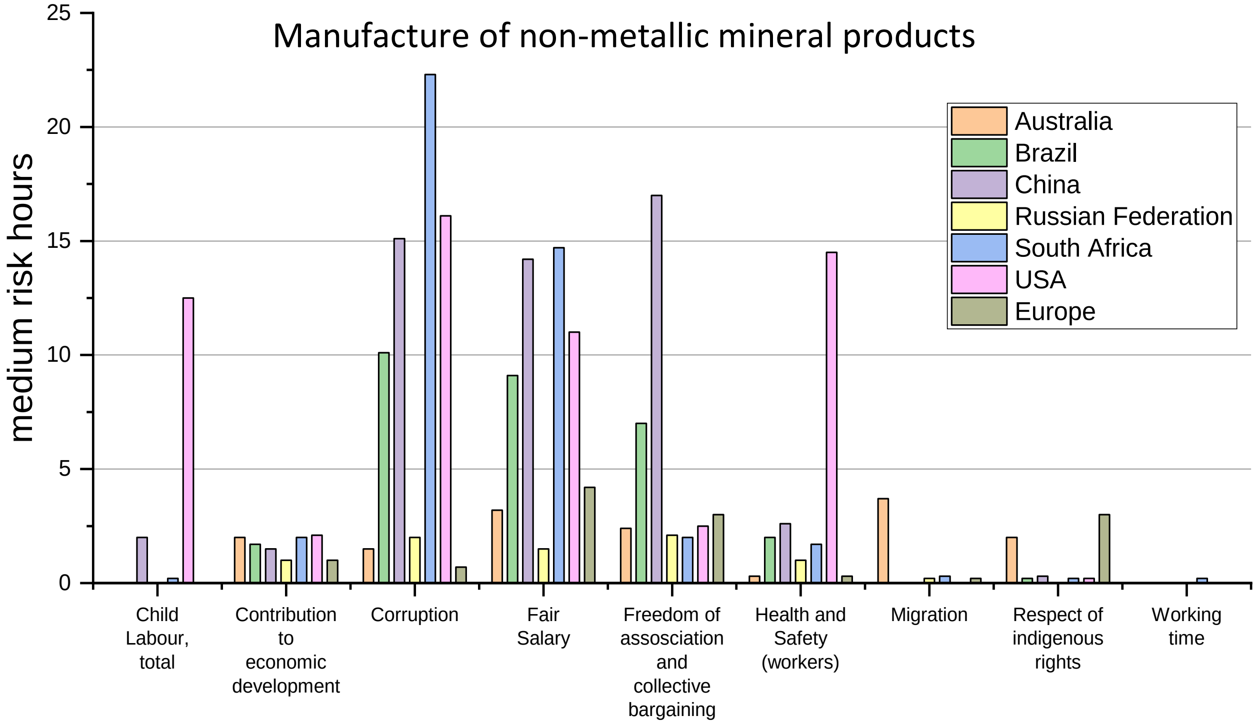


***Figure** 19: Life cycle-based results on the social risk associated with the minerals products manufacturing sector, in all selected countries reproduced from [94]*

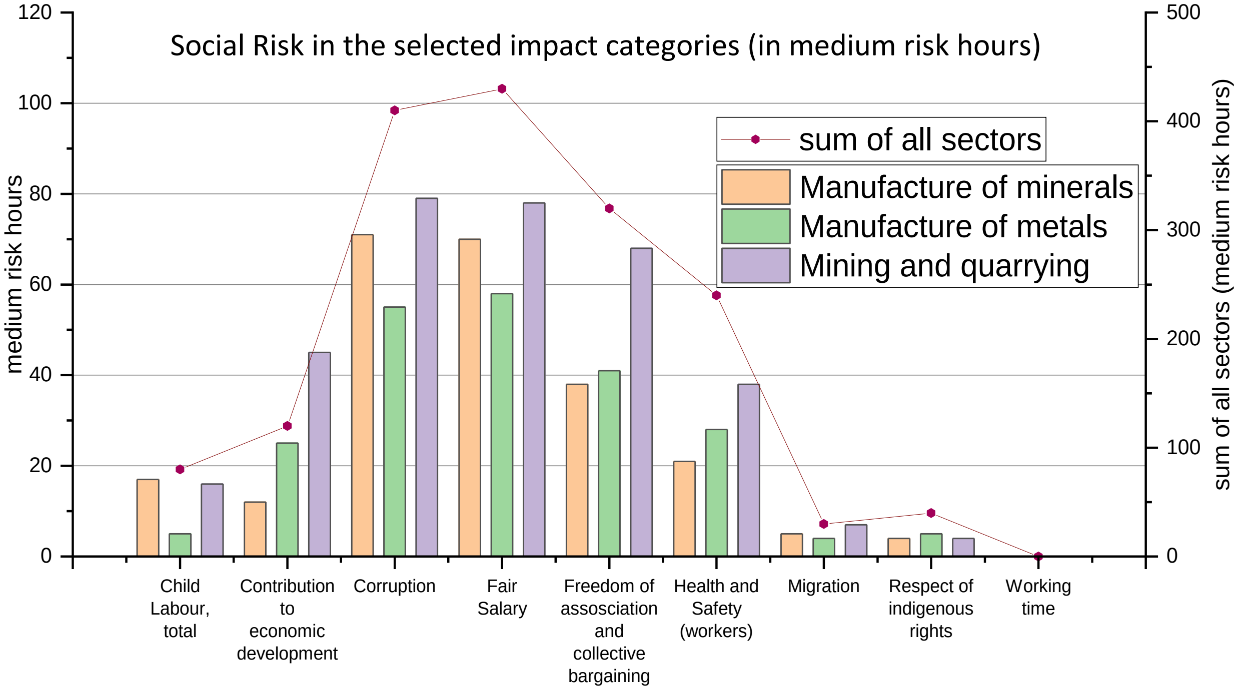


***Figure** 20: Social risk in the sectors under investigation (as a sum of countries under investigation) and total (sum of sectors and countries, right axis) reproduced from [94]*

6. Conclusion and Recommendation

In this review, we performed a comprehensive study on PCM types in buildings to find out the best candidates in terms of performance, environmental, economic, and social aspects. Commercial PCMs, used in buildings, have comparable performance and specific attributes and drawbacks for each type.

