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Review

Phase Change Materials from Waste Streams: A Comprehensive Review

Kamal A. R. Ismail [1,*], Fatima A. M. Lino [1], Aissa Atia [2], Abdelghani Laouer [3], Ameur Mechraoui [4], Naseer H. Hamza [5] and Mohamed Teggar [4]

[1] Energy Department, Faculty of Mechanical Engineering, State University of Campinas, Campinas 13083-860, Brazil
[2] Department of Physics, Higher Normal School of Laghouat, Laghouat 03000, Algeria
[3] Department of Physics, Faculty of Exact Sciences and Computer Science, University of Jijel, Jijel 18000, Algeria
[4] Laboratory of Mechanics, University Amar Telidji, Laghouat 03000, Algeria
[5] Department of Mechanical Engineering, University of Al-Qadisiyah, Ad'Diwaniyah 58001, Iraq
* Correspondence: kamal@fem.unicamp.br

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Abstract: Phase change materials exhibit high latent heat and nearly isothermal phase change, which make them excellent candidates for many thermal storage as well as cooling applications. Waste generation, on the other hand, is steadily increasing, posing serious management challenges. These wastes are usually rich in chemical elements, oils, and fats and can therefore serve as raw materials for manufacturing valuable chemical products, including PCMs, encapsulations for PCMs, or thermal enhancers for improving heat transfer characteristics of PCMs. Suitable waste materials for the production of PCMs include agricultural and food-processing wastes, such as vegetable oils and fatty acid residues, as well as food-industry by-products. Industrial waste includes materials like polyethylene glycol, polymer processing waste, and industrial by-products. Municipal solid waste can be converted into energy-rich materials and PCMs by adequate thermal and chemical processes. Bio-based PCMs, usually obtained from fatty acids & esters, are derived from waste vegetable oils, animal fats, and food industry byproducts, after being chemically modified via esterification to form effective organic PCMs. Natural waxes are sourced from agricultural residues. Industrial waste-based PCMs are usually obtained from recycled plastics processed by pyrolysis or blended to create composite PCMs. By-products from polymer manufacturing and lost-wax casting wastes can serve as sources for PCMs. Waste-derived PCMs can be incorporated into building components, such as cement mortar, to improve thermal resistance and comfort. Waste-derived PCMs can be used for thermal management in electronics and battery systems to maintain a uniform and acceptable temperature within battery packs. Encapsulated PCMs can be incorporated into fabrics for flexible, medical and protective wearable applications. The continuously expanding application fields of PCMs, such as functional textiles and biomedical applications, require detailed and rigorous characterization of their thermochemical properties, including biodegradability, biosafety, and biocompatibility. This will certainly open new fronts for research and development in the area. The review's contents can help researchers and professionals involved in waste management and in the development and production of PCMs.

Keywords: waste-derived PCMs; industrial wastes; food processing wastes; agriculture wastes; urban solid waste

1. Introduction

The continuous increase of the world population and industrial activities provoke increase of the energy demands causing environmental pollution and global warming achieving alarming limits. To reduce pressure on the environment and decelerate global warming global mitigating measures are required to shift to renewable energy sources, conserve energy and materials and reduce wastes and losses.

Annually the world produces a large amount of waste due to people's daily consumption. Inadequate disposal of these wastes contributes to environmental pollution, waste of energy and materials. Therefore, recycling can be an advisable solution for eliminating the consumption of materials and using natural resources effectively. Upcycling waste into valuable products is a promising strategy to mitigate the environmental impact of waste both globally and locally and support the economic development and well-being of the society.

Phase change materials (PCMs) are widely used to store thermal energy. Its favorable characteristics include among others the phase change isothermal behavior and the high latent heat, but their low thermal conductivity, leakage and high cost issues limit their wide utilization. To address these issues, waste materials undergo a series of treatments aimed at creating a porous structure able to effectively encapsulate the PCM, by accommodating it within the porous matrix besides increasing its thermal conductivity and its thermal leakage resistance.

Phase change materials can be classified into organic, inorganic, and eutectic materials, Figure 1. The choice of PCM for certain application depends primarily on its thermal and chemical properties and its suitability for integration with the application systems.

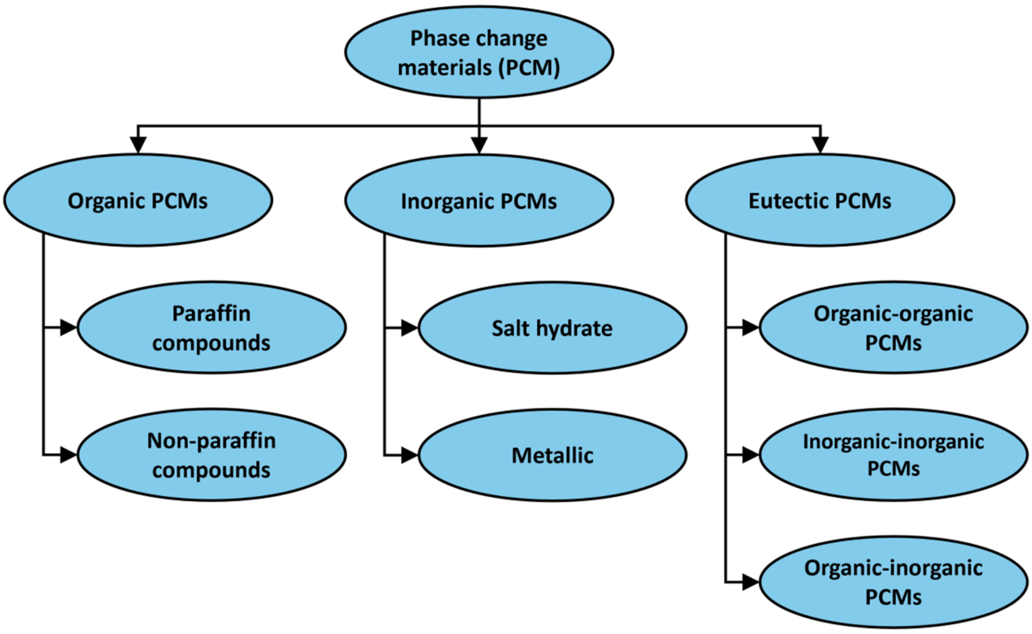

Figure 1. Classification of phase change materials.

Organic PCMs include paraffin and non-paraffin, which are thermally stable, non-corrosive and characterized by the thermal energy density (latent heat), while non-paraffin includes esters, alcohols, fatty acids and other organic compounds. They have a wide range of melting temperatures and can be tailored according to the intended application. Inorganic PCMs include salt hydrates and metals and alloys, where salt hydrates are compounds formed by combining a salt with water, such as calcium chloride hexahydrate. They exhibit generally high latent heat of fusion and are relatively inexpensive. Metals and alloys can be used for high-temperature applications. Eutectic PCMs are mixtures of two or more organic or inorganic compounds that change phase at a single, well-defined temperature. They offer the advantage of a sharp melting point and can be tailored to specific temperature ranges [1,2].

Phase change materials can be produced from various sources, including natural, synthetic, and waste materials. Natural resources include animal fats and vegetable oils, while synthetic materials include metals, paraffin, eutectics, etc. Waste resources include oils, fats, metals, and salts. Figure 2 shows the different types of PCMs and the resources used to produce them.

PCMs produced from waste materials, or waste-derived PCMs can be utilized in buildings, solar thermal systems, and thermal management of electronics, among others. The use of waste materials like industrial byproducts, agricultural residues, and food wastes can reduce reliance on virgin materials and promote a circular economy, providing several financial, environmental and social impacts, minimizing waste generation and associated environmental concerns, besides waste materials availability [3].

Waste can be classified in several ways, most commonly by origin, such as industrial, commercial, domestic and agricultural wastes. Industrial waste generated by manufacturing processes and factories. Commercial waste is produced in businesses, offices, and retail settings. Domestic (household) waste is generated by everyday living activities and consists mainly of organic matter, while agricultural waste includes crop residues, animal waste, and other organic materials from farming. Projections indicate that municipal solid waste (MSW) can reach 3.8 billion tons by 2050 (Figure 2).

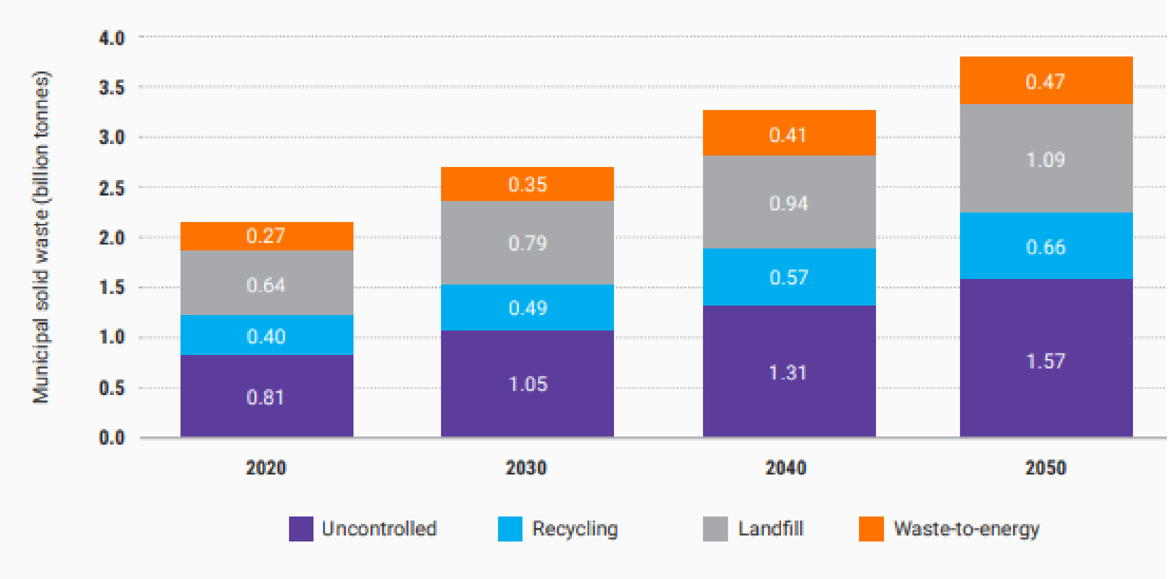

Figure 2. Projected global MSW destinations in 2030, 2040 and 2050, from Kaza et al. [4].