In general, PCMs come in various types. For instance, some PCMs can be acquired from plants such as (rapeseed oil, palm kernel oil, palm oil, soybean oil, and Coconut oil), while others are manufactured from crude oil such as paraffin wax, which is a nonrenewable resource, and others are produced from metallic ions and minerals. When it comes to the level of sustainability and effects on nature and societies, PCM's impact and cost depend on the materials' production processes. For that, four different types of PCM materials (salt hydrates represented by Magnesium Nitrate Hexahydrate, paraffin represented by Octadecane, and bio-based represented by Coconut oil, and Coconut oil with biofertilizers) were analyzed using LCA, where the emissions of each type were examined and compared to each other. Among the four studied types of PCMs, it was noticed that in terms of effectiveness they all have shown promising results, however in terms of cost and environmental and social impacts, there were substaintial differences. For instance, Octadecane has the highest purchasing cost (about 8$/kg), followed by Coconut oil (about 2$/kg), then Magnesium Nitrate Hexahydrate (about 0.3$/kg). In general, the hydrocarbon PCMs are the most expensive and salt hydrates are the cheapest. Also, Octadecane has the highest environmental impact among the studied PCMs, however, it stores/releases higher energy during phase change, because of its relatively high latent heat of fusion. This makes it desirable for small spaces. To have a better comparison that takes performance into consideration, the ECI for storing/ releasing the same amount of energy (100 KJ) is estimated and is highlighted below:

- **Magnesium Nitrate Hexahydrate** shows emissions equivalent to ECI of 4.5 £.
- **Octadecane** shows slightly higher emissions which are equivalent to ECI of 4.7 £.
- **PCM Coconut oil PCM** has the highest ECI of 8.28 £.
- **PCM Coconut oil PCM using biofertilizers** shows the lowest emissions which are equivalent to ECI of 0.085 £.

This study highlighted a critical issue, which is the hazardous effect of manurial fertilizers used in agricultural practices to produce fruit/plant-based PCMs. The results showed that manurial fertilizers have the highest ECI cost, while Coconut oil PCM using biofertilizers has the lowest ECI, this assures the hazardous effect of the manurial fertilizers and their significant effect on the ecosystem and climate change. So, bio-fertilizers should be used to avoid hazardous emissions and reduce the overall environmental impact of the produced PCM.

We can add the purchasing cost to the ECI and evaluate the total cost to store and release 100KJ. The results are summarized in Table 9. The Coconut oil produced using biofertilizers is the best candidate when all the factors are combined: economic, environmental, and storage capacity. Being much cheaper than Octadecane and with lower environmental impact, Magnesium Nitrate Hexahydrate becomes the second option.

Table 9: Total cost (purchasing and environmental) of each material to produce 100 KJ

Materials	Magnesium Nitrate Hexahydrate	Octadecane	Coconut oil using biofertilizers	Coconut oil using manurial fertilizers
Price (£)	4.8	8.3	3.2	11.4

For a thorough sustainability assessment, we should not overlook the social aspect. For the lack of specific quantitative data on PCMs, we relied on the work done on the social impact of different production sectors that interfere in the production of PCMs to get insights on their potential effects on societies and local communities. We deduced that the major social impacts are related to unfair salaries and corruption, which touch all production sectors, and hence all PCMs. In addition to that, there is the category related to the health and safety of workers, which are mainly at risk in production processes that involve quarrying and mining and manufacturing of metals and minerals. Hence, hydrocarbons (like Octadecane) and salt hydrates (like Magnesium Nitrate Hexahydrate) PCMs are more hazardous than biobased ones in this category.

In conclusion, the Coconut oil PCM using biofertilizers is ecofriendly, non-toxic, transparent, and has excellent chemical and thermo-physical properties for TES. This makes it suitable for various applications. Besides, PCM Coconut oil is relatively cheap and is obtainable, renewable, and biodegradable, unlike paraffin which requires decades to be fully decomposed. Its production positively affects the economy of the agricultural communities that produce it, despite some issues related to cheap and child labor. Consequently, relying on biobased/ plant-based materials is recommended for improving the sustainability of PCM production keeping in mind the need to enhance the socio-economic conditions of the labor.

There are different types of biobased PCMs other than Coconut oil, such as beef tallow combined with Coconut oil, rapeseed oil, palm kernel oil, palm oil, soybean oil, etc. Besides, there are other types of PCM materials which are from waste or by-products such as animal fats, fish wastes, pork lard, beef tallow, chicken fat, plastics, carbon PCM (C-PCM) [95], etc. The use of these waste materials in PCMs is regarded as a carbon sink and will allow the reuse of materials that would have been, otherwise, disposed in landfills. New findings and research conducted on these waste products can pave the way for the creation of resilient and inexpensive PCM alternatives in the near future. As a result, more work and further research are essential to make it a reality, and their potential must be completely explored to build a cleaner land greener prodcution for a better future. Eventually, improving the sustainability of PCMs improves the overall sustainability of buildings and allows the reduction of energy consumption and greenhouse gas emissions.

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