In 2024, global food waste was estimated by 1.05 billion tons, including losses in the supply chain and food discarded at the retail, food service, and household levels. Households are responsible for a significant share, with 60% of food waste originating from households. On average, each person wastes 79 kg of food annually. Food waste accounts for 8–10% of global greenhouse gas (GHG) emissions and represents a significant financial loss.

Industrial residues account for almost half of worldwide waste, or about 9.2 billion tons annually, and consist of solid, chemical, and liquid waste generated by industry and commercial establishments. These wastes negatively impact the planet, causing damage to ecosystems and wildlife, polluting water sources, and contributing to GHGs. Adsorbent materials and carriers can be prepared from industrial solid waste due to their rich pore structure and good adsorption capacity. Industrial solid waste contains significant amounts of metal oxides and trace elements [4–6].

Global agricultural waste accounts annually for 10–50% of agricultural products and poses significant environmental, economic, and social challenges. Also, it accounts for a significant part of global waste, predicted to reach about 2.6 billion tons by 2030 [4,5,7,8].

There exist various disposal avenues of wastes. The most financially viable way to manage these wastes is to use ordinary landfills and dumps, which are commonly used in most developing and poor countries. Other eco-friendly methods need to be employed to reduce the offensive effects of waste and reuse its materials and energy potential. Recycling part of the waste for reuse saves energy and raw materials, reduces emissions, and reduces the volume of waste to be landfilled, while also creating jobs and income and promoting the circular economy. Metallic cans, glass bottles, paper, and cardboard are among the most recycled materials. Used oils and animal fats are among the waste materials used to produce biodiesel.

Research and developments have shown that the organic part of waste is rich in chemical elements and energy, which can be extracted mainly with available technologies. Some organic wastes were evaluated for use as bio-based PCMs, and the tests showed encouraging results. Fibrous agricultural wastes are used mixed with mortar and bio-PCM in the construction of building walls and bricks to promote passive thermal and acoustic comfort.

The review explores the potential, strategies, and techniques for producing PCMs, their carriers, and enhancing additives, as well as possible applications in the building industry, energy storage, cooling of PV panels, electronic equipment, electric batteries, and food and water desalination. The new fields of waste utilization, especially organic waste, can strengthen the circular economy, promote social inclusion and create jobs and income.

The current study presents a detailed review of the framework for PCM obtained from waste, covering waste materials as sources of PCMs and focusing on process-based analyses, including chemical, thermochemical, and physical processes involved in waste-to-PCM transformation. Moreover, the current study highlights the comparative thermophysical behavior of waste-based PCMs, which is an aspect that is rarely discussed in the literature. Furthermore, the study reviews the use of waste-derived PCMs in applications such as building management, electronic cooling systems, energy storage, and smart textiles. The study also incorporates the concept of circular economy to illustrate the benefits of waste valorization. A specific focus on the utilization of agriculture residues, food processing waste and residential organic wastes for the production of PCMs represents a unique feature of this review.

This manuscript is organized into nine thematic sections. Following an Introduction (Section 1), Section 2 contextualizes global waste generation and characterization. Sections 3 treats PCMs from agriculture and food processing wastes, Section 4 handles PCMs from industrial waste, Section 5 treats PCMs from food leftovers and kitchen waste, Section 6 treats PCMs from municipal solid waste (MSW), Section 7 treats the encapsulation technologies for waste-based PCMs, Section 8 discusses the challenges and limitations of waste-based PCMs, while Section 9 presents the main conclusions and future research opportunities

2. Global Waste Generation, Characterization and Reutilization

Wastes are increasingly generated as a result of human living and production activities since the early settlement ages. During the last decades, due to extensive and intensive global industrialization associated with continuous population increase and standard of living improvement, the personal, local and global wastes substantially increased to alarming limits. These wastes for long time have been dumped in open areas and rivers or deposited in landfills where it is decomposed producing bad odors, insects, diseases, leachate and greenhouse gases. On average, each ton of landfilled MSW can release approximately 1807 kg of CO_2-eq in greenhouse gas (GHG) emissions. For these reasons correct treatment of MSW is extremely important to mitigate global warming and reduce its disastrous effects.

Adequate waste disposal and advanced treatments for generating energy and other products are practices used in rich countries. Because of poverty, financial costs and lack of technology, besides other issues, the common practice in poor countries is open sky dumping or simple landfilling without any further treatment. Figure 3 shows the global treatment and disposal of wastes.

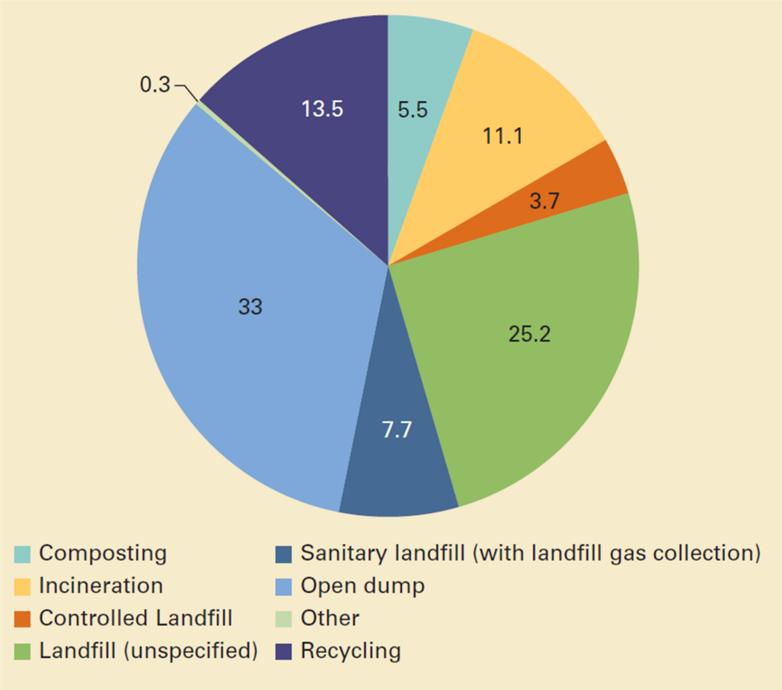

Figure 3. Global treatment and disposal of waste [9].

Wastes can be classified according to their physical state (solid, liquid, gaseous), or according to biodegradability (biodegradable, non-biodegradable), or according to origin/composition (organic, hazardous, industrial, medical, electronic, etc.). Each category has a different impact on the environment and requires specific management. Solid wastes includes common household refuse, business trash, and factory byproducts like paper, plastic, metal, and glass, liquid waste includes wastewater, chemicals, and process liquids from industries, laboratories, and households while gaseous wastes include emissions like carbon dioxide, sulfur dioxide and other gases. Industrial waste is generated from manufacturing and other industrial processes, while agriculture waste is composed of byproducts from farming, such as crop residues and animal manure.

In 2024, global industrial waste generation was estimated to be around 9.2 billion tons**,** while a significant portion of global organic waste, primarily food waste, continued to be a major environmental and economic problem, contributing 8–10% of greenhouse gas emissions. Households are the largest source of waste, responsible for 60% of the total, with an estimated 631 million metric tons generated. Efforts to manage this waste are ongoing, focusing on reducing food loss, promoting circular economy solutions, and improving waste management infrastructure, particularly in developing countries [10,11].

MSW generation is predicted to increase from 2.1 billion tons in 2023 to 3.8 billion tons by 2050, with approximately 220 million tons of plastic waste of which one-third is inadequately managed. The global food waste is estimated at 1.3 billion tons annually. Globally, the composition of municipal solid waste (MSW), Table 1, is dominated by organic materials (44%), followed by recyclables (paper, cardboard, and plastics) of (38%), and other materials (18%), [12]. The specific values vary by region and income level, but organic waste consistently makes up the largest component, Figure 4.

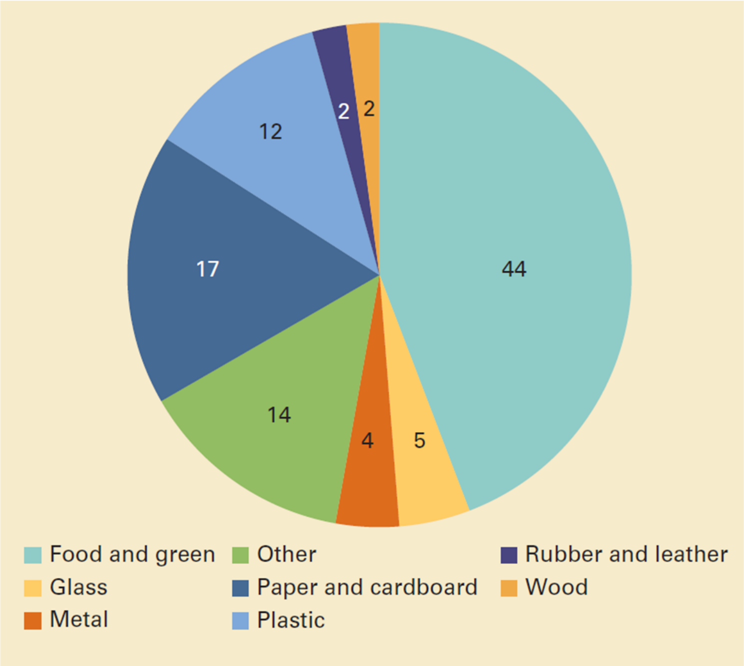

Figure 4. Global waste composition [9].

Table 1. Composition of global MSW [9].

Waste Type	Percentage of Global Waste
Food and green waste	44%
Paper and cardboard	17%
Plastic	12%
Other materials	14%
Glass	5%
Metal	4%
Wood	2%
Rubber and leather	2%

The global waste problem, with over 2 billion tons generated annually, demands urgent action. About 90% of plastic isn't recycled, and one-third of food is wasted. Systemic barriers like inadequate infrastructure and inefficiencies exacerbate the issue, but opportunities like composting, chemical recycling, and policy interventions offer pathways to a circular economy. By addressing waste through innovation and global collaboration, it is possible to mitigate its environmental impact, and conserve resources [13].

Considering the amounts of wastes generated daily, its varieties the need to find economic, effective and permanent solutions to mitigate global warming and collapse of the ecosystem, many research and developments were dedicated and still ongoing to find solutions that are economically profitable, eco-friendly and sustainable. Solid metallic wastes are generally recycled into the same or other products saving energy, raw materials, avoiding emissions and reducing disposed mass to landfills. Other solid matters as glass, demolition materials, etc. are recycled and reused. The main part of wastes is the organic portion which is responsible for greenhouse gases, odors, insects and diseases. Research and developments have shown that organic wastes, including forest, agriculture and food wastes and liquid wastes can be used for producing a variety of useful products which can reduce dependence on fossil based products.

Food and agriculture wastes can be used to produce second generation biofuels such as bioethanol and biodiesel to substitute fossil based fuels, reduce use of food crops for biofuels. Other investigations showed their big potential for producing biohydrogen, jet biofuel for aviation, biogas, biomethane and can be pelletized to form solid fuel to be used in commercial and residential applications. Also, food and agriculture wastes can be used to produce bioPCMs of different kinds and different melting temperatures, used to make porous materials for encapsulating PCMs and capsules for protecting PCMs and avoid leakage and contamination.

Wang and Yuan [14] reviewed the recent progress in the food waste management to understand the circular model and provide solution to existing linear model. Cayumil et al. [15] presented an overview of municipal solid wastes and industrial waste. Relevant waste issues, recycling, resource recovery, disposal and the associated environmental impacts were analyzed. Benyahya et al. [16] investigated the parameters affecting the anaerobic digestion process, highlighted the inhibiting parameters and their possible solutions and discussed challenges and future research. Abdel-Shafy et al. [17] presented an overview on the behavior of landfills, its impact on the environment, and treatment methods. Several treatment technologies were discussed presenting highly efficient system including leachate transfer, biological treatment and chemical and physical procedures and membrane technologies. Yatoo et al. [18] presented a review on global municipal waste issues including landfill heat and leachate formation, and discussed integrating waste management approaches to achieve sustainability. Hamdi et al. [19] reviewed the global production of bio-ethanol and highlighted the best agricultural wastes used for this purpose. Lackner et al. [20] reviewed the biomass gasification, raw material including dry biomass and MSW. Yadav et al. [13–21] presented a study that dealing with global agriculture waste, its environmental effects, and the governing bodies involved in these issues. Lackner et al. [22] and Mesjasz-Lech [23] explored strategies for managing agricultural waste, highlighted solutions to produce biofuels from lignocellulosic materials and wastes, and recommended circular economy practices, emphasized the importance of policy frameworks, public-private partnerships, besides shaping waste management policies, and strengthening local cooperation.

Remarks

Utilization of waste-derived PCMs has gained popularity for various applications, including energy-efficient buildings, electronic cooling, TES, and intelligent textiles, as they are cost-effective and support the principles of the circular economy as well as sustainability. In the building sectors, PCM is implemented in walls, roofs, and composite panels for thermal management leading to cooling/heating loads by 15–30%. Among PCMs types investigated, those produced from biomass waste, such as bio-oils and fatty acids, with melting points of 20–35 °C, are ideal for building applications, as their melting point correspond to the thermal comfort level inside buildings. Unfortunately, these PCMs have low thermal conductivity, which can be improved by adding carbon materials. The use of PCMs derived from electronic waste in cooling involves using these materials to mitigate transient heating events in highly efficient equipment and to serve as thermal buffers that absorb heat surges, thus ensuring constant operating temperatures. The inclusion of heat-conducting additives such as graphene and carbon materials derived from plastics in waste greatly increases the heat-transfer capabilities of these materials, which can then be applied to the development of heat sinks and battery cooling systems. When discussing the application of PCMs derived from waste as thermal energy storage solutions, it is important to note their utilization in solar thermal technologies, waste heat recovery, and low- to medium-temperature energy storage. Organic PCMs derived from waste are preferable for low-temperature applications, whereas inorganic PCMs derived from slag and salts are preferred at higher temperatures. Moreover, for use in the textile industry, waste-derived bio-based microencapsulated PCMs can be incorporated into fibres and coatings to improve thermal comfort by regulating heat transfer between the human body and the environment. Waste-derived PCMs are particularly suitable due to their biodegradability and non-toxicity, although durability and washability remain issues. In general, the performance demands for waste-derived PCMs will differ greatly based on their intended application: thermal stability and low cost take precedence in building systems; conductivity and responsiveness are most important for electronics; and latent heat capacity and cycle endurance are most important for thermal energy storage systems.

3. PCM from Agriculture and Food Processing Wastes

Organic waste products have become increasingly important in the development and enhancement of PCMs through the processes of carbonization or pyrolysis. Porous carbon is essential in offering structural stability to PCMs because it creates a stable matrix that can encapsulate the PCMs, effectively preventing leakage and maintaining the integrity of the material. The porous structure can incorporate relatively large quantities of PCMs enhancing the efficiency and effectiveness of the PCMs.

Huang et al. [24] presented a review showing the merits and defects of porous materials, the effects of its geometrical parameters on the shape stabilized PCMs. Future research topics and challenges were also discussed. Ghani et al. [25] presented a review on the utilization of waste materials as feedstock for future production of cost-effective and environmentally friendly PCM. Jiang et al. [26] provided a review focused on cover materials for high temperature shape stabilized PCMs and their effects on the mechanical and thermophysical properties. Dominici et al. [27] investigated sepiolite, diatomite, palygorskite and zeolite to achieve shape-stabilized PCMs. The results showed both good stability and thermal performance. Zhang et al. [28] reviewed the recent studies on porous shape stabilized PCMs including materials, methods and numerical advances. Zhang et al. [29] provided a review on solid waste base form-stable PCMs, including preparation strategies, application solutions, and future research recommendations. Wani et al. [30] commented that traditional food waste reduction strategies are ineffective in lowering GHG emissions and food waste treatment. The authors provided details of the methods of prevention and minimization of food waste. Choure et al. [31] showed that the use of fins is the most common heat transfer enhancement media and the use of various shapes and orientations gives a better thermal performance. Metal foam material has a very high heat transfer rate in PCM but reduces the storage capacity of PCM. The effect of carbon fiber, carbon nanotube, graphene, nanoparticle, and metal oxide was investigated. Nandi et al. [32] provided a review on PCM enhancement techniques, including utilization of fins, geometric modifications, metal foams, nanoparticles. The review evaluated the thermophysical improvements, highlighted advancements and underscored the urgent need for further research to address existing gaps.

Pereira et al. [33] provided a review that explores how pore structure, material composition, and activation processes influence PCM encapsulation and composite performance. Key research gaps have been identified, including the absence of standardized biomass classification, limited progress in enhancing energy storage capacity, a lack of system-level validation, and the need for comprehensive environmental impact analysis.

3.1. Agricultural Waste

The conversion of agricultural waste into PCMs is a process that utilizes an abundant resource and addresses waste management challenges in the agricultural sector. The approaches to recycling of these types of waste include chemical treatment, physical drying and high temperature process such as pyrolysis and carbonization, Figure 5.

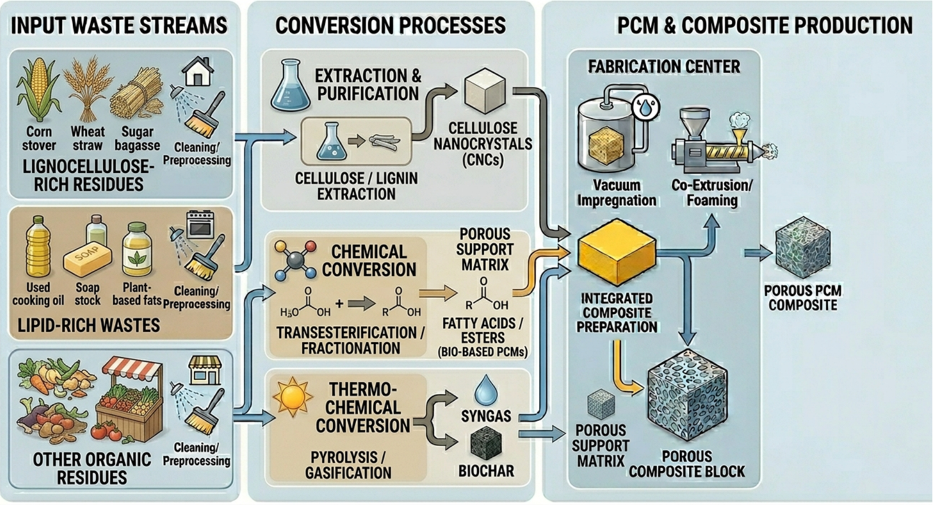

Figure 5. Flowchart of PCM process from agricultural waste.

Gunasekara et al. [34] conducted a research study for possible PCMs candidates from food wastes. The chosen candidates include Erythritol, Glycerol and Olive oil. The results indicated that these three candidates are adequate PCMs. Duquesne et al. [35] identified two eutectic mixtures of fatty acids as promising economic and eco-friendly alternatives and could compete with paraffin, while He et al. [36] prepared a shape-stabilized and flexible phase change film based on polyethylene glycol which can be used for electronic devices. Lawag and Ali [37] presented a review PCMs for thermal management of electronics and energy storage, including PCMs types, characteristic, applications and methods of enhancing the thermal conductivity. Baptista et al. [38] studied the beeswax and its composites to evaluate their potential as PCMs and reported an increase of about 15% in melting enthalpy occurring at 10 °C higher melting temperature with the minimum undercooling, make them good PCM candidates. Mishra et al. [39] provided a review on beeswax as a PCM. Reviewed studies showed investigations using conducting particles to increase its thermal conductivity and porous materials to prevent leakage. Tawalbeh et al. [40] provided a review of the recent advances in materials for thermal energy storage, enhancement techniques, and concluded that inorganic phase change materials could be used for high-temperature applications.

Lv et al. [41] prepared shape-stable composite PCMs from waste phoenix leaf biochar and favorably compared with the original PCMs. Sari et al. [42] used carbonized sugar beet pulp as a porous framework to develop a thermally conductive and highly leak resistive composite PCM. The developed composite is cost-effective and eco-friendly. Ong et al. [43] mentioned that residues from coffee brewing process are rich fatty acids, are promising green alternative bio-based PCMs and confirmed, after tests and analysis, that the PCM produced can be used for cold-chain transportation and cold therapy. Ong et al. [44] prepared a series of coconut peat (CP)/polyethylene glycol (CP/PEG) composites as shape-stabilized PCMs and showed that the developed composite can be used for thermal storage applications. Saberi et al. [45] proposed a shape-stabilizing porous matrix of cellulose from recyclable resources forming a cellulose hydrogel to encapsulate the PCM. The results showed improvement of the thermal conductivity, enhanced stability, reduced leakage, and improved thermal properties

3.2. Food Processing Waste

Food and biomass wastes make up 44 % of the total generated waste. Globally, huge amounts of food waste are generated annually and mostly deposited in landfills, incinerated, composted or used for anaerobic digestion to produce biogas. In this regard, food waste is a potential source of carbon due to its high content of organic components. Carbon materials are widely used in diverse application areas, including energy storage and conversion. Thus, transforming food waste into PCMs is a sustainable approach that helps management of organic wastes. This process involves converting various types of food waste into biochar or other products in order to incorporate these products into PCMs composites. Hence, upcycling waste into valuable products such as PCMs can help mitigate the environmental impact of waste both globally and locally and support the local economic development.

Gao et al. [46] commented that biological porous carbon used for the production of shape-stabilized phase-change materials has low thermal conductivity and poor loading capacity and suggested the use of cabbage mustard biochar to improve these defects. Choi et al. [47] investigated the thermal and acoustic performance of a bio-based microencapsulated PCM composite and coffee waste. The results showed improvement of the thermal and acoustic performance of the composite. Atinafu et al. [48] pyrolyzed waste biomass materials to produce biocarbon for organic PCM encapsulation. The composite materials showed decreased leakage tendency, enhanced thermal stability and thermal conductivity, and improved PCM loading capacity. Abdulmunem et al. [49] investigated the use of waste paper and PCM within polyvinyl chloride (PVC) panels for inner cladding of buildings. The results showed an enhancement of the acoustic performance and reductions in the cooling load and electricity. Yue et al. [50] investigated three kinds of porous bamboo-derived materials used as the framework for paraffin to form PCM composite. The results showed that the product can effectively reduce temperature fluctuation, minimize leakage, and improve thermal conductivity. Cui et al. [51] provided reviews on the PCMs types, characteristics, encapsulation, shape stabilization, waste-derived PCMs, and their advantages and limitations.

Innovations in PCMs including photo switchable PCM, magnetically multifunctional PCM, 3D printed PCM and flexible PCMs remain underexplored. The authors identified gaps for future research and highlighted the potential application in biomedical fields, cotton fabrics and smart packaging Kalidasan and Pandey [52].

Remarks

A promising solution lies in converting agriculture and food residues and kitchen waste into PCMs for thermal storage and other applications. These wastes are rich in fats, oils, fatty acids, and sugars, which can be transformed into waxes or esters capable of storing heat within the 6–60 °C range. Repurposing them for latent heat storage not only reduces disposal-related impacts but also offers a cost-effective alternative to conventional

PCMs. Although waste oils and fats often present complex compositions, they are viable feedstocks for producing low-melting-point PCMs.

4. PCM from Industrial Waste

The continuously increasing demand for energy has led to a search for new techniques to store and reuse energy efficiently. PCMs are among these sources because of their promising characteristics in terms of latent heat storage, almost isothermal process of heat release-storage, compatibility with encapsulation and integration in other systems that require energy storage and many other helpful thermal characteristics [53–55]. One of the major sources of PCM is derived from industrial waste, Figure 6, as industrial processes typically produce significant amounts of waste that can be recycled in the manufacturing of PCM. The advantageous characteristics of high thermal conductivity, chemical stability, resistance to corrosion, and hardness motivate the incorporation of these wastes into PCM [55,56].

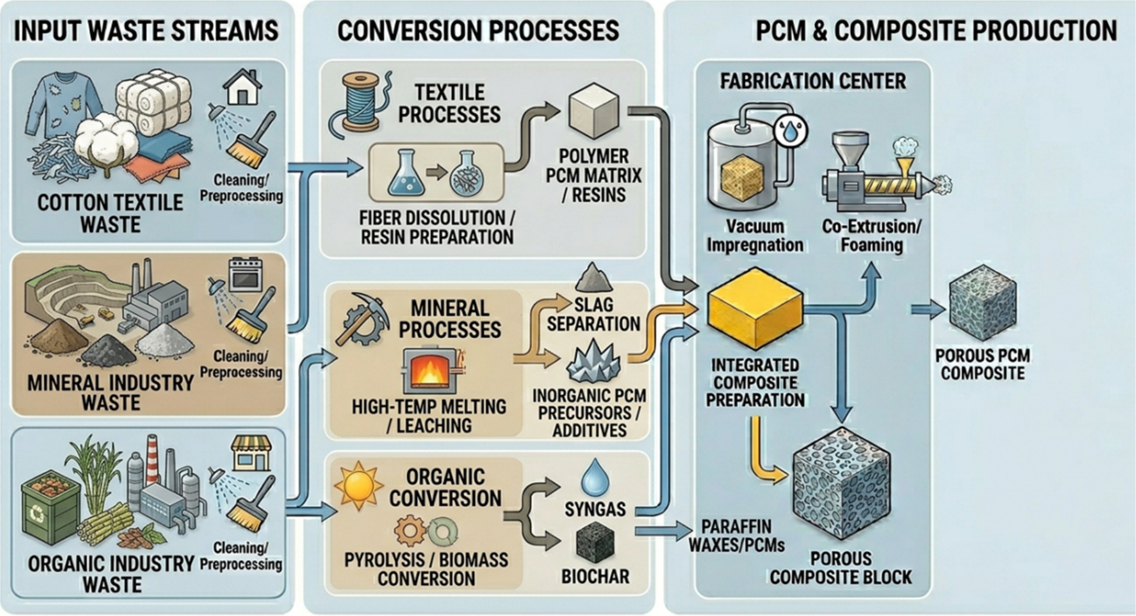

Figure 6. Flowchart of PCM process from industrial waste.

In the metallurgy and metal processing sector, the largest sources are identified, which include steel slag, blast furnace slag, and red mud from aluminum production [57–60]. Reports estimate significant amounts of steel slag (about 17 million tons per year) in the US, it is a significant contributor to the development of PCMs from industrial waste. Additionally, blast furnace slag contains large concentrations of silica, which can be utilized in thermal storage composites [59,60]. From the mining and mineral processing field, another main set of inputs exists with silica contents that range from 27% to 90%, depending on the process involved [59]. In iron ore tailing, some of that may go up to 90% silica content, and for the post-flotation waste of copper ore, that number may be between 27% to 59% [59]. Also included in this is coal mining, which reports an average silica content of 55%, as well as waste from oil and gas production, which reports an average silica content of 62% [59]. The textile and organic industry can be a base for producing composite PCM. Carbonized cotton fabric waste is a suitable candidate that can absorb as much as 70% polyethylene glycol content without failure, thereby producing excellent thermal storage materials [61]. Additionally, it is reported that sewage sludge and other organic industrial wastes contain the right materials for the base of energy storage materials [62,63].

In the sugar industry, some products such as dry sugar beet pomace, molasses, and sugarcane bagasse, which, though they have inorganic elements like silicon dioxide, sodium chloride, and calcium fluoride, still function as mineral PCMs [62]. In energy production and waste treatment, some products can be derived including coal fly ash, municipal solid waste incineration residues, and flue gas desulfurization gypsum [63–65], which in many cases contain alkaline elements that play a role in carbonation processes and thermal storage applications [63,66]. Chemical and pharmaceutical industry byproducts present special components for PCM development. Phosphogypsum from phosphorus fertilizer production and cesium carbonate waste from drug manufacturing may be used to produce nanocalcite particles with controlled thermal properties [67]. The byproducts of the wax casting industry and various polymer processing wastes present low-cost options for PCMs [68]. In addition, the embodied energy for instance can be reduced by 40% in case of using used cooked oil while gas emissions can be mitigated by 35% if PCM is sourced from agriculture waste streams [68].

In the area of industrial processing, which produces PCM sources, mineral carbonation is a key industrial process for creating materials suitable for use in PCMs from alkaline waste products [63,66]. In these processes, CO_2 is chemically reacted with calcium and magnesium in the waste to form stable carbonates that can be used as thermal storage materials. The carbonation process also has the advantage that industrial waste products do not require mining, usually have a proper particle size, which in many cases does not require additional milling, and also in many cases do not require pre-treatment for reaction [63]. Coal fly ash, metallurgical slag, concrete waste, and mining residues are highly suitable for mineral carbonation, with the added benefit that these materials are typically produced near major CO_2 emission sources, thereby reducing transportation costs. Geopolymer synthesis is another large-scale industrial process that utilizes inorganic waste streams for the production of functional thermal storage materials [69]. It is observed that a significant proportion of inorganic byproducts, such as calcined clays, fly ashes, and metallurgical blast furnace slag, being utilized in geopolymer cement formulations. The synthesis process reveals the pozzolanic properties of these waste materials, yielding materials that perform as well as traditional cement binders but with a significantly lower carbon footprint. Vitrification processes transform solid waste from incineration into PCM-suited materials via high-temperature treatment [70].

Fly ash and bottom ash from incineration can be vitrified to produce materials which have a silica, calcium and aluminium base used for silicate-based building materials. Furthermore, this process produces useful thermal storage materials, which is simultaneously the safest way to deal with hazardous incineration waste and promotes waste resource recovery.

Biomass ash, a byproduct of biomass energy production and agricultural waste, is considered a source for supplementary cementitious materials [71,72]. It is noticed that agricultural waste products, such as palm oil fuel ash, sugarcane bagasse and rice husk, exhibit enhanced pozzolanic properties when subjected to calcination processes.

Moreover, there is a synergy in the use of multiple waste types, which, when combined, create new composite cementation materials [58]. This process not only neutralizes the issues of each separate waste stream but also produces functional thermal storage materials and identifies which individual waste streams may exhibit low reactivity or contain problematic chemical compositions. Catalytic and thermal processes are employed to convert industrial organic waste into carbon-based materials for thermal storage [73,74]. In the pyrolysis and depolymerization processes, industrial solid waste is turned into carbon catalysts and thermal storage composites. Textile, galvanic, and tannery industry sledges subjected to thermal treatment produce materials that possess the right thermal properties for PCM.

The incorporation of waste-based PCMs into buildings and construction is a step forward in sustainable architecture and energy-efficient building design. This approach helps supporting the circular economy and the mitigation of negative waste impacts [75].

Additionally, there exist issues related to the low thermal conductivity of traditional bio-based PCMs, but these have been addressed through the use of innovative manufacturing processes. To overcome thermal conductivity issues, researchers have proposed advanced integration, which in turn utilizes metallic structures. Bio-based PCMs have been incorporated into metal frameworks made of copper and aluminum [76]. Thermal storage improved by 10% for the copper framework.

Waste-derived PCMs have seen significant use in thermal energy storage, particularly for waste heat recovery, which is proposed to enhance energy efficiency, and it is observed a growing interest in PCMs for latent heat storage technology due to the waste thermal energy they can utilize [77]. Agricultural and industrial waste used as PCMs presents advantages in thermal energy storage design because of the large variation in thermal properties.

Research has shown that it is practical to convert industrial waste into functional PCMs, a finding that was demonstrated in the lost-wax casting industry [78]. Furthermore, these waste-derived materials were subjected to rigorous analysis, including chemical makeup, thermal characterization, and thermal stability. The results showed that PCMs derived from industrial waste performed as well as commercial alternatives in terms of durability. In addition, the durability with respect to thermal stress was not inferior to that of commercial PCMs [78]. This improved performance is evident in many industrial settings, from construction to electronics, where these materials excel at meeting the specific requirements of each individual application due to their flexibility and excellent energy storage capacity.

In the industry, one can see that implementation strategies have grown to include hybrid solutions that put waste-derived materials with commercial PCMs together. It was reported that PCM blends produced using commercial PCMs and waxy industrial byproducts have very promising results, which in turn demonstrate that waste can be incorporated into existing industrial processes without a loss in performance [79,80]. Moreover, it is noted that this approach presents environmentally friendly energy storage solutions, which simultaneously address waste disposal issues and reduce material costs.

Remarks

- PCMs can be synthesized from various industrial waste sources, including waste plastics, industrial residues such as fly ash and waste fats and oils from agro-industrial processes. This approach promotes a circular economy and offers a sustainable, low-cost alternative to conventional, non-renewable PCMs.
- Utilizing waste for PCM production reduces landfill negative impacts, lowers the carbon footprint, and decreases reliance on fossil-fuel-derived materials like paraffin. Waste-derived PCMs possess good latent heats and appropriate melting temperatures which make favorable alternatives for commercial PCMs. Since they are manufactured from abundant waste materials as feedstock generally results in lower production costs.
- These waste-derived PCMs are used in applications such as integration into building materials (walls, roofs, floors) for passive cooling and heating, thermal management in electronics and automobiles, and waste heat recovery systems in various industries.

5. PCM from Food Leftovers and Kitchen Waste

Food and kitchen waste are among the largest components of global waste today [81]. Mismanagement or improper disposal methods such as open dumping or uncontrolled landfilling lead to the release of harmful greenhouse gases, particularly methane, which plays a major role in global warming [82]. The negative impacts extend beyond the environment, affecting the social and economic systems too [83]. Reducing food waste and implementing effective management strategies are urgent priorities to ensure the sustainability of ecosystems [84]. In addition, reclaiming food waste often yields economic benefits that make this approach more cost-effective, particularly in areas with large waste streams. Its implementation can also substantially reduce disposal costs and mitigate the associated environmental impacts [85,86].

The conversion of food residues and kitchen-derived wastes into PCMs has emerged as a strategy to address both waste valorization and sustainability of thermal energy storage [87], Figure 7. These wastes contain fats, oils, fatty acids, and sugars that can be transformed into waxes or fatty esters compounds highly effective at storing heat in the range of 20 to 60 °C [88]. Current estimates indicate that over 1.3 billion tons of food waste and approximately 190 million metric tons of waste cooking oils are generated globally each year [89–93]. Repurposing these waste streams for latent heat storage applications helps mitigating the environmental and economic impacts due to their disposal and offers a sustainable alternative to conventional PCMs used in thermal management systems [94–97]. Both natural and waste-derived oils and fats are organic materials suitable for preparing low-melting-point PCMs. In contrast, inorganic salts are commonly used to produce high-temperature phase change materials.

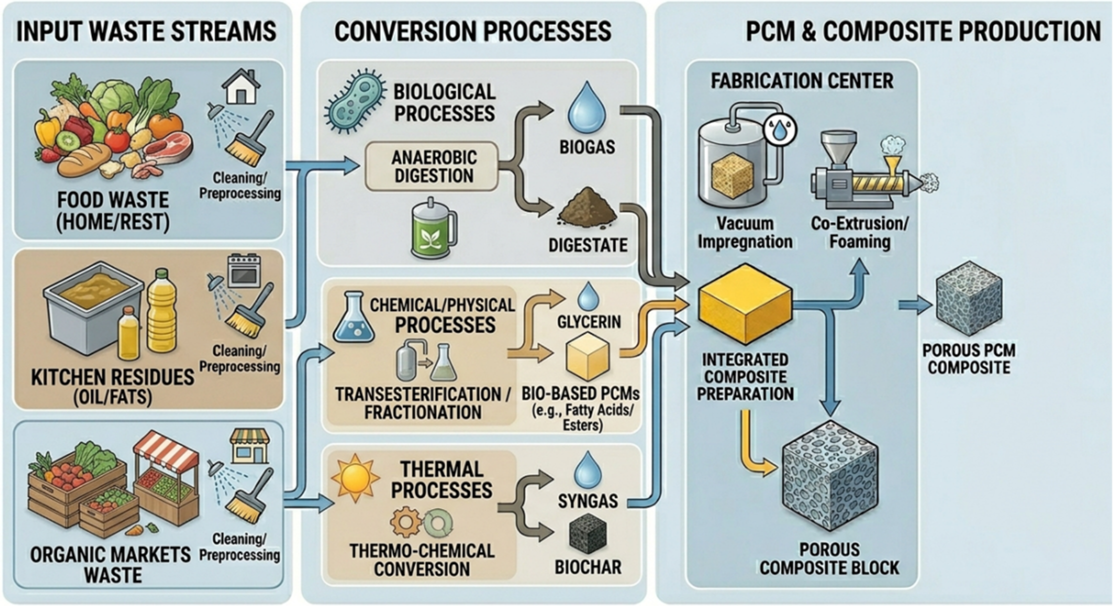

Figure 7. Flowchart of PCM process from food waste and kitchen residues.

Table 2 presents some thermal properties of composite PCMs derived from waste foods. It is evident that some of these materials, such as watermelon rinds and coffee waste, do not have specific melting point values in the literature. This is attributed to their impure nature; they do not possess a single, defined melting point like pure materials. This behavior stems from their complex organic nature, which tends to decompose thermally rather than melt, as their various components react to heat in multiple stages.

Table 2. Thermal properties of composite PCMs derived from waste foods (NA = Not Available).

Refs	Food waste	Processing Method	Thermal Conductivity ($W m^{-1} K^{-1}$)	T_m (°C)	ΔH_m ($J g^{-1}$)
[94]	Water melon Rind	Hydrothermal	0.78–1.09	NA	255.5–281.9
[95]	Pomelo Peel	Carbonisation	NA	58.3–63.9	159.4–166.4
[96]	Garlic Peel	Activation	NA	60.2	52.5
[98]	Rice Husk Ash	Acid, Ultrasonic	0.4168	48.2	95.7
[47]	Coffee Waste	–	0.14771–0.18869	NA	1.39–3.23
[46]	Cabbage Mustard	Pyrolysis	0.597	49.67–50.6	103.55
[99]	Fly Ash	Acid Treatment	0.95	45.00	42.83

Using food waste as a source of raw materials is a fundamental step in building a green, sustainable, and circular economy. This waste is converted into biochar used in the absorption of PCMs. This approach contributes to reducing emissions of CO_2, CH_4) and N_2O. Atinafu et al. [91] investigated the upcycling of food leftovers into high-value carbon materials for sustainable thermal energy storage. Using a simple vacuum impregnation method, the researchers converted common food waste into porous biochar with a micro-mesoporous structure and partial graphitization through carbonization and KOH activation. Activation produced greater carbon lattice expansion than in non-activated samples, enabling significantly higher phase change material (PCM) loading and enthalpy values, 243.9% to 346.9% higher compared to inactivated composites. The resulting biochar-supported PCMs also exhibited thermal stability and no leakage.

Studies conducted by Bragaglia et al. [92] have revealed that waste fat from sausages could serve as an effective and environmentally friendly solution for renewable energy applications involving thermal energy storage (TES), as well as a sustainable alternative to conventional synthetic phase change materials. This fat has melts at approximately 32 °C and has a fusion heat of about 20 J/g, making it a suitable for use in passive cooling systems. Jin et al. [93] discussed the potential for converting food waste into value-added products. For instance, food waste can yield several prospective PCM candidates, particularly in the form of oils and acids.

Liu et al. [94] proposed a novel strategy for manufacturing phase change composites from biomass-derived carbon aerogel (BDCA) and mannitol, using water melon peels as the raw material and a simple vacuum impregnation technique. Owing to its unique properties, BDCA serves as an ideal support material for producing stable phase change composites. The resulting BDCA/mannitol composites exhibited a high heat capacity exceeding 280 J/g, markedly reduced supercooling, enhanced thermal conductivity, excellent thermal stability, and outstanding shape retention during repeated heating and cooling cycles. Most notably, these composites achieved exceptional heat release efficiencies of over 95%. Li et al. [95] utilized pomelo peel to produce biocarbon through simple carbonization, which was subsequently impregnated under vacuum with four types of polyethylene glycol (PEG) of different molecular weights to obtain stable composites. The resulting phase change composites demonstrated high thermal stability, showing a mass loss of only about 5% and a loading capacity exceeding 20 times their own mass. Their solar thermal conversion and storage efficiencies ranged from 75% to 84% at temperatures up to 223 °C. Owing to their low cost and recyclability, these materials present promising potential for solar energy conversion and storage.

Using activated garlic peel, Luo et al. [96] developed a stable-shaped PCM (SSPCM) produced through hydrothermal treatment and chemical activation of raw garlic peels. Microscopic analysis revealed that the pores of the AGP were filled with paraffin, and the material exhibited a high specific surface area of 1309 m^2/g. The SSPCM showed good morphological and thermal stability. Xiong et al. [97] prepared eco-friendly, low-cost biochar microparticles from garlic stems (food leftovers). These GSB particles were incorporated into paraffin wax (PW) at concentrations of 1%, 3%, and 5% to evaluate their effects on thermal properties.

Waste cooking oils (WCOs) are generated globally from households, the hospitality industry, and other sectors. Presently, WCOs are mainly employed as feedstock for biodiesel and energy production. Beghetto [100] provided a review of the impacts, regulations, and their possible uses for producing high-value products. The results show that WCOs has a big potential as renewable resources and recommend collaboration among the involved parties to maximize the use of WCOs. Zadshir et al. [101] investigated the bio-PCMs derived from animal fats and plant oils as alternative substitutes to paraffin-based PCMs. The conversion of bacon fats to bio-PCMs offers advantages such as non-toxicity, availability, cost-effectiveness, and stability. The authors discussed future research and guidelines to develop the large scale production with improved thermal conductivity and large latent heat capacity.

WCOs produced in quantities exceeding 190 million metric tons annually are emerging as a viable resource for the production of waste-derived PCM. Their valorisation aligns with circular economy principles due to their waste origin, global availability, and large supply. However, their recycling is hindered by significant compositional heterogeneity arising from frying-induced reactions such as hydrolysis, oxidation, and polymerization [102,103]. The phase-change substances fractionated from waste cooking oil offer a significant cost advantage compared to conventional organic PCMs. Moreover, the methyl palmitate content in waste cooking oil is approximately 15%, making it suitable for large-scale recycling [104]. Previous studies have indicated that waste cooking oils possess favourable thermal properties for cooling and thermal management applications [105–108]. Saji et al. [89] blended waste cooking oils with soybean oil to develop PCMs for low- and medium-temperature applications. The blending process was conducted efficiently, ensuring that the materials exhibited the desired thermal properties.

De Silos et al. [109] explored the production of PCM from lauric acid derived from waste cooking oil, with coconut oil (containing 50% lauric acid) as the primary source. Using data from literature and field sources in Los Baños, Laguna, a plant design was proposed. The plant is capable of producing 6,200 m^3 of PCM (approximately 477,000 packs per year). The projected return on investment is 25%, with a payback period of two years. Zhao et al. [110] developed PCM capsules of wax from waste cooking oil for regulating asphalt binder temperature. Their findings indicated that hydrolyzed waxes are particularly suitable for this application because of their favourable phase transition temperature, high heat capacity, and strong thermal stability. Yunlong et al. [111] investigated the valorisation of waste cooking oil derivatives, particularly methyl palmitate (MP), as core materials for microencapsulated phase change materials. This strategy transforms waste resources into a functional PCM exhibiting a melting temperature of approximately 20 °C and a latent heat of 68 J/g. Among kitchen waste, edible oils may represent easy and affordable alternatives to conventional PCMs. They are readily available, relatively inexpensive, and have a good shelf life. In this context, Kawaji and White [112] tested margarine and coconut oil. Margarine was found to be unsuitable due to its low melting point and thermal instability, while the coconut oil exhibited thermal stability, high melting point (105 J/g), suitable transition temperature (24.5 °C), and poor supercooling, making it a promising option for use in building TES. Similarly, Zhau et al. [113] demonstrated that waste edible oils have a melting temperature of approximately 18 °C and a latent heat of around 140 J/g, which make them adequate for buildings' applications. Table 3 presents some potential kitchen wastes for PCM development.

Table 3. Potential kitchen waste sources for PCM development.

Source/Reference	Extracted Material	PCM Type	Phase Change Temp	Application
Used cooking oils [105]	Fatty acids (oleic, palmitic, stearic acids)	Organic (fatty acid PCM)	20–60 °C	Passive building cooling/heating
Animal fat residues [92]	Stearic/palmitic acid	Organic PCM	55–70 °C	Hot water systems
Fruit peels [106]	Biowax, pectin-based composites	Composite PCM	30–40 °C	Food packaging, cold storage
Egg shells, bones [107]	Calcium carbonate carrier for PCM encapsulation	Support matrix	N/A (as encapsulant)	Stabilizing PCMs
Coffee grounds, tea waste [108]	Carbon matrix for PCM composite	Encapsulation support	N/A	Shape-stabilized PCMs

Remarks

The review results showed that food leftovers and kitchen wastes contain fats, oils, fatty acids, and sugars that can be transformed into waxes or fatty esters compounds highly effective at storing heat from 20 °C to 60 °C. Repurposing these waste streams for latent heat storage applications mitigates the environmental impacts, the disposal economic issues and offers a cost-effective and sustainable alternative to conventional PCMs. Waste-derived oils and fats are organic materials suitable for preparing low-melting-point PCMs. The utilization of food wastes for producing PCMs and biochar for their absorption, is a fundamental step in building a green, sustainable, and circular economy.

6. PCM from Municipal Solid Waste (MSW)

The global MSW is estimated of more than two billion tons per year. This generation rate would result in 3.8 billion tons by 2050 which is seriously critical [114]. MSW generally encompasses non-hazardous solid and semi-solid waste originating from households, commercial entities, institutions, and non-hazardous industrial activities, as well as waste collected from markets, agricultural sources, street cleaning, and yards. By contrast, hazardous and infectious wastes—such as industrial by-products and untreated biomedical waste—are excluded from this category and are treated through distinct streams. The functions of MSW management extend beyond simple disposal; they encompass collection, transfer, transportation, processing, recycling, and final disposal. Each of these stages requires careful coordination to ensure that the environmental footprint of waste management is minimized while maintaining economic feasibility. MSW a has significant potential for energy supply [115].

Municipal waste including sludge is managed through methods like landfilling, incineration, or biological treatments such as anaerobic digestion and composting. However, they can be of a significant potential use in advanced energy storage technologies through the development of PCMs and their encapsulation, Figure 8. By embedding waste-derived materials into PCMs, research has identified opportunities to simultaneously address waste management challenges requirements of sustainable energy storage systems [116]. Linkage between MSW and sanitation further strengthens its role in resource recovery. For example, municipal sludge can be converted into composites with energy storage potential while non-biodegradable components such as plastics can be transformed into porous carbon for PCM encapsulation. These applications exemplify the versatility of waste streams in supporting both waste reduction and clean energy initiatives.

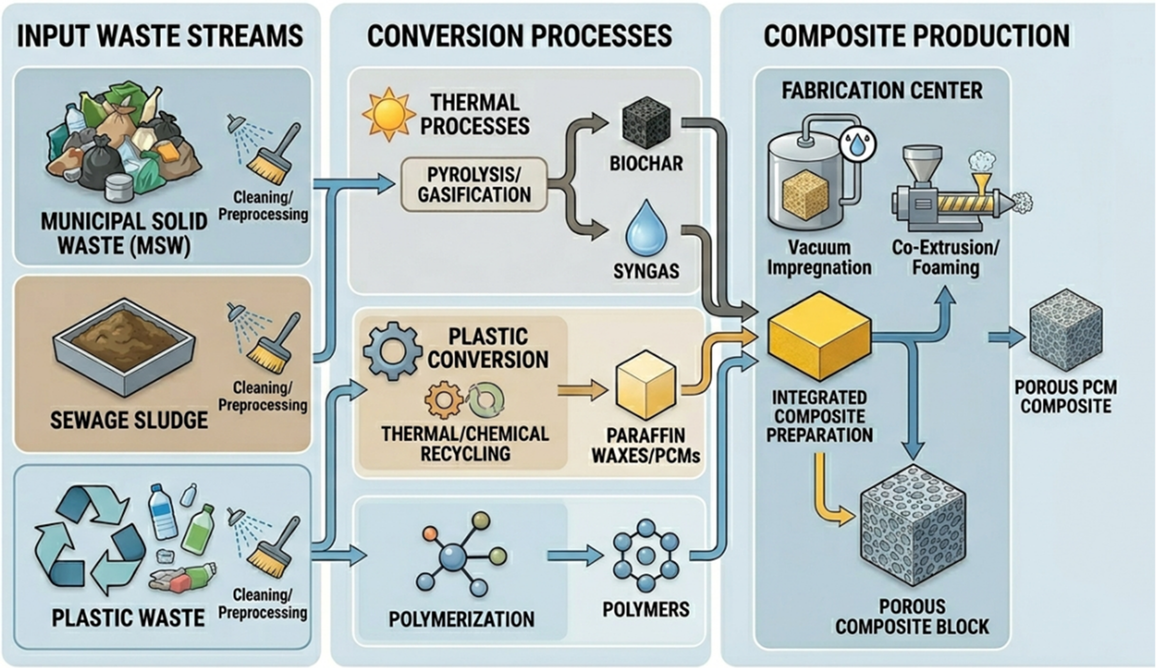

Figure 8. Flowchart of PCM process from municipal solid waste.

In a linear model, waste is primarily viewed as an endpoint, managed through collection, transport, and disposal, often in landfills or incinerators. However, such practices have proven unsustainable, given the mounting pressures of urbanization, population growth, and industrialization. The circular economy paradigm instead conceptualizes waste as a resource, emphasizing reuse, recycling, and valorisation to close the loop of material flows. Within this framework, MSW is no longer regarded as a liability but as a potential input for new value chains, including sustainable energy storage systems. Incorporating MSW into circular economy strategies provides multiple environmental and socio-economic benefits. First, the recovery of valuable resources such as plastics, organic matter, and sludge reduces the dependence on virgin raw materials. Second, integrating waste valorisation with energy systems, such as the development of PCMs, enhances the sustainability of both waste management and energy storage. Third, by extending the lifecycle of materials, waste valorisation reduces the environmental footprint associated with landfilling and incineration, processes that are often associated with methane emissions, leachate generation, and air pollution. Thus, Integration of MSW into circular economy models is not merely a technological shift but also a policy imperative. Governments, industries, and research institutions are increasingly called upon to design regulatory frameworks, financial incentives, and innovative technologies that enable the transformation of waste into value-added products. Among the most promising avenues within this context is the utilization of MSW in the fabrication and encapsulation of PCMs, which advances energy storage technologies. Valorisation of municipal solid waste (MSW) into PCMs represents a transformative approach that bridges waste management and energy sustainability.

Municipal sludge, a by-product of wastewater treatment plants, has traditionally posed significant environmental and economic challenges due to its moisture content and heavy metals contamination. Recent research [116,117] demonstrated that sludge can be combined with salt (potassium nitrate) to form low-carbon composite PCMs. Ash derived from municipal sludge was mixed with salt, compressed, and sintering process was performed to obtain phase change composite (PCC). The storage capacity of the derived product was about 330 J/g for equal ratio parts. Relatively significant thermal conductivity 1.04 W/(m·K) was obtained as well. Other advantages included high mechanical strength of 153.78 MPa alongside thermal stability and chemical compatibility of the composite components. This waste-derived composite not only provides thermal energy storage potential but also immobilize hazardous components, including heavy metals.

A dominant fraction of MSW is plastics. Waste plastics can be thermochemically transformed into porous carbon structures and interconnected pore networks ideal for PCM encapsulation. Such porous carbons can host organic PCMs like paraffin wax, preventing leakage during phase transitions while simultaneously enhancing thermal conductivity and stability. Research has been conducted to make use of these waste materials. Dai and al. [118] reviewed carbon materials produced from plastic wastes including graphene, carbon nanotubes (CNT), and porous carbon materials, which are commonly used for thermal performance enhancement of thermal energy storage through macro/micro/nano-inserts or as porous container. Graphene has excellent thermal conductivity therefore it is widely used to enhance thermal characteristics of PCM. It can be inserted as nanoparticles inside PCM to enhance thermal conductivity and reduce the supercooling effect [119]. Various techniques can be used for graphene production from plastic waste including pyrolysis [120]. Owing to their large surface area, layered structure, and superior thermal conductivity, graphene oxide nanosheets are used with PCMs. Moreover, the two-dimensional structure of graphene oxide allows for uniform dispersion of PCMs, which enhances energy storage stability and efficiency. Other promising and emerging thermal energy systems for instance hydrogel-PCM-thermoelectric generator in tandem structure [121] could benefit also from such sustainable waste-derived porous enhancement structures.

Bending of graphene nanosheets in hollow cylinders to obtain carbon nanotubes which has high mechanical strength, elasticity, and excellent thermal conductivity. Cheng et al. [122] reviewed preparation of CNTs from organic waste materials including plastics. One of the approaches uses porous carbon obtained from waste plastics through pyrolysis and chemical activation resulting in porous carbons with abundant pore structures. Porous carbon material can be produced from waste plastics using vacuum absorption approach [123]. These porous networks act as host frameworks for organic PCMs such as paraffin wax, effectively confining the liquid phase during melting, preventing leakage and enhancing the heat transfer efficiency and improving charging and discharging rates. This dual functionality makes porous carbon encapsulation one of the most promising techniques for waste valorisation. Numerous studies showed the high performance of porous structure for enhancing thermal energy storage [124].

Remarks

Studies have validated the potential of municipal waste in the development of PCMs, demonstrating both technical feasibility and environmental benefits and highlighted how waste-derived PCMs can be engineered for enhanced energy storage performance, while also addressing pressing waste management challenges. Waste materials can be converted into PCMs as well as supporting materials derived mainly from plastics waste. By converting plastic wastes into encapsulation matrices for PCMs, researchers provide an innovative outlet for recycling and upcycling plastics. From an economic perspective, the use of waste-derived resources lowers raw material costs. Conventional PCM encapsulation methods often rely on expensive polymers, inorganic supports, or advanced nanomaterials. Substituting these with waste plastics offers a cost-effective alternative while also alleviating the financial burden of waste disposal.

The scalability of these technologies is another important economic consideration. Municipal waste streams, including plastics, sludge, and other residues, are generated in large volumes worldwide, ensuring a steady and abundant supply of raw materials for PCM production. This availability enhances scalability and positions waste-derived PCMs as a sustainable option for industrial deployment. However, consistent quality and standardization of waste-derived composites remain challenges that must be addressed to enable widespread commercialization. At the policy level, supportive frameworks that encourage waste valorisation, promote circular economy practices, and incentivize innovation in energy storage are essential.

Although there are multiple waste streams from which PCM can be synthesised, the heat transfer properties and operating conditions of these streams vary widely depending on the source. Tables 4 and 5 provide an overview of these waste streams.

Table 4. Summary of waste-derived PCMs and their thermophysical properties.

Refs	Waste Category	PCM Source	Typical Melting Range [°C]	Typical Latent Heat [kJ/kg]
[34,45]	Agricultural and food	Glycerol and Olive oil, fatty acids, coconut	5–60	100–300
[57–68,71–73,125]	Industrial	steel slag, blast furnace slag, and red mud from aluminum production, silica	1200–1600	250–500
[46,47,94–96,98,99]	Food	Water melon, Rind, Pomelo Peel, Garlic Peel, Rice Coffee Waste	NA	100–300
[92,105–108]	Kitchen-derived	Fatty acids (oleic, palmitic, stearic acids), Stearic/palmitic acid, biowax	20–70 °C	100–300
[116,117]	MSW	Low-carbon PCM	NA	330

Table 5. Comparisons of various waste-derived PCM categories [29,75,91,92,126,127].

Category of Waste-Derived PCMs	Advantages	Limitations
Agricultural & food processing	Abundant, low-cost, renewable; good porosity for leakage prevention; improved thermal conductivity when carbonized; strong circular-economy benefits	Wide variability of composition; possible odor, biological degradation; often require carbonization/activation (energy input); mechanical strength of some biocarbons is low
Food Leftovers & Kitchen Waste	Operates at building-comfort temperatures; directly replaces edible oils/fats with waste streams; strong circular-economy value; supports made from the same waste stream improve stability and thermal conductivity	Latent heat of some pure fats is modest; risk of oxidation and rancidity, requiring encapsulation; composition varies with diet and cooking practice; pre-treatment and hygiene constraints
Industrial waste	High mechanical strength and porosity (FA/slag/tailings) reduce leakage and give structural robustness; very large volumes available; valorizes problematic hazardous wastes	Potential leaching of heavy metals or hazardous species; inconsistent composition; need for surface treatment; plastic-based PCMs may have low thermal conductivity and flammability issues
Municipal & domestic (MSW)	Integrates multiple waste streams (biological, industrial, construction) into building materials, significantly reducing operational energy and embodied carbon in envelopes.	Very heterogeneous feedstock; contaminants (metals, organics) and regulatory barriers; limited systematic data specifically on MSW-derived PCMs vs. "solid-waste-based supports" more broadly

7. Waste-Based PCM Encapsulation Technologies

Phase change material (PCM) encapsulation is a fundamental solution for increasing thermal energy storage efficiency. It acts as a barrier, preventing molten material from leaking and protecting it from reacting with the external environment.

7.1. Macro-Encapsulation

In this type of encapsulation, PCMs are contained within relatively large containers (greater than 1 mm), such as tubes, spheres, or sheets. These containers offer high leak-proof performance and provide robust physical protection for the material. However, the low thermal conductivity of PCMs results in slower thermal charging and discharging cycles. Among the most prominent waste-derived materials used in manufacturing these containers, recycled plastics, particularly high-density polyethylene (HDPE), are a suitable choice due to their high chemical and thermal stability.

7.2. Micro-Encapsulation

These capsules range in diameter from 1 to 1000 μm and are characterized by a very high surface area-to-volume ratio, which enhances heat transfer efficiency. These containers also possess high leak-proof capabilities, but they require flexible walls to accommodate the volume changes that occur during the melting process, as well as high thermal stability. Rice husks are among the most prominent waste-derived materials used in manufacturing these capsules, due to their richness in active silica, which contributes to the development of durable and fire-resistant coatings. Paper waste is also an important source for extracting cellulose fibers, which can be used to create porous structures that enhance the mechanical stability of phase-change materials (PCMs).

7.3. Nano-Encapsulation

This type of encapsulation deals with capsules less than 1000 nanometers in diameter and aims to improve the material's thermal conductivity and enhance its direct integration into fluids. It is characterized by high molecular-level effectiveness in reducing leakage, along with high thermal stability that significantly reduces the phenomenon of supercooling. Among the most important waste-derived materials used in manufacturing these capsules is biocarbon produced from agricultural waste through pyrolysis. It possesses a nano-porous structure and high thermal conductivity, making it an ideal medium for containing phase change materials (PCMs) and preventing their leakage with high efficiency.

8. Challenges and Limitations of Waste-Based PCMs

Despite the potential advantages of using waste-derived PCMs for thermal energy storage, various limitations and drawbacks must be addressed to achieve the commercial viability of these novel materials.

Firstly, the problem of heterogeneous feedstock is fundamental, as the composition of the waste varies with geographic location, season, the method used to collect it, and even the form of preliminary processing, leading to differences in thermophysical properties such as melting point, latent heat, and viscosity. Second, technical performance barriers persist. The majority of organic waste-based PCMs have low thermal conductivity, ranging from 0.15 to 0.35 W/m.K, whereas carbonized waste can increase it to about 1.09 W/m.K; these values remain inferior to those of metal foam and expanded graphite composites. Leakage after many heat-exchange cycles is a serious concern, as some researchers report that mass loss exceeds 5% after 100 cycles, and data on long-term cycles (beyond 1000 cycles) are scarce. Thirdly, there are environmental and health considerations related to contamination, since industrial wastes such as fly ash and sludge can contain hazardous metals like lead, cadmium, and chromium, and leaching studies are rarely conducted. In applications where bio-degradability and biocompatibility matter, there is insufficient information on how to handle waste-derived PCMs. There is also an inadequate evaluation of environmental benefits due to the absence of logistics and disposal considerations in lifecycle assessments that claim up to a 40% reduction in greenhouse gases. Fourth, economic and scalability limitations include high preprocessing costs (sorting, cleaning, drying, and purifying), low conversion efficiency (e.g., less than 20 wt% from plastic pyrolysis), and the complete absence of internationally agreed-upon purity, thermal, or safety specifications. Lastly, the lack of consistent testing procedures for leakage, cycling performance, and thermal conductivity hinders comparative studies across different works. The interconnected nature of the abovementioned limitations demands research on standards, longevity tests, environmental impact assessments, and effective manufacturing techniques [126,127].

9. Conclusions and Future Research Opportunities

9.1. Conclusions

Research has demonstrated the viability and importance of waste-derived PCMs and encapsulation and skeleton materials. Textile and organic waste conversion are promising areas, where studies reported that carbonized cotton fabric waste takes in as much as 70% polyethene glycol content without failure, and showed good performance.

In the case of industrial solid wastes materials like fly ash and steel slag, are repurposed as porous carrier materials for PCMs. Modifying these wastes can enhance their adsorption capacity for organic PCMs like paraffin, resulting in composite PCMs with robust thermal performance and stability suitable for waste heat recovery and building applications. Industrial sludge and metallurgical waste are key areas for reducing carbon emissions and promoting environmental protection. Research reports a drop of about 83.48% in carbon emissions from sludge used in concrete treatment as opposed to traditional cement. Furthermore, there is a variety of skeleton materials, including Al_2O_3, MgO, expanded graphite, fly ash, and semi-coal ash.

The use of wastes from the chemical and pharmaceutical industries involves valorizing specific waste streams by converting them into the active PCM material itself or using them for encapsulation to prevent leakage. Research involving plastic wastes has demonstrated the successful production of organic PCMs from waste plastics, such as low-density polyethylene (LDPE), via processes like pyrolysis. The resulting waxy products have thermal properties comparable to commercial paraffin wax PCMs and can be mixed with other waste polymers to create stable composite PCMs for applications like battery thermal management or construction. Research indicates significant potential for utilizing chemical and certain organic/fatty-acid-based pharmaceutical wastes in PCM production, primarily as composite materials or feedstocks for bio-PCMs, promoting more efficient, cost-effective, and environmentally friendly thermal energy storage systems.

Studies on environmental impact support the sustainability of waste-derived PCMs. From analysis, PCMs from used cooking oil demonstrated 40% drop in greenhouse gas emissions, or saving about 2.5 kg of CO_2 equivalent per kg produced. PCMs derived from agricultural wastes reduce energy use by 35% during production. Food residues and kitchen waste are rich in fats, oils, fatty acids, and sugars, which can be transformed into waxes or esters capable of storing heat within the 20–60 °C range. Repurposing them for latent heat storage not only reduces disposal-related impacts but also offers a cost-effective alternative to conventional PCMs. Certain industrial wastes, such as those from the sugar industry (leaves, residues, bagasse), can contain high concentrations of inorganic salts (e.g., NaCl) that may be extracted and utilized as inorganic PCMs for thermal energy storage.

The production of PCMs from MSW involves recovering materials that can serve as the core PCM or as supporting and/or encapsulating materials. Organic waste streams in MSW can contain animal fats and plant oils, which are non-toxic, and cost-effective bio-based PCMs. A process involving hydrolysis can convert these fats into PCMs with tunable phase change properties. Municipal sludge can be converted into PCM by combination with salts, while pyrolysis of sewage sludge produces biochar (carbon-rich material) which can be used as a matrix to hold liquid PCMs (shape-stabilized PCMs) to prevent leakage and improve thermal conductivity.

The conversion of waste streams into valuable products such as PCM and integrating them into applications such energy storage systems, building sector, food transport and processing among others, can help addressing pressing challenges such as pollution reduction, resource conservation, and climate change mitigation, while simultaneously promoting sustainable waste management practices and circular economy.

9.2. Future Research Opportunities

Research on PCMs production from agriculture and food processing wastes needs to focus on improving inherent drawbacks such as the low thermal conductivity and leakage resistivity, which involves developing PCMs composites by using the waste material itself as a porous carrier or incorporating additives/nanostructures to enhance thermal performance. Also, future research should address the chemical stability of the waste-derived PCMs, including minimizing super-cooling, biodegradability, biosafety and preventing degradation from microbial activity or oxidation, besides developing robust encapsulation methods to ensure PCM integrity and enhance leakage resistivity.

Research involving industrial waste for production of PCMs should focus on performance enhancement, encapsulation techniques, and system integration to achieve sustainability goals and improve energy efficiency. Research must ensure the long-term chemical and thermal stability of the waste-derived material and verify its compatibility with container's or encapsulation materials to prevent corrosion or degradation.

The integration of municipal waste as well as other waste streams into the production of PCMs holds significant promise, but several technical challenges still limit wide adoption. These challenges are related to material consistency, energy storage density, and long-term durability. Addressing these issues is critical to advancing waste-derived PCMs from experimental concepts to commercially viable solutions. One of the most persistent technical concerns is the heterogeneity of waste streams. This variability complicates the standardization of waste-derived PCM composites, as inconsistent properties may cause variations of the thermal performance and structural instability.

Investigations have validated the potential of municipal waste in developing PCMs, demonstrating both technical feasibility and environmental benefits. The encapsulation technologies address key limitations of PCMs and expand their applicability in energy storage. However, optimizing encapsulation processes remains an ongoing area of research, particularly with respect to adjusting thermal performance, and cost-effectiveness.

Comprehensive studies are needed on the long-term performance and durability of waste-derived PCMs under repeated thermal cycling to ensure their reliability over an extended lifespan.

Author Contributions

K.A.R.I.: conceptualization, methodology, reviewing and editing; F.A.M.L.: writing—original draft preparation, reviewing and editing; A.A.: writing—original draft preparation, reviewing and editing; A.L.: writing—original draft preparation, reviewing and editing; A.M.: writing—original draft preparation, reviewing and editing; N.H.H.: writing—original draft preparation, reviewing and editing; M.T.: methodology, supervision, reviewing and editing. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data is available upon request.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work the authors used the Gemini (Google AI) for the generation of Figures 5–8. The AI was provided with specific technical text by the authors to ensure the accuracy of the illustrated processes. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Abbreviations

BDCA	Biomass-derived carbon aerogel
Bio-PCM	Bio-based phase change material
CNT	Carbon nanotubes
GHG	Greenhouse gas
GSB	Garlic stems biochar
PCC	Phase change composite
PCM	Phase change material
PEG	polyethylene glycol
PW	Paraffin wax
SSPCM	shape-stable phase change material
TES	Thermal energy storage
WCO	Waste cooking oil

